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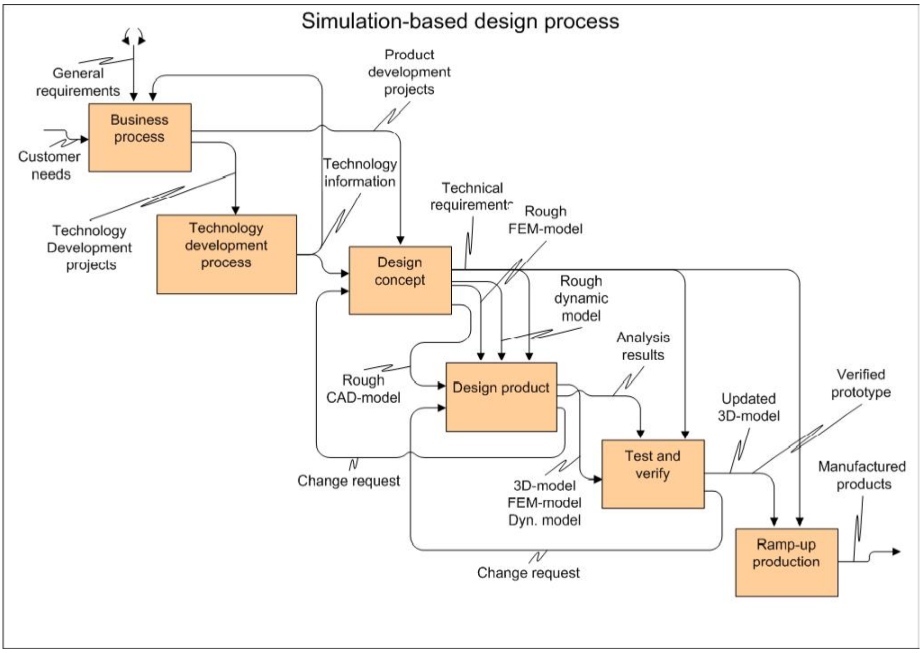

Mikko Lehtonen (ed.)

Simulation-based design process of smart machines

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Edited by

Mikko Lehtonen

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Abstract

This publication is intended to serve as a key to the results of the research project ‘Simulation-based design process of smart machines (KONEMASINA)’. The basic idea of the project was that the simultaneous design of different technical processes is inevitable in order to develop modern, optimized products. The project had three principal themes: simulation-based design, control of machine reliability and operability and the interaction between these two.

The project included development of simulation-based design processes and particularly application of computer simulation tools and methods on these processes, and actual modelling- and simulation-related practices in managing complex sub-models as well as an overall system simulation model base. Methods and tools were developed for the use of real-time simulators and virtual technologies in the product development process, such as condition monitoring, operator training and determination of a customer’s needs regarding new procedures and products. The practical process of determining dynamic properties of components for simulation work was developed. This study aims to enhanced simulation model with adequate methods and tools focused on an interactive human machine system.

A new concept for model- and simulation-based machine operability and reliability was studied. This publication also represents methods for reliability analysis and real time simulation applications, as well as load monitoring applications and solutions for estimating remaining lifetime. Methods to control safety and reliability in product design, applications of probability-based design methods and ways to control various uncertainties were studied.

Preface

This publication is intended to serve as a key to the results of the research project 'Simulation-based design process of smart machines (KONEMASINA)'. The project was part of the national 'Technology programme for mechanical engineering (MASINA)'.

The basic idea of the project was that the simultaneous design of different technical processes is inevitable in order to develop modern, optimiszed products. The project had three principal themes: simulation-based design, control of machine reliability and operability and the interaction between these two.

The project was divided into seven work packages. These work packages, and the persons in charge, were
– Simulation-based design process. Mr. Juha Sääski[1].
– Dynamic properties of structural components. Mr. Markku Juntunen[1].
– Product and system simulation. Mr. Tero Kiviniemi[1].
– Real-time simulation and virtual reality technologies. Dr. Asko Rouvinen[3].
– Future operating place. Mr. Juhani Viitaniemi[1].
– Control of machine reliability and operability. Mr. Jari Halme[1].
– Safety and reliability in product design. Dr. Tiina Ahlroos[1].

Research partners in the project were VTT Technical Research Centre of Finland, Lappeenranta University of Technology, Tampere University of Technology and Helsinki University of Technology.

The project manager was Mr. Mikko Lehtonen[1] and the manager in charge of the project was Mr. Pekka Koskinen[1]. The chairman of the project management group was Mr. Timo M. Pekkarinen, Metso Oyj (2002–2004) and Mr. Jorma Nurmi, Kalmar Industries (2004–2006).

The project was funded by Tekes (Finnish Funding Agency for Technology and Innovation), Armeka, John Deere Forestry, Kalmar Industries, Finnish Navy, Metso Oyj, Metso Paper, Moventas, Nokia, Patria Vehicles, Teknikum, Wärtsilä and VTT.

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I would like to thank all project partners: researchers, representatives of companies, Matti Säynätjoki (Tekes) and Juhani Lempiäinen (MASINA-technology programme) for their contributions to the project and excellent co-operation.

Espoo, May 2006 Mikko Lehtonen

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Contents

1. Introduction

The roles of machine end user and manufacturer are changing, with the focus shifting to core competence and networking. The product is no longer simply a machine but production capacity; for example, machine maintenance is managed by the manufacturer. The end user can thus focus on core competence rather than on maintaining machines. The share of service business operations is indeed growing. Carefree and reliable use is expected of the machine. This goal is achieved through good design and manufacture and by increasing the intelligence of the machine. In the industry the message is clear: in the future, the focus must be on operational reliability and related costs, and the provision of operational reliability warranties calls for new and highly developed, comprehensive design methods.

The speed, quality and cost-efficiency of operations form important competitive advantages. Companies are increasingly interested in product sustainability throughout the entire life cycle. The information that can be gained from the product is constantly increasing, as, for example, automation, sensors and diagnostics during use are becoming more common. This increases the demands on the product process and product data management.

Modelling and simulation are becoming more common in the development of products and systems. Products are more complex. Managing and optimising the overall solution is becoming increasingly important. It should be possible to combine all factors essential to operation in a simulation: mechanics, actuators, control systems, active components and structures, user impact etc. on the system to be analysed.

Broad utilisation of simulations significantly expands the product model. Simulations add their own requirements to the product information and its documentation. It is necessary to always ensure the availability of the latest data. It is possible to construct approval procedures for changes in the product data and the results of the simulations and analyses, thus easing the work of the networked product development community. A simulation-based product development process requires a systematic approach to assembling and managing the simulation data.

Information technology has strongly changed the way we work and the characteristics of the workplace. Virtual reality and especially augmented reality ensure that this changing will go on. In the future, a safe user location and interface will include more and more technology based on continual, real-time simulation. Multi-technical machines will be interactively controlled and operated with the help of an intelligent user interface/control. Development targets include, e.g. interactive controls with multiple sensors, data presentation methods as well as automatic, user-specific adaptation features.

With the help of virtual prototyping and simulation, the human machine interaction can be tested already at the design phases. For example, it will be possible to evaluate and develop safety and comfort by analysing human load. In a human machine system model, it will be possible to take into account, e.g. mechanics, acoustics, air-conditioning, electronic and electrical equipment and control devices. Factors that can be simulated through a system model include safety and ergonomics as well as the core processes of managing user interface functions.

Real-time simulation is needed when one wants to study human impact to system, or when real components or subsystems have been added to the simulation (Hardware-in-the-Loop simulation). In real-time simulation, time proceeds at the same speed as in the simulated system, in other words, the rate of change in the state of the system in the simulation is the same as in the real world. Real-time simulation and virtual technologies are areas generating a lot of interest in various fields. Virtual technologies are already being used to a fairly large degree, but real-time simulation is still mostly utilised for research or training purposes. For example, real-time simulation provides efficient tools for the development of control systems as a real control system can be attached to the real-time simulation system.

The dynamic behaviour of machines and devices is often significantly impacted by small but important structural components. Such structural components include various connections, fixing elements as well as shock and vibration insulators. In vehicles, special features include the tyres and the engine suspension system. Devices containing electronics, on the other hand, have various mechanical systems to protect the sensitive electronic components. If these components, crucial to the dynamic behaviour of the product, are not sufficiently taken into account, simulation models cannot provide very good results. The dynamic properties of structural components are often complex. Strong damping, various damping mechanisms, cross coupling of different translation directions and fundamentally non-linear behaviour all require the adoption of highly developed modelling and response calculation methods.

Simulations can be utilised in many ways in managing machine reliability. With simulations it is possible to calculate responses caused by faults in the machines, which, on the other hand, can be utilised when diagnosing those same faults. Variables that are difficult or expensive to measure can, thanks to real-time simulations, be calculated in the condition monitoring system. It is also possible to compare the variables measured to those received through real time simulation, in which case any differences may indicate faults. Diagnostics data can be used in machine control. When, for example, the expected service life of the machine is estimated on the basis of the data received, it is possible to prolong its service life by slowing down certain processes causing strain and thereby achieving the desired length of service. Design requires more detailed information about load and strain on the machine as well as operating conditions. Design is still often based on imperfect data. By combining simulation-based design and control of machine reliability and operability to feed off each other, it is possible to achieve significant advantages.

2. Simulation-based design process

2.1 Introduction

2.1.1 The need for the improvement of the design process

The actual elaboration of the product development process was first touched on in the 1920's, but it took thirty years for the first suggestions for the systematic methodologies for designing products to be published. The first actual methodologies for the product development, which were published in 1965, were Hansen's Konstruktionsystematik [Hansen 1965]. As early as in this methodology, the product development project was divided into clear and distinct stages. The following step was taken in the 1980's and several design process models were presented [Andreasen & Hein 1987, Pahl & Beitz 1977, Hubka 1987, Roth 1981, Tjalve 1979, VDI 2221 1987]. These methods presented the product development as an algorithm, in which the goal was generally to improve product development. Later 1990's design process models were extended to cover production, quality and economy issues and tools to control the above-mentioned issues were also connected to the models [Pugh 1991, Pugh 1996, Suh 1990, Ulrich & Eppinger 1995]. The most significant trends during the last few years for the design process model has been NPD (New product development), see for example [Cagan & Vogel 2002]. NPD-based process models emphasise customer-orientation and thus these models emphasised consumer products. However, the contents of the actual design process phase have not really changed from what they were in the models of the 1980's.

The applicability of design process models has been criticised because a universally applicable path or order of functions which could be used as such in all the product development projects does not exist. Instead, the theory models can be used as reference models from which suitable items are brought into use and supplemented by specific tools according to an enterprise's field of business [Andreasen & Hein 1987]. A reason for the minor adapting of design process models is that the improvement concentrates on the introduction of new tools, such as the CAD, CAM and CAE, and the product process itself is not perceived as the subject of the development. Also, there is a lack of people at the management level who would have time to study the newest research results and adapt them in practise. The persons who work in product development are bound up with designing products, so they do not have time to go into the product process itself. Characteristic of the design work are several overlapping projects and hard schedule pressures. The customers and the management of the company wait for the immediate reaction to new demands and to the emerging problems. The working method at its worst may be like damping fires [Birkhofer 2005]. Furthermore, the product process improvement does not show any direct advantage, as in for example the introduction of new design software tools.

The significance of the uniform product process, however, will increase when the product development enlarges to contain the whole product life cycle. When manufacturing, maintenance, supplementary services, recycling, etc. are considered, the scope of the product process will increase and at the same time its controllability will become more difficult. The distribution of product development work between partners has the same effect. Many subcontractors bear the responsibility for the product made by them and controlling the whole is difficult if the conceptual system of the product development is very different in the companies which make the same project. Uniform methods ease the control of the product process.

The problem in the big companies is to find a process model which is simultaneously practical and universally applicable enough. Furthermore, there should be an advantage from the use of the model to the project leaders, as well as to the designers, so that it will be implemented.

2.1.2 Objectives

The main objective was to improve the effectiveness of the product development process when product simulations are utilised. The sub-objectives were:

- to develop methods for discussing the product development process in a systematic way
- to identify what possible problems the simulation-based product process brings out in the product development
- to secure as efficient utilisation as possible of different product simulations

- to improve product development in which the simulation tools are integrated into the whole life cycle of the product.

2.1.3 Combining modelling and simulation in product development process

Computer-based modelling and simulation assists in developing an idea into a product and in the improvement of the properties of the existing product. This improves the competitive ability of the company and shortens the path of new innovations from the idea to the market. Increasing requirements for existing products calls for e.g. environmental-friendliness, cost-orientation and adaptability. Using modelling and simulation it is possible to improve product life cycle cost and usability. The enterprises which aim at competitive ability really have to invest in top know-how when it comes to modelling and simulation.

The use of simulation methods belongs to modern product development. The advantages which are reached with the simulation are manifold: expensive and time-consuming prototypes and the number of the tests decrease, the properties of the products improve, the time which is used for making products shortens and the quality standard of products rises. The simulation tools also have progressed.

In the future there will still be growing challenges. The introduction of modelling and simulation requires a lot from the whole product development organisation. To seamlessly combine modelling and simulation in the product development requires a new way of thinking in the whole product process. Payback from an investment to simulation is shifted towards the quality, price and usability of the products. The product portfolio, the modelling resources and simulation resources (the product developers and software & devices), and networking possibilities affect the right strategy for how the modelling and simulation of the product should be connected to product development.

2.2 Methods

This research studies six different theoretical product development models with a standardised IDEF0-flowchart, in order to make them easily comparable with each other. These six models were the basis for a reference model that was used as a communication tool in interviews with product development management members. The generic model was composed after interviewing the design project leaders of five different companies.

The product development theories found in literature are quite similar, but they differ from the process used in companies. The process used in companies includes less tools (e.g. for innovating) and is usually more focused on gathering technological information and administrating ongoing development projects than theoretical models.

To make the product development processes easily comparable, they needed to be harmonised. This was done by modelling all of the product processes with the same modelling language. The IDEF0 was chosen as the modelling tool because of its simplicity and good experiences of it in the same type of projects. To gather the necessary information about the product development process in industry, a series of interviews of design project leaders were carried out.

2.2.1 IDEF0

The IDEF0-flowchart (IDEF0 1993) used for modelling all the product processes in this research is a standardised, purpose-built tool for modelling decisions, functions and actions in an organisation or a system. IDEF0 was chosen because the models made with this technique are relatively simple to understand, even without prior experience. The models are very straightforward and therefore they are usually interpreted right even without prior knowledge of the semantics of the system. IDEF0 models use only a very limited amount of symbols and with the decomposition technique they can be focused to a suitable level of detail.

The two primary modelling components are functions (represented on a diagram by boxes) and the data and objects that inter-relate those functions (represented by arrows). Each side of the function box has a standard meaning in terms of box/arrow relationships. The arrows may represent inputs, outputs, controls, mechanisms or calls for other processes (Figure 2.1).

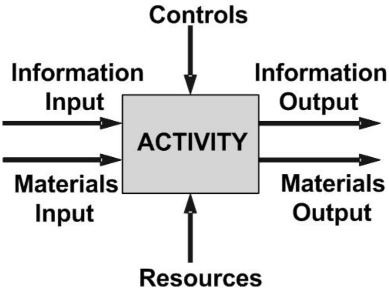

Figure 2.1. The basic concept of the IDEF0-method.

Every IDEF0 sheet may contain between three to six functions and every function can be decomposed into its own sheet as a new sub-process. The decomposition can be continued until the subject is described at a level necessary to support the goals of a particular project. Therefore the same model can be shown at a very detailed level or in a more general view to give a good overall understanding of the modelled process. In this research the models were usually modelled down to the third level from the main diagram.

2.3 The comparison of product development theories

Six widely-recognised product development processes were chosen as the basis of the research. The chosen processes are the Systematic Approach of Pahl and Beitz (SAPB) [Pahl & Beitz 2003], Generic Product Process of Ulrich and Eppinger [Ulrich & Eppinger 1995], Pugh's Total Design [Pugh 1996], Integrated Product Design of Andreasen [Andreasen & Hein 1987], Suh's Axiomatic Design [Suh 1990], and TRIZ [Mann 2002]. All processes were modelled with IDEF0 flowchart tool in order to make them easily comparable with each other.

Thirteen different aspects of the methodologies, which describe the basic elements of each methodology, were compared and the similarities and differences were highlighted.

The SAPB-model covers the entire design process from task clarification to the detail design phase. Other models have concentrated on more or less narrower parts of the design process. All of the models have some sort of guide to clarifying the task and formulating the problem, but the next step, the generating of solutions, is guided only in SAPB, GPP, Triz and Axiomatic Design. The IPD and Total Design do not have any tools implemented to guide the generation of solutions.

The search space of potential solutions is limited only in TRIZ, which right from the early stages of the design process focuses only on the most promising solutions and assumes that the existing system is changed as little as possible. This approach requires less work, but may lead to some promising solutions being neglected. Other product development processes in this research have a much wider scope for the solutions; actually they try to widen the search space as much as possible by making the problem formulation as abstract as possible. This ensures that no promising solutions are missed, but requires more effort.

The IPD-model doesn't contain any tool for evaluating the solutions found; the others however have some kind of rules as to how the evaluation should be carried out. The second axiom of axiomatic design guides the evaluation phase. According to this information axiom, the design which has the smallest information content, i.e. which is the simplest, is the best. Because TRIZ tries concentrate on the best solution from the very beginning of the design process, it has no evaluation tool, though it has a checklist to ensure all the necessary matters have been taken into account.

Differences between different theoretical models are minor. Some models place more emphasis on the manufacturing stage, some on marketing etc. In addition, the amount and type of methodologies to be used as tools in different stages of the product development process vary from one model to another. The product embodiment stage itself is quite similar in all of the six models.

2.4 Generating the model of the product development process used in industry

The generic product development process model was composed after interviewing the design project leaders of five globally operating Finnish companies (Figure 2.2). All of the project leaders involved had participated in a large scale product development project in their company within the last twelve months. The interviews were based on the IDEF0 model, mainly made out of the SAPB. This model, which we will call the reference model, was chosen as the basis of the research because it is widely used in product development education and therefore quite well-known.

Together with the design project personnel, the differences between the reference model and their product development process were identified by adding or hiding functions. Based on the interviews, a company-specific IDEF0-model of the product development process was created and verified with the personnel of the company in question.

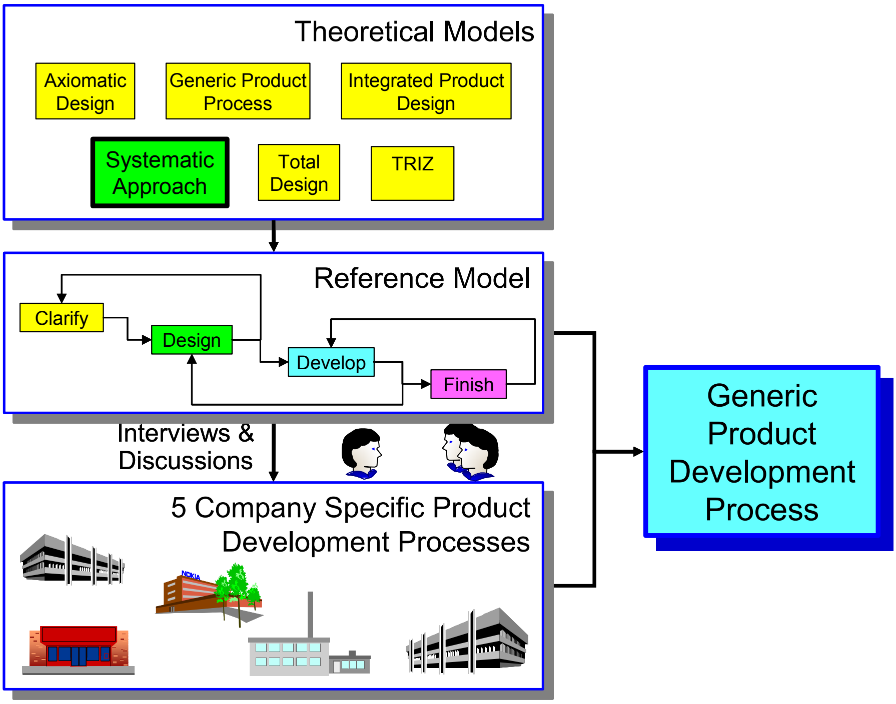

Figure 2.2. Method for generic product development process.

2.5 Present practices of the studied companies

The product process used in industry is divided into six phases (Figure 2.3). The first stage is the business process, where business cases are investigated and technology development processes or product design processes start. In a technology development process, new technologies and components are researched and the technology information collected in this phase is transferred to the first stage of the product development process, the conceptualisation, or back to the business process as information.

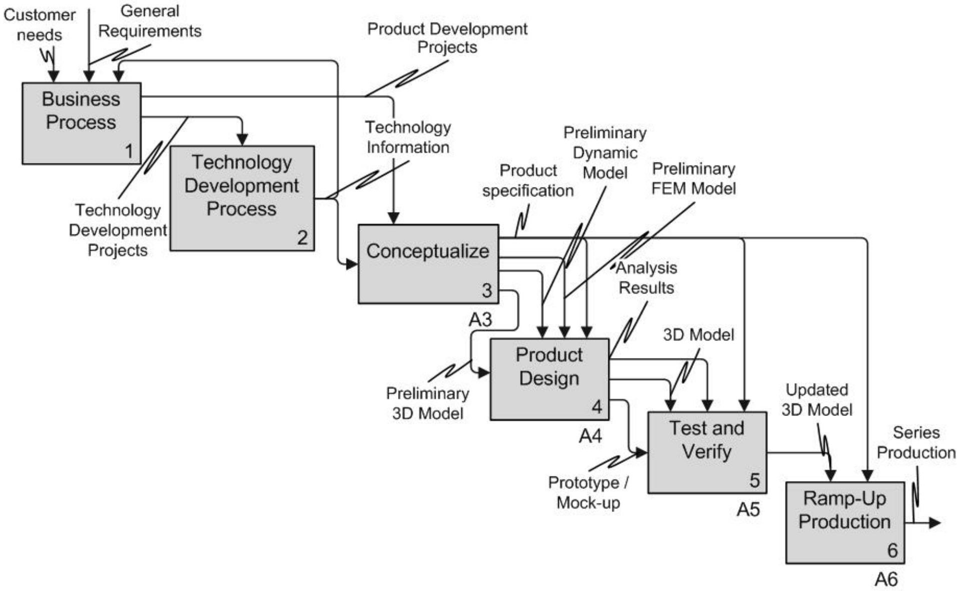

Figure 2.3. The overall product process used in industry is divided into six phases.

In the conceptualisation phase, the preliminary 3D-CAD model of the product is created and the first simulation tests are carried out (Figure 2.4).

The principal solution of the product is outlined by making the simple 3D models and carrying out preliminary dynamic and structural analyses. The load information needed in the structural analyses is obtained as the results of dynamic analyses. The concept sharpens up iterating between modelling and the analyses to the level in which the coarse 3D model of the product exists. The model contains all components and subsystems which are essential from the point of view of functionality, but details like chamfers have not been designed. In a very iterative manner, the concept is finalised and the product design stage begins.

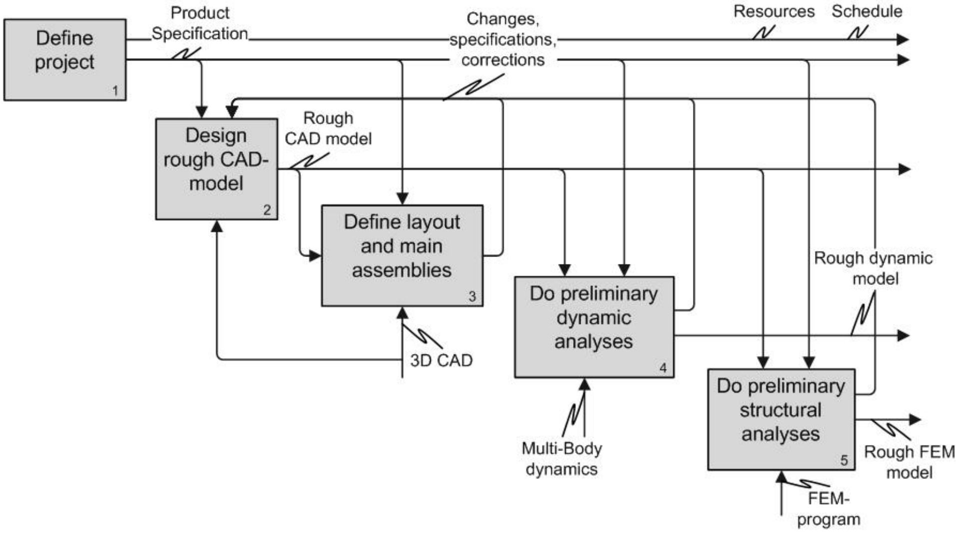

Figure 2.4. The conceptualisation phase is divided into five phases.

In the product design phase (Figure 2.5), the preliminary CAD-models are detailed with iterative cycles of simulation, tests and redesigning. All the parts and components are designed in detail, iterating between the 3D modelling and dynamic and structural analyses. The building of the prototypes of the whole product or part of it, or of different mock-up models is begun when the design of the product has proceeded to a sufficient level to build the models in question.

After suitable results have been obtained from the tests, the simulations are verified by the means of prototype tests (Figure 2.6).

The tests are performed according to the testing plan. The purpose of the tests is to make sure that the product meets the demands of the specification: for example operating characteristics, serviceability and performance. The results of the prototype tests are compared with the results of analyses that have been done at the product design stage. If there are significant differences between the real tests and the analysis results, the input parameters of analysis methods or methods themselves have to be explored for future needs. The design errors that have been perceived in the prototype tests are corrected, the necessary parts or components are designed again and the changes are updated in the 3D model. Prototype tests are carried out with the renewed parts to the extent necessary. Redesign and testing are performed until the demands of the product specification are met.

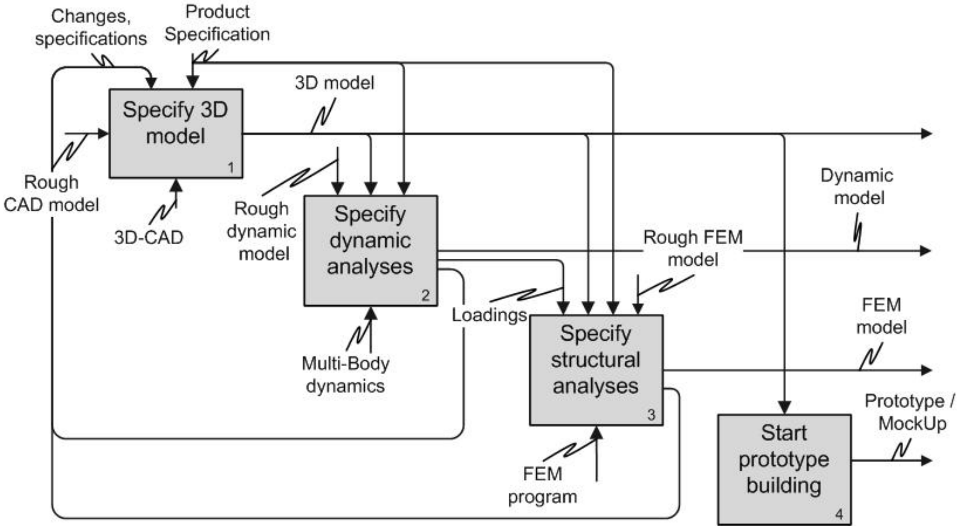

Figure 2.5. The product design phase.

The necessary changes to the product are made and production is ramped up. The verification results are also used to update the simulation tools to make them more accurate.

2.6 Theoretical models versus generic product development process

There are big differences between the product development theories and the synthesis model, i.e., the current method of action. The biggest difference can be noticed before the product development itself starts. The companies use much more effort in managing their product portfolios. Business cases are studied very carefully and only the most promising projects are funded. The second stage after the business case is researching and developing new relevant technologies, methods and tools to be used in the future products. In this phase, both simulation software and prototype tests are used. The strong emphasis placed on the technology development stage might be a result of the cooperation that companies have experienced in technology development programmes in Europe and in Finland.

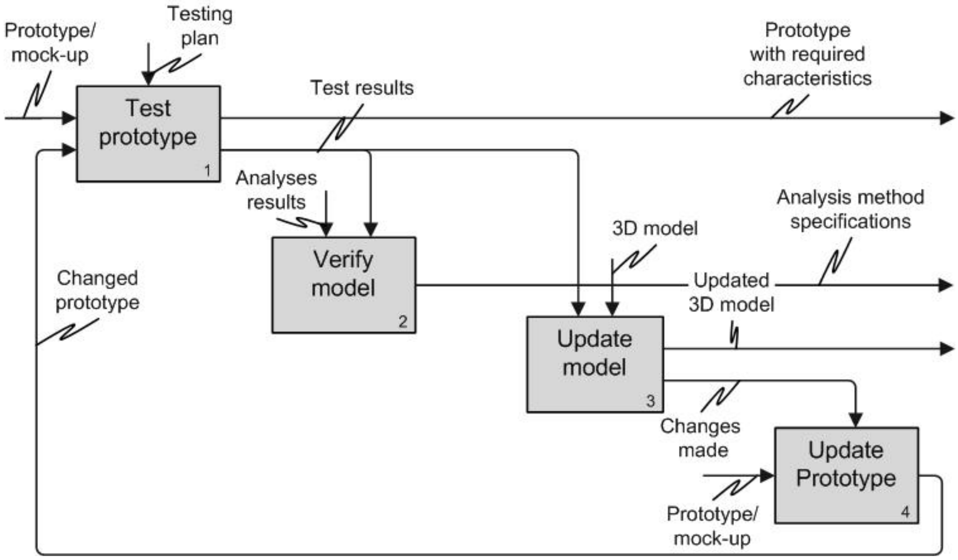

Figure 2.6. After suitable results have been obtained from the tests, the simulations are verified by means of prototype tests.

The conceptual design and the embodiment design stages are much more iterative than those in theoretical models. Design solutions are found with the aid of simulation tools and 3D-CAD-systems by the active probe-and-learn type of design, instead of using methods, like establishing function structures and searching for solution principles, that form the key concepts of Engineering Design by Pahl and Beitz. In general there has been a shift away from the traditional way of using simulation as a verification tool towards using simulation for studying different design alternatives. The simulation of the product is a visual and powerful way to add to our understanding of the behaviour of the product.

Based on the current research, we have defined a requirement list that will act as basis for future research:

- sufficient information for each simulation in each design stage
- feedback from simulation to design phases (simulation results)

- guarantee usability by reducing design work load
- control of “must-be” documents (safety, environment, etc)
- creativity methods included
- possibility to integrate data flow between sub-contractors
- guidance in making simulation models
- generic enough to support different types of projects
- control over acquiring knowledge from the project history base
- guidance and criteria for project evaluation (gate model)
- support for harmonising design terminology (design process dictionary)
- support for using different models for simulation (rough, detailed).

2.7 Simulation-based design process

Simulation-based product development can be very challenging for organisations. This is due to the many new techniques required in order to bring the product development process to a new level. Information and new ideas must be created, examined, processed, tested, and transferred to organisations.

An analysis activity may seem to be performed ad hoc, but it is always based on a lot of experience and careful consideration [Andersson 1999]. The reason for conducting a modelling and simulation activity is always a request to determine what behaviour a specific product or part of a product shows in a specific situation. A general description of the analysis activity is given in IDEF 0 notation in Figure 2.7.

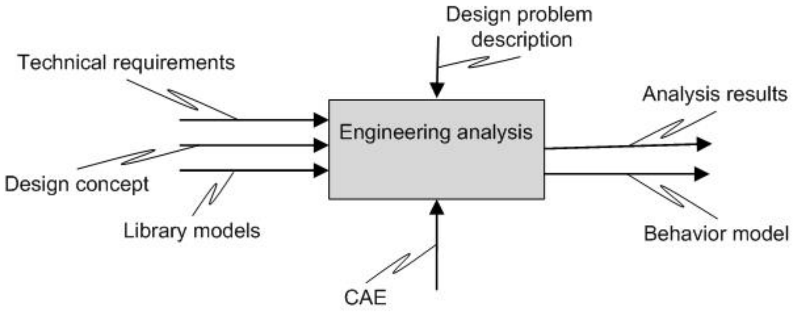

Figure 2.7. A general description of the analysis activity.

The description in Figure 2.7 says that the engineering analysis activity has three input sources; a design concept, technical requirements and library models. Library models are prepared and stored models of some or all parts of the design concept. The design problem description is a control mechanism that will give the scope of the analysis, and CAE refers to the mechanism or tool that will assist the activity. As a result of this activity, we will reach a behaviour model of the actual system and numerical results from a given set of boundary conditions.

The presented simulation-based design process consists of six phases (Figure 2.8). The input of the process is customer needs and the output of the process is the product launch. The two first stages remain the same as in the present practise of studied companies. The first stage is the business process, where business cases are investigated and technology development processes or product design processes start. In a technology development process, new technologies and components are researched and the technology information collected in this phase is transferred to the design concept phase.

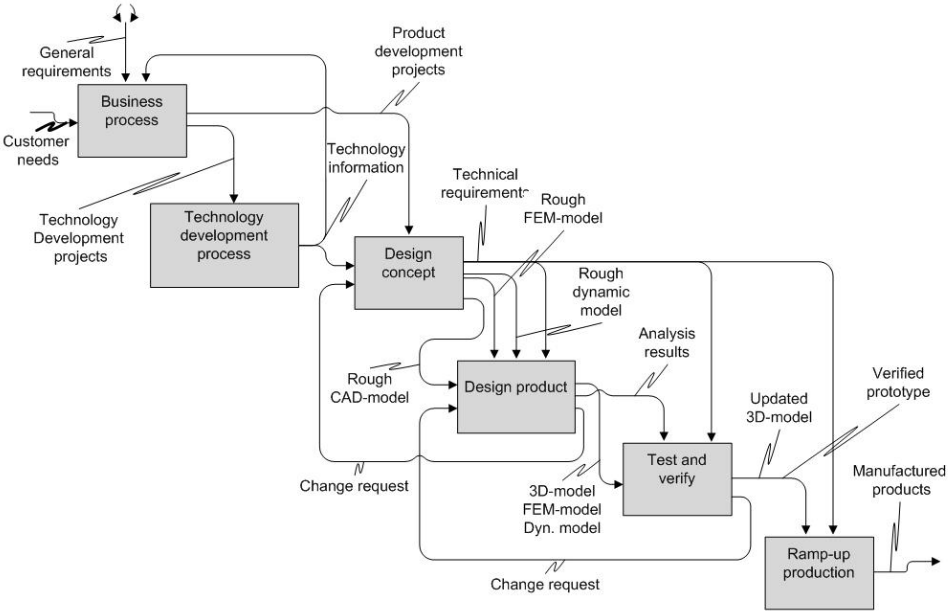

Figure 2.8. The simulation-based design process. The topmost level includes six phases.

2.7.1 Design concept

In the design concept phase, the technical requirements are identified, and they control establishing function structures for the input for making rough CAD-models (Figure 2.9). In this context, the CAD-model comprises components and assemblies. The rough CAD-model is a simple representation of the product, and can be basic 3D solids, such as blocks and spheres. Rough CAD models are utilised in analysing spatial constraints ("Analyse kinematics"), simulate strength and dynamic behaviour. Strength and dynamic simulation results, such as displacements, stress, strain, acceleration and velocity are analysed to evaluate different design concepts. In this phase, alternative product concepts are generated and evaluated, and a single concept is selected for further development. A concept is a description of the form, function, and features of a product and is usually accompanied by a set of specifications, an analysis of competitive products, and an economic justification of the product development project.

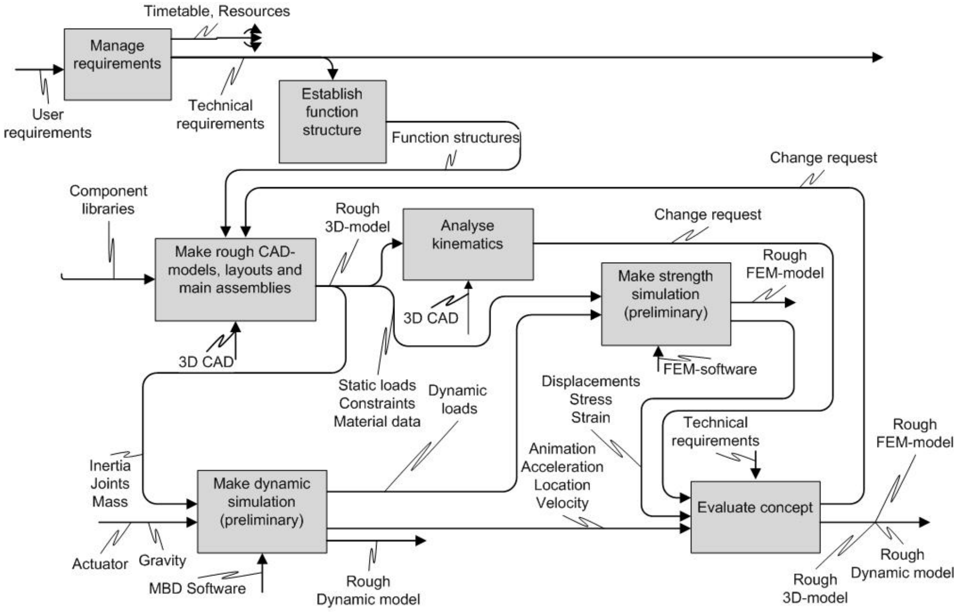

Figure 2.9. The design concept phase.

Dynamic analysis

In the concept phase, dynamic analyses using the coarse method are performed. The suitability of the mechanical design may be assessed using dynamic and strength simulation techniques. A CAD model of the concept is generated and dynamic analyses can be performed. A dynamic simulation is performed to assess e.g. dynamic loads on a mechanical structure. The structural finite element model (FEM) parameters may be utilised in order to consider flexibility issues. Dynamic loads on a component may reveal structural deformation, which can be eliminated through modification of the mechanical design. (Figure 2.10.)

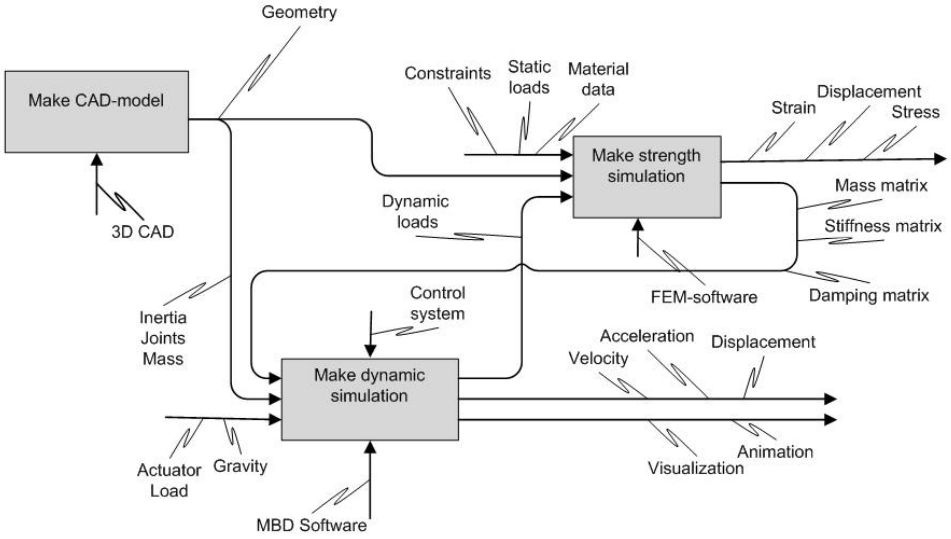

Figure 2.10. The dynamic simulation loop.

2.7.2 Design product

The design product phase (Figure 2.11) includes the definition-detailed 3D model, which includes the product architecture and the division of the product into subsystems and components. Dynamic simulation may utilise component libraries, and as the 3D-model has evolved, real-like mass, inertia and joint locations are even being used. Strength simulation can also be computed at a detailed level and stresses and strains can be used to estimate fatigue life. In the design product phase, a light real-time simulator model can be created and ways to simulate and assess human performance, safety and comfort in work places like mobile machines and vehicles can also be discovered.

The output of this phase is the complete specification of the geometry, materials, and tolerances of all of the unique parts in the product, the identification of all of the standard parts to be purchased from suppliers, and a detailed 3D-model for fabrication purposes.

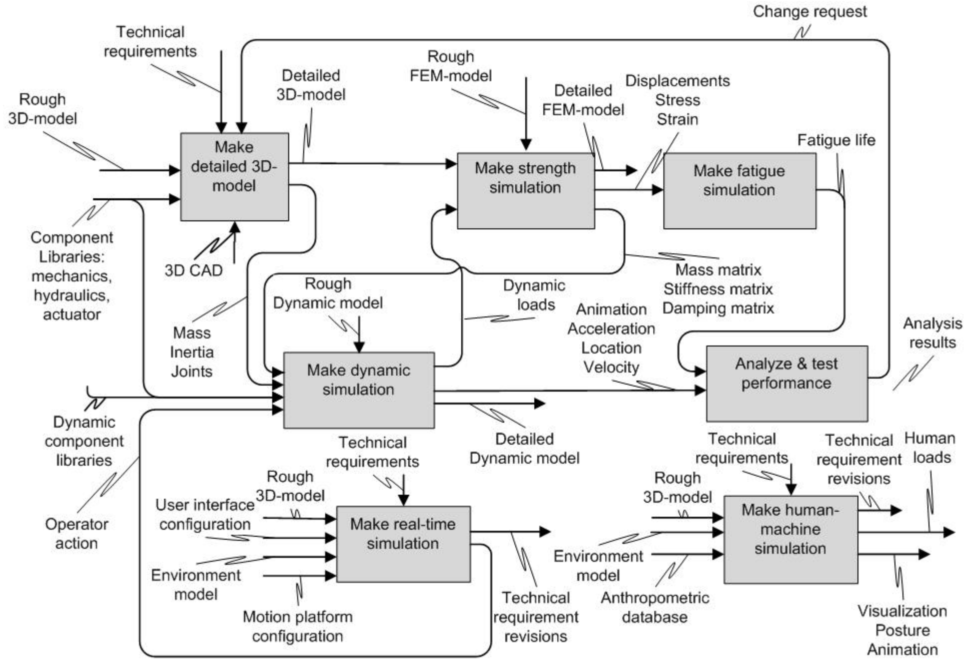

Figure 2.11. Design product phase.

Real-time simulation

The primary goals for the usage of real-time simulators are to reduce product development cost and time by design optimisation. Putting real-time simulation technologies into practical usage in the engineering field has always been an interesting goal within the research community. The performance limit of computing hardware and the efficiency of software algorithms are critical obstacles in this field. Additionally, real-time simulation environments are complicated systems consisting of different engineering disciplines.

One of the challenges of using real-time simulation as part of the design process is to produce the necessary systems set-ups fast enough so that the process is not delayed. The simulation results need to be available well before important design decisions have to be made.

Real-time simulators can be used in the design process to help to define various physical properties, functional characteristics and process requirements of the product in virtual world. In the product definition phase and in concept design, accurate behaviour is usually less important. Instead, virtual mock-ups with simplified functionality may be used. (Figure 2.12.)

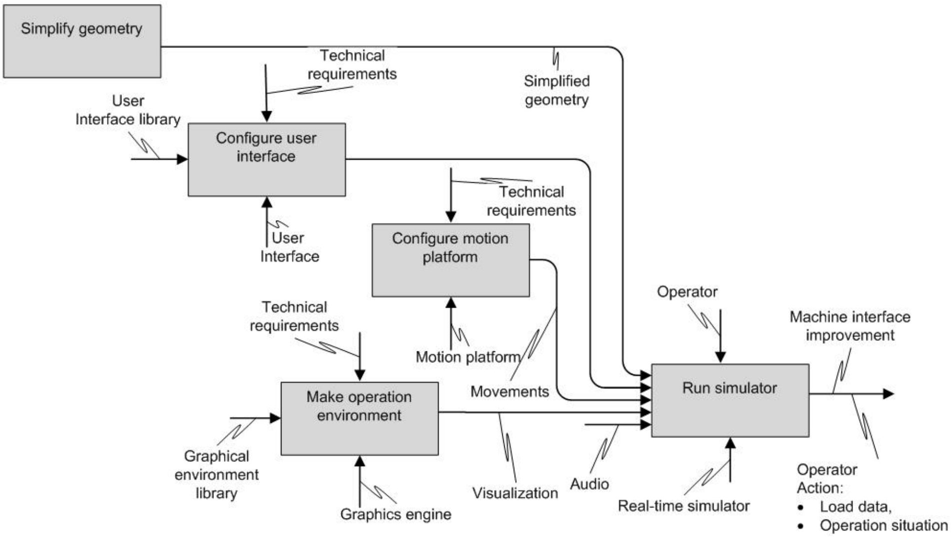

Figure 2.12. Real-time simulation in the design product phase.

Fatigue analysis

During the design process, one of the main concerns of a design engineer is the fatigue life. When estimating fatigue life the major parameters are stress/strain values under dynamic load history and material parameters. In addition, environmental conditions are crucial for fatigue life computation.

The determination of stresses and strains using the finite element method (FEM) is common practise in many companies. FEM has broad applicability to different types of analyses (deformations, stress, plasticity, stability, vibration, impact, fracture etc.), as well as to different classes of structures, e.g. shells, trusses, frames and components like gears, bearings, and shafts. Several models have been developed for estimating the fatigue life of components, e.g. S-N curves, ε-N curves or crack growth, and their suitability is considered case-by case. (Figure 2.13.)

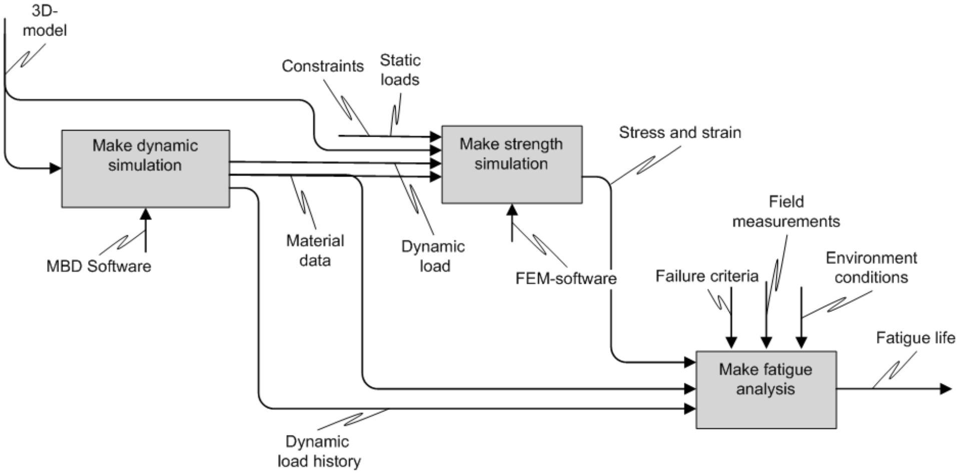

Figure 2.13. Fatigue analysis in design product phase.

Human-machine interaction

From the point of view of a human as an operator, product design demands a knowledge of the human being his- or herself, and of his or her relationship with the environment. The design process needs to be able to cover the whole system, instead of being restricted to a product. Product developers have to comprehend the whole field of human work. This means that 3D models and simulation are needed to identify human physical needs in a working environment. Simulation provides possibilities for collaborative design. Human-centred design methods need to be developed so that they better support today's concurrent and distributed design processes.

In the design concept phase, specifying the technical requirements for the product or system is a major task. For human-centred design, it is essential to extend these technical requirements to better include human physical needs. For example, these include comfort, safety, health, and effective task performance. The design product phase has to create potential design solutions. The process therefore involves using existing knowledge (standards, guidelines examples of other systems etc.) to develop a proposed design solution, making the design solution more concrete (using computer simulations, physical prototypes, mock-ups etc.), showing the prototypes to users and observing them as they perform specified tasks, with or without the assistance of evaluators, using this feedback to improve the design and iterating this process until the design objectives (including usability objectives) are met.

Human operator simulation uses 3D-models, the biomechanical model and the environment model to simulate human operation. The human model is composed of rigid segments that are connected using joints and forces. The conventional type of controllers or spring-dampers of applied human models do not seem to be the best possible way of simulating human actions accurately in many scenarios and applications. The use of soft computing (i.e., fuzzy logic, neural networks and genetic algorithms) offers more satisfactory possibilities for simulating human motion control. (Figure 2.14.)

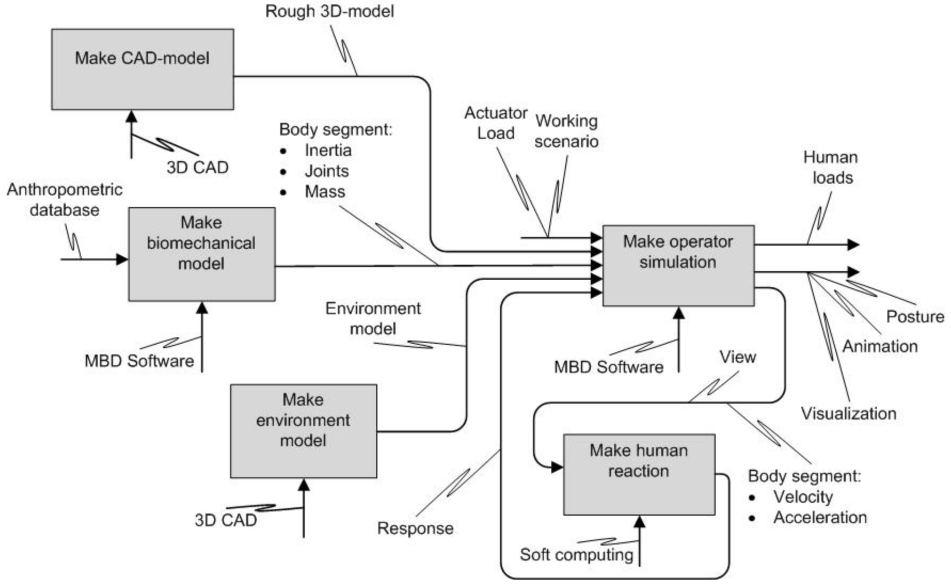

Figure 2.14. Human-machine interaction in the design product phase.

2.7.3 Test and verify

The test and verify phase involves the construction and evaluation of virtual and physical prototypes. Early prototypes are usually built with production intent parts, parts with the same geometry and material properties as those intended for the production version of the product but not necessarily fabricated with the actual processes to be used in production. Prototypes are tested to determine whether or not the product will work as designed and whether or not the product satisfies the key customer needs. An important issue is to update the digital models using results from testing. (Figure 2.15.)

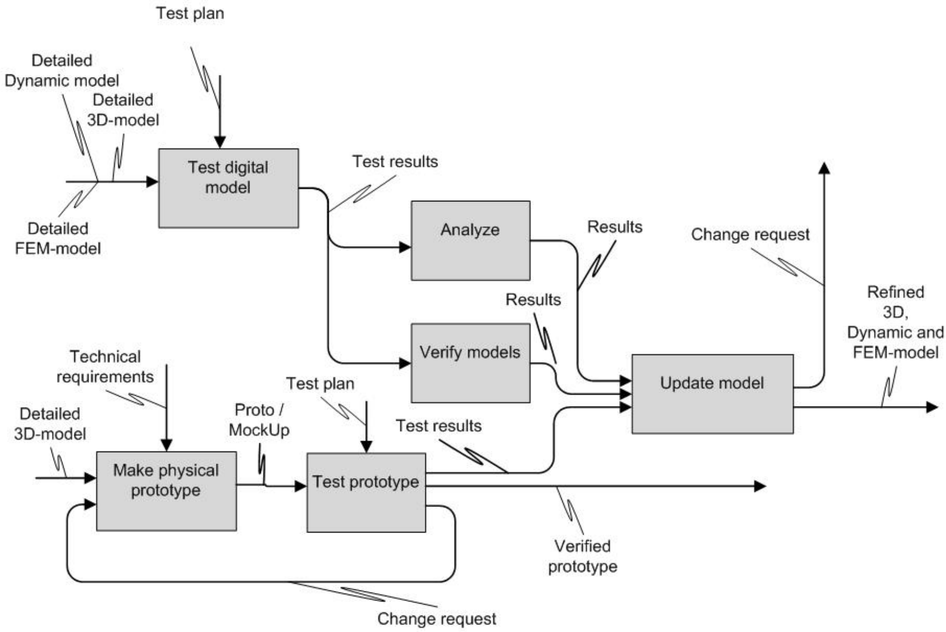

Figure 2.15. The test and verify phase.

2.7.4 Ramp-up production

In the production ramp-up phase, the product is made using the intended production system. Fabrication simulation is performed to produce instructions for CNC-machines etc. Production simulation offers features that simulate the complex movement of equipment such as robots, machine tools, transfer lines, and special machinery. Factory simulation software features are also used to define the physical layout of manufacturing, material handling, and distribution systems. The purpose of the ramp-up is to work out any remaining problems in the production processes. The artefacts produced during production ramp-up are sometimes supplied to preferred customers and are carefully evaluated to identify any remaining flaws. The transition from production ramp-up to ongoing production is usually gradual and continuous. (Figure 2.16.)

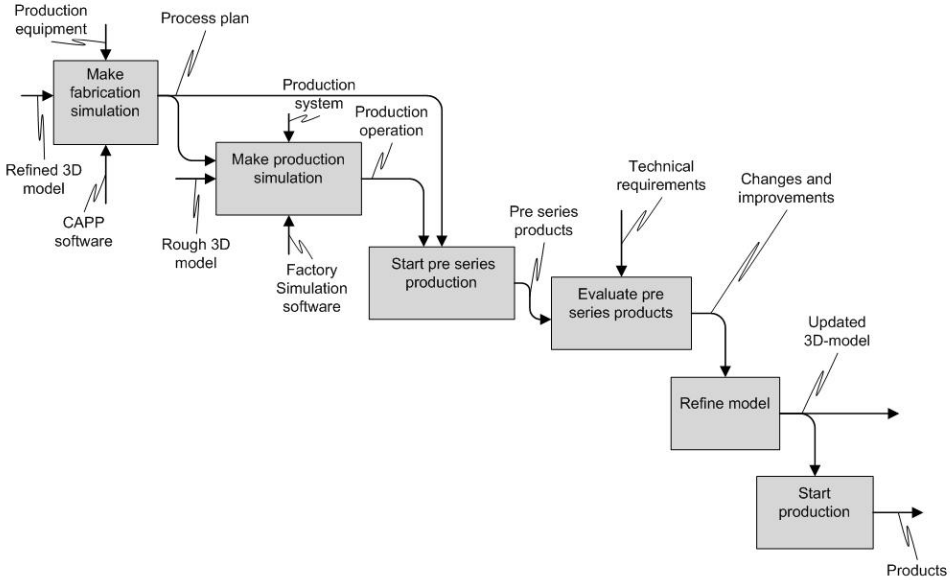

Figure 2.16. The ramp-up production phase.

2.7.5 Conclusions

Simulation-based product development can be very challenging for organisations. This is due to the many new techniques required in order to bring a product development process to a new level. Information and new ideas must be created, examined, processed, tested, and transferred to organizations.

The usage of simulation methods belong to modern product development. The advantages which are gained from the simulation are manifold: expensive and time-consuming prototypes and the number of the tests decrease, the properties of the products improve, the time which is used for making products shortens and the quality standard of products rises. Computer based modelling and simulation assists developing an idea into a product. This improves the competitive ability of the company and shortens the path of new innovations from the idea to the market.

The introduction of modelling and simulation also requires a lot from the whole product development organisation. Combining modelling and simulation seamlessly to product development requires a new type of thinking about the whole product process.

The simulation-based design process typically involves a large number of disparate software tools evaluating a number of different and diverse characteristics (structural, operational performance, production scheduling, etc) in order to produce an intelligent machine that satisfies the customer's requirements. The software tools generally produce point solutions to a particular problem with respect to a particular set of requirements, that is, they have their own model and solution representations. As such, a large and complex engineering design project may have multiple representations of different aspects of the same design model, distributed either organisationally, or more commonly, globally. Managing the data within these models to maintain consistency is an important but complicated task.

This research studies six different theoretical product development models. These six models were the basis for a reference model that was used as a communication tool in interviews with product development management. The generic model was composed after interviewing the design project leaders of five different companies.

The product development theories found in the literature were quite similar, but they differ from the process used in companies. The process used in companies includes less tools (e.g. for innovating) and is usually more focused on gathering technological information and administrating ongoing development projects than theoretical models.

There are significant differences between the product development theories and the generic (synthesis) model, i.e. current way of action. The largest difference can be seen before the product development itself starts. The companies use much more effort to manage their product portfolios. Business cases are studied very carefully and only the most promising projects are funded. The second stage after the business case is researching and developing new relevant technologies, methods and tools to be used in the future products. In this phase both simulation software and prototype testing are used. A strong emphasis on the technology development stage might be a result of the cooperation which companies have made in technology development programs in Finland and around Europe.

The conceptual design and the embodiment design stages are much more iterative than ones in theoretical models. Design solutions are found with the aid of simulation tools and 3D-CAD-systems.

In the product design, the preliminary CAD-models are detailed with iterative cycles of simulation, testing and redesigning. All the parts and components are designed in detail, iterating between the 3D modelling and dynamic and structural analyses. The building of the prototypes of the whole product or its part or of different mock-up models is begun when the design of the product has proceeded to a sufficient level to build the models in question. After suitable results have been obtained from the tests, the simulations are verified by means of prototype tests.

The new process model which was developed for smart machines emphasises more detailed description of design activities than the generic model used. In the new model the business cases are studied and thereafter only the most promising projects are funded. The second stage after the business case is researching and developing new relevant technologies, methods and tools to be used in the future products. The two first stages remain the same as in the present practise of studied companies.

In the design concept phase the simulation activities are performed using rough models and the main task is to generate and evaluate feasible concepts so that technical requirements are met. Product properties are studied on a conceptual level and possible system elements are connected. Traditionally during the concept design phase many alternative designs were sought, usually without regards for their value and quality. In a simulation-based design process, the alternative concepts are quantified and therefore the best concept is selected for further development.

In the design product phase, real-time and human-machine interface simulation are introduced to product development. 3D-models are detailed and dynamic and strength simulations are performed. Fatigue simulation comes into picture. In the past, analysis of individual components was carried out by using prototypes and if a part failed then it was redesigned, manufactured and tested again. Virtual models can be immediately analysed and optimised. This phase helps in design perfection so that a part may not be rejected in further testing. After the part is designed, it can be analyzed so that its acceptability in that application is determined.

The test and verify phase involves the construction and evaluation of virtual and physical prototypes. Prototypes are tested to determine whether or not the product will work as designed and whether or not the product satisfies the customer's key needs.

In the production ramp-up phase, the product is made using the intended production system. Fabrication simulation is performed to produce instructions manufacturing. Additionally, factory simulation software features are used to define the physical layout of manufacturing, material handling, and distribution systems. The purpose of the ramp-up is to work out any remaining problems in the production processes. The transition from production ramp-up to ongoing production is usually gradual and continuous.

It is believed that application oriented product models will become the standard unit of smart machines, but it will probably be an evolutionary process as advances in technology and modelling capabilities and requirements are incorporated. A great deal of the literature reviewed has discussed the use of "intelligent" data, the inclusion of useful functionality according to the data type, and of behavioural aspects. It is anticipated that this functionality, behavioural aspects and so on will increasingly become part of the model to the extent that the model no longer has any need for interfaces and translators to legacy software. For example: the structures model would automatically calculate stress characteristics. The simulation would essentially be part of the model and the model would contain additional information and knowledge to effectively manage the simulation. Current and future distributed IT technologies may be utilised in order to distribute the model across a network whilst giving the impression to the user that the system is monolithic. Smart machine functionality would be distributed either within a single company or in partnership with other companies.

For example, there currently appears to be a significant opportunity for the specialisation of the immersion of an entire smart machine product model into an artificial environment to determine the operational performance. Increased opportunity would therefore arise for designing the smart machine to meet a more rigorous set of customer-specified life-phase requirements and would represent a significant commercial advantage.

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3. Modelling and simulation of complex products

3.1 Introduction

During the past few years the use of simulation as a standard tool in product development has spread widely to areas other than the automotive industry. Several reasons have lead to this, including the increased complexity of the products being designed, the increase in computational resources, and improvements in the usability of simulation software. The direction of evolution in utilising computational methods is evident; the challenge is to manage the process and tools efficiently so as to get the most out of the investment.

Quite often simulation is used for some specific problem area like component structural analysis or a local control system development. With these kind of simulations the surrounding system is often either strongly simplified or even left out completely. This can lead to inaccuracy in system boundaries and over-simplification of the simulation model. On the other hand, the trend in industrial vehicle development seems to be going to more integrated systems and the increasing of intelligence and complexity. This means that sub-systems are more dependent on function of the other systems, which should also be taken into account in the design phase of the systems. The use of computer aided simulation creates an excellent platform for multi-domain estimation of the sub-system interaction in complex designs of multi-domain systems.

In this task the research work has concentrated mostly on mechanical system simulation and its application to overall and sub-system simulation. The work has included abstract processing of the product development process and especially applying of computer simulation tools and methods to the process, and actual modelling and simulation related practices in describing and managing complex sub-models as well as an overall system simulation model base.

In a well managed simulation system the model base enables both detailed simulation of a sub-system as well as simulation of the overall system. These tasks set quite different requirements for the simulation models and running the analyses. Both kinds of simulations should be able to run using the same model components so as to prevent fragmentation of the model base into many variations of the modelling components.

The idea in this section of the project has been to gather experience of a real scale development process from the mechanical system simulation point of view and to understand the effort needed to manage the entire product data used in simulation. During this process some fundamental observations have been made:

- To be most effective, system simulation should be applied from the very beginning of the product development process and be kept up-to-date for the whole product life cycle.
- Centralised product and development data management including design geometry, material, and component information is one of the key components of success.
- Simulation work should be able to be divided into small, independent portions in order to ease simulation component modelling and debugging, and therefore increase the modelling and simulation quality, enable parallel design, modelling and simulation, and also increase re-use of the modelling component.

This trend can be seen in the simulation software development. There are already several integrated simulation and analysis environments available to manage product development simulation, including test data analysis. Most of these systems are proprietary, closed systems which tie the user to one tool and make it difficult to transfer to another tool or environment. Furthermore, the use of open standards and the actual lack of these standards raise the concern of how well design data can be preserved.

3.1.1 Objectives

In the beginning of the project the following objectives were set for this research section:

- To understand modelling and simulation methods and the most appropriate simulation tools for different kind of sub-system and component simulation of mechanical systems, and to understand the interfaces between them.

- To master procedures and methods for multi-domain system simulation with selected mechanical system simulation software, and generation and management of system models. Investigation of possibilities of the tools available and the influence of different methods on accuracy, efficiency, and costs.
- Exploitation of an overall, multi-domain system model in the product development process, use of simulation for design of safety and reliability, and use of simulation for condition monitoring and diagnostics.

Right from the beginning of the project, the research was done using a case study – an industrial vehicle simulation model on which all the practices and actual modelling and sub-model management concepts were tested.

3.2 Case study – An overall simulation model of a industrial vehicle

Already at the formation phase of the project some results and work of the research were thought to be implemented in an overall system simulation model of a industrial vehicle. This simulation model was built in a mechanical system simulation environment and it contains also hydraulic and control sub-systems as well as several versions of mechanical sub-systems for different requirements in complexity and simulation performance.

Building the simulation model, especially developing methods to manage large simulation model base and complex simulation requirements, was the subject of this section. From the beginning of the project the co-operation between different research partners and exploitation of the system simulation model was built into the project research plan.

3.2.1 Co-operation with other research partners through the case study

There has been the following co-operation between the participants of the research project concerning modular modelling and simulation of a complex product and especially the case study simulation model:

- Implementation of mathematical models of vibration isolators into the mechanical simulation environment and verification of the models. Exploitation of the tyre research results.
- Verification of the real-time simulation model using off-line simulation. Sharing modelling data between the real-time and off-line simulation models.
- Including a dynamic human model into an overall system simulation model of a industrial vehicle.
- Using a system simulation model for the design of reliability and usability and applying simulation results as boundary conditions of reliability analysis.

Having the case study simulation model as a common platform for different research tasks to test the ideas and concepts in practice has increased the co-operation between the researchers and has created a clear focus for the research project.

3.3 Modelling methods

The Free On-line Dictionary of Computing defines ‘simulation’ to mean:

> *Attempting to predict aspects of the behaviour of some system by creating an approximate (mathematical) model of it. This can be done by physical modelling, by writing a special-purpose computer programme or using a more general simulation package, probably still aimed at a particular kind of simulation (e.g. structural engineering, fluid flow). Typical examples are aircraft flight*

> *simulators or electronic circuit simulators. A great many simulation languages exist, e.g. Simula.*

When talking about computational simulation, almost anything can be simulated and there are numerous ways of formulating simulation models and running the actual simulation. In this section the following three general approaches for mechanical system simulation are selected for further discussion:

1. equation based modelling and simulation
2. simulation using special software
3. modelling and simulation using a simulation language.

3.3.1 Equation based modelling and simulation

In equation based modelling of mechanical systems the user describes the simulation model mathematically using equations of motion, constraint equations and necessary algebraic and differential equations. The solving and time integration are usually done using routines available in mathematical software such as *Matlab* or *Octave*, or by programming the problem using programming languages like FORTRAN, C or C++ and using available libraries of mathematical routines.

Among the advantages of using equations based modelling are the following:

- Modelling tools usually do not restrict the modelling.
- There are several excellent tools available for equation based modelling, both commercial and freely available.
- The usability of a model can be high depending on the skills and experience of the person doing the modelling.

One of the biggest problems when using equation based modelling is the amount of modelling data that must be handled during the modelling process. Because of this and because the numerical solving algorithm must also be provided, this method of modelling and simulating is usually quite slow and prone to errors. The method also requires strong knowledge of numerical solving methods and programming principles. The feedback of modelling tools is usually quite limited and hence the possibility for mistakes is high. For example an error in location of the centre of mass of a part might have a strong influence on the behaviour of a model, but this kind of a physical error can be very difficult to find.

The equation-based modelling is very flexible, Partly because of this flexibility, the differences of modelling practice between individuals influence the usability and ease of reading equation based models. An experienced modeller or programmer can create models that are easy to read, use and modify.

The equation-based modelling is at its best in cases where a quite small but specific problem must be simulated. In cases where, for example a control system is attached with a simple mechanism this method can be useful.

The basic formulation methods of mechanical system problems have a strong influence on equation solving efficiency and therefore on the speed of simulation.

3.3.2 Modelling and simulation with special software

At this time the most efficient way of modelling complex and large mechanical systems is by using specific mechanical system simulation software like *LMS Virtual.Lab*, *MSC.ADAMS* and *SIMPACK*. With these kinds of software the model of a mechanism is described in a CAD-like graphical environment by creating bodies, connecting bodies with constraints and applying forces to bodies. The modelling tools create the mathematical representation of the problem according to the visual model and solve and integrate the simulation case automatically.

Advantages of modelling with special software:

- Modelling and simulation of mechanical systems is quite fast and these tools can be used for rapid prototyping and for checking new ideas.

- The understanding of physical phenomena is usually enough for modelling, so the knowledge of details of the mathematical representation is not mandatory.
- Describing a mechanical system model with bodies, constraints and forces is intuitive for engineers.
- The usability and ability to modify a model is usually good.
- The amount of modelling data that must be handled during a modelling process is quite tolerable.

The disadvantage of using special software is often the cost of the software and its maintenance. Because development of these kinds of software requires special knowledge and they are not directed to mass markets, the prices will most likely remain high. In addition, the competition in this market sector seems to be quite low.

As the size of a model grows, the problem of handling modelling data that arose when using equation based modelling can also cause trouble when using special software. The modelling of large and complex systems is like development of a software product. There can be several people working on the same model and concentrating on some specific sub-system or problem area. All the participants should have access to the latest model version but the confusion of two people modifying the same sub-system at the same time should be avoided. These problems, the product data management and version control, are typical for software development and there are several tools and systems available to handle this problem.

The lack of standardisation and partly because of economical reasons the ability to exchange models between different mechanical system simulation environment is either difficult or it is practically impossible. Also the usability of a model created with some older version of the same software can cause some difficulties which should be taken to account when planning to archive the model and simulation results.

3.3.3 Modelling and simulation using a simulation language

The concept of software product development presented in the previous section can be taken further by describing the model with a simulation language. This means using a language that is open and either standardised or standard-like and specific for modelling. The language should be a full featured programming one including all necessary data and control structures.

An object-oriented language is well suited for describing mechanical system models. The object-model naturally supports the idea of sub-systems and so helps dividing the model into logical sub-models. Furthermore, the basic features in object-oriented languages, like public and private properties and information hiding, allow the model creator to use arbitrary abstraction levels in the model. This makes the model easier to handle and reduces the probability for human errors. If the language used to describe the model is open and standardised or standard-like, the model information is separated from modelling tools and the model will probably be usable in future.

Modelling of different kind of system domains in the same model is possible if the language used for describing the model is extensible and includes several standard libraries for different domains. This helps the users because they can use the modelling tools they are familiar with for different kind of tasks.

The problem with using modelling languages at the moment is the lack of modelling tools. At the moment there exists at least one open modelling language, *Modelica*. *Modelica* is an object-oriented language for modelling large, complex and heterogeneous systems. It is developed and maintained by a non-profit organization, Modelica Association. There are only two commercial modelling and simulation tools available at the moment that fully support Modelica: *Dymola* and *MathModelica*.

3.3.3.1 Example of using simulation language

In this example a fictitious process of modelling industrial vehicle case using a simulation language is illustrated. At this point the modelling language and the used modelling tools should be separated. The modelling language sets the methods and limitations of describing the model. In addition, the reusability of the model is strongly influenced by the syntax and structure of the modelling language. Modelling tools such as graphical and text editors comprise the user interface to the actual modelling work. These tools determine the efficiency of the modelling process.

In a modern modelling and simulation project the user controls the modelling process using graphical tools. A good example of these kind of tools are the IDE (Integrated Development Environment) tools that are used for software development. In these environments all the necessary development tools are collected under the same framework and behind the familiar user interface.

The idea of sub-models and abstraction levels makes it possible to handle only the important information at every stage of the modelling process. If the modelling language used supports object-oriented modelling, the abstraction levels can be chosen in an arbitrary manner. With information hiding and the use of abstraction levels the user can handle the model on the level that is convenient for the modelling problem. In Figure 3.1 there is an illustration of abstraction levels of a simulation model.

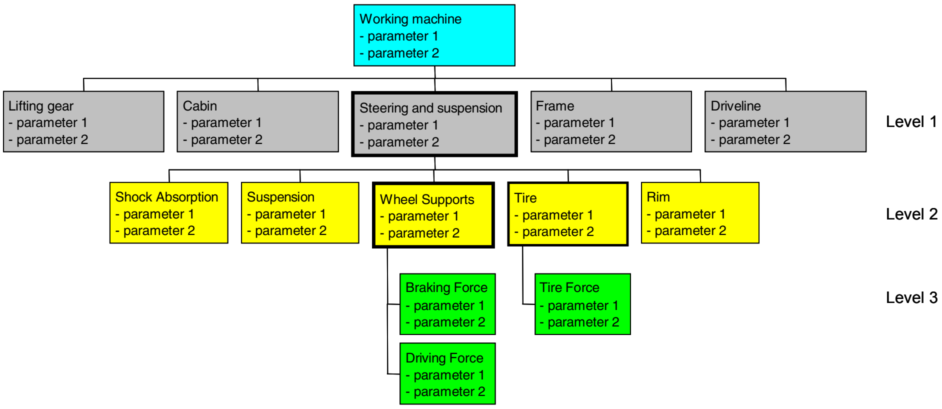


Figure 3.1. An illustration of abstraction levels of a simulation model [Kortelainen 2003a].

In the top level (of the model) the user sees only the components and their public parameters, marked in gray in the figure. All the sub-systems and their details under these components are hidden. When selecting a sub-system like wheel support, the user sees the components of this sub-system but not the other sub-systems on level 2 or their parameters. The amount of components and parameters is limited to those of the actual level, which makes handling the model easy and convenient. When diving deep enough into the model, the user comes to the level of mathematical description of the components in the modelling language used.

The research report *Modelling Methods* [Kortelainen 2003] is confidential due to the design material of a product in production.

3.4 Modelling sub-systems

3.4.1 Control system simulation in mechatronics

Simulation of control systems includes simulation of the control and signal processing algorithms and hardware as well as simulation of the static and dynamic behaviour and events of the controlled physical system. Hence, software tools for pure controller simulation are rare, and the process modelling part is also needed. An exception is real time hardware-in-the-loop simulation, where the controlled physical system is real and only the control hardware and algorithms are simulated. However, for hardware-in-the-loop simulation the situation is most often reversed: the control hardware is real and the physical process is simulated. For this reason control system simulation software can be regarded as a general dynamic system simulation tool, which includes support for the design, simulation and analysis of controller and signal processing algorithms and hardware.

Mechatronic systems are characteristically composed of mechanical, electrical and/or hydraulic sub-systems and control systems with signal processing and control algorithms, using both analogue and digital electronics. Optimal simulation software should then include good support for the design, modelling and analysis of all of these domains. There are software packages such as *DADS, AMESim, EASY5, VisSim* and *Dymola,* which aim at multi-domain simulation by incorporating model libraries for different domains (usually general, mechanical, thermo-hydraulic, electrical and control libraries are included). Another trend in multi-domain simulation is the development of a general model description language, which would enable consistent manipulation of models from all domains. The result is an object oriented language called *Modelica*, which so far contains libraries for, among other things, thermal and ordinary hydraulics, power systems and fuzzy control. Modelica models are currently supported by *Dymola* and *MathModelica*, which is closely integrated into *Mathematica* and *Microsoft Visio*.

From a control engineering point of view, the support for control system design and simulation is naturally compared to the most popular tool *Matlab/Simulink*. All of the above mentioned software packages advertise at least some sort of link mechanism to Simulink, which demonstrates the superiority of that software in that area. *Matlab/Simulink* is also the most popular companion with simulation systems which are more or less dedicated to one domain, simulation, most importantly mechanical simulation. With *MCS.ADAMS* the created models can be exported to be used as a block in Simulink model, which makes it possible to model the control system in Simulink and simulate it together with *MSC.ADAMS* model for the mechanical dynamic system. Additionally, coupling with *MATRIXx* dynamic system simulation software is available in some packages (e.g. in *DADS*) for control system simulation purpose.

The co-operation with Simulink models is done either by co-simulation or by the coupled-equations method. In co-simulation, the Simulink models and others are integrated by their own solvers and the models communicate via defined input and output signals with defined time interval. One problem with this technique is that the possibly coupled dynamics of the models are de-coupled between communication instances, which clearly is erroneous if both models are continuous time models. If one model is purely discrete time and the communication interval is the same as the sample interval, the interface between the models can represent D/A and A/D converters and this problem does not exist. Hence, simulating digital control with Simulink and the controlled hydraulic and mechanical system with *MSC.ADAMS* in co-simulation manner should be acceptable. If the hydraulic system is also modelled in Simulink, the interaction between hydraulic actuators and mechanical systems is not simulated correctly. Another problem in co-simulation is that there are sudden changes in variable values at communication instances, a problem which can cause difficulties for numerical integration. An advantage of co-simulation is that the domain specific analysis tools of both simulators can be used, e.g. 3D visualisation of *MSC.ADAMS* and signal analysis tools of Simulink.

The coupled equations method means that the model can be exported in a format which can be included into a Simulink model, and the simulation is done by Simulink's integrator only (or vice versa in some cases). The de-coupling and sudden change problems are avoided in this case.

DADS offers coupled-equations method. *VisSim* can translate and incorporate Simulink models into *VisSim* simulation diagram and also supports data import and export in '.m' or '.mat' format. *Dymola* can generate C-code, which can be exported to *Simulink*. *AMESim* supports both co-simulation and coupled-equations with Simulink, as well as generate Matlab s-functions from its models. In addition, AMESim supports interfacing with *MSC.ADAMS*. *MSC.ADAMS* itself can export models for co-simulation within Simulink models. *MSC.ADAMS* can also export linearised state model parameters, which can be used for generating model blocks for Simulink (coupled-equations simulation).

Another alternative to include complicated control algorithms into simulation systems is to use standard programming languages like C or FORTRAN. At least *MSC.ADAMS, EASY5, AMESim* and *VisSim* (and Simulink) support that, although at least with *MSC.ADAMS* and *Simulink* the timing of discrete time digital control functions requires some creativity. Writing control algorithms with C for simulation purposes might seem needlessly laborious but the advantage is that it is possible to develop and test controller code for the real physical system while doing the simulations.

On the other hand many simulation packages which support control system design and simulation also support exporting controller models as C or FORTRAN functions. Often this is enabled with an add-on module or toolbox. At least *Matlab/Simulink, MATRIXx, EASY5, Dymola* and *VisSim* have this feature. In some cases (at least with Simulink) the usability of the generated C code in the actual control system is somewhat restricted by the need of runtime libraries.

Hardware-in-the-loop simulation is especially useful for testing controller hardware and software without the need to employ real physical mechanisms. This can be advantageous for safety and cost reasons. In some cases it can also be useful to simulate the control system together with a real physical system. Hardware-in-the-loop simulation requires real time capability from the simulation software. For most simulation packages the real time simulation option is coupled with C-code generation and uses some real-time platform to run it. VisSim provides real-time simulation and communication with PC's I/O-cards without code generation. Considering Modelica modelling language there is an EU project *RealSim*, which aims at development of tools for efficient simulation of complex, coupled multi-domain systems with real-time constraints.

3.4.1.1 Experiences in combining digital control system with MSC.ADAMS model

The authors have experience in combining control systems with *MSC.ADAMS* mechanical and hydraulics models in two cases: active damping of heavy rotor vibrations [1] and active damping of tractor cabin vibrations. In the first case, co-simulation with *MSC.ADAMS* and *Simulink* was used. In the latter case the best results were obtained when the controllers were included as C-functions into the *MSC.ADAMS/Solver*.

In the rotor damping case the actual system consisted of a heavy rotor, electric drive for it and roll bearings as supporting bearings. The damper consisted of three hydraulic cylinders, which were used for generating radial forces to the rotor via a third ball bearing. Hydraulic cylinders were controlled with high-speed servo valves. The active control of the system consisted of analogue force control of each cylinder and digital feedback control from rotor vibration measurements (laser displacement sensors). The rotor, the bearings and the support mechanisms were modelled with *MSC.ADAMS*. The digital and analogue controllers were modelled in *Simulink.* First the hydraulic system was also modelled in Simulink and the inputs to the *MSC.ADAMS* model were the cylinder forces. This first solution was unsuccessful. The couplings between the dynamics of the hydraulic cylinders (pressure gradients) and the rotor mechanism were too strong and co-simulation with even a very small communication interval (0.05 ms) tended to crash. After that the hydraulic system was modelled in *MSC.ADAMS* using its hydraulics option. The resulting *Simulink* model structure is shown in Figure 3.2. The inputs to the *MSC.ADAMS* model are in this case the control signals to the servo valves. This model worked well and its behaviour was reasonably close to the actual system. However, the communication interval needed to be rather small, 0.1 ms, probably due to the stiffness of the *MSC.ADAMS* model. The analogue PID controllers in the Simulink model caused no problems.

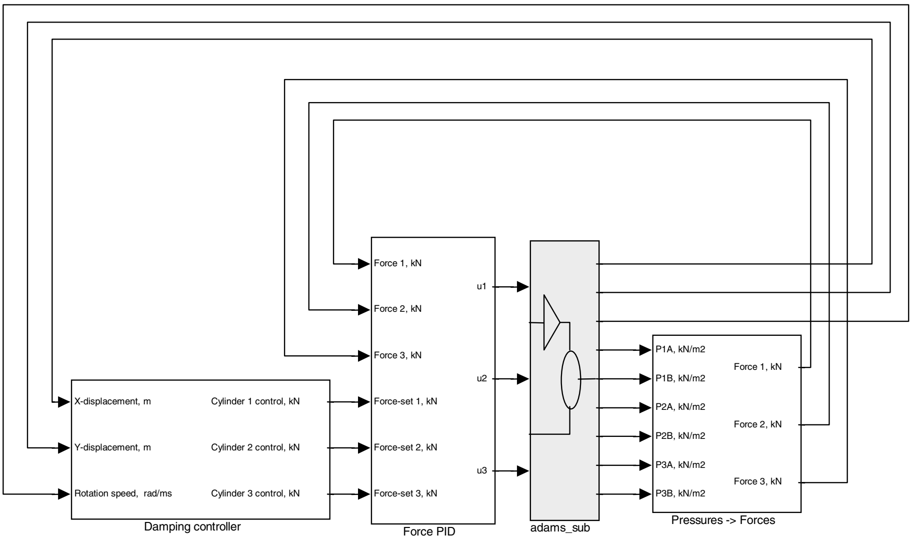


Figure 3.2. An example of the interoperability of a mechanical and control system simulation model [Kortelainen & Järviluoma 2003].

In the tractor cabin case the cabin was supported by two hydraulic cylinders at the two rear corners and the aim was to attenuate the vertical vibrations of the cabin in the range of 1 to 10 Hz. The control system was digital and it performed feedback control using cabin acceleration and cylinder length measurements. The simulation model in *MSC.ADAMS* consisted of the tractor body, the four tyres, the power transmission (motor and gears) and the cabin with rubber bushings at the front corners. The hydraulic system was modelled with *MSC.ADAMS* hydraulics. The controller was written with C-language and it was included in the *MSC.ADAMS* solver (custom solver) as a request-function (REQSUB function). This function is executed at the time instances, which are defined as sample instances in the simulator. Hence, it is a discrete time function, which can be used as an interface to a discrete time control algorithm. The interface between *MSC.ADAMS* variables and the request-function was done using VARSUB function and global variables. VARSUB function is a continuous time function, which is used for customized calculation of variable values, and it is executed when needed for the numerical integration by the solver. After some trial and error this arrangement worked well. The results were comparable to the ones obtained with the real tractor. The same C-functions for the control algorithms and frequency response measurements were used as in the real control system. Only small interface functions were needed.

The C-code, which was used in the tractor case, was hand written. The use of *Matlab's Real Time Workshop* for code generation was not tested. However, successful application of *Matlab* code generation with *MSC.ADAMS* has been reported [Järviluoma & Kortelainen 2003].

3.4.2 Mechanical system simulation

3.4.2.1 Trends and visions

The usage of simulation as a development tool has been growing steadily in recent years. Simulation is used for practically every kind of system development to decrease the development time and to increase the quality of products. In the field of mechanical system simulation this can be seen in the increasing size and complexity of models. One obvious trend nowadays is the use of combined simulation of different kind of systems. There are several simulation environments available that support simultaneous simulation with some other simulation software. An example of this is using a control system simulation tool *Matlab/Simulink* to simulate the control system besides a mechanical model simulated in *MSC.ADAMS* software. The simulation can be run from *Matlab/Simulink*. The mechanical system simulation is run as a sub-process. By using this kind of a method the designers of each sub-system can use the software tool that best matches their needs. The level of details and accuracy of the simulation are also increased.

Mechanical system simulation tools usually make available several specific tools or modules for different kinds of simulation tasks like hydraulics, power train or control systems. The number of these kind of special application modules seems to be increasing.

The integration of mechanical system simulation tools into CAD/CAE environments has evolved. The modern geometry transferring formats have increased the quality of the geometry representation and made it easier for the user to exploit the design models already available in the CAD/CAE system. In general, mechanical system simulation has proved its potential and it has established its position as an effective development tool.

The reference *Modeling Methods* [Kortelainen 2003] includes a short discussion about three modelling and simulation methods of mechanical system, equation based modelling and simulation, use of special software and modelling and simulation using modelling language. The reference *Modeling Methods in Computational Dynamics of Mechanisms* [Korkealaakso & Rouvinen 2003] contains a closer look at the specific topics of this modelling method.

3.4.2.2 Software

The following introduction to some of the commercial mechanical system simulation tools is mostly based on the material available on the web sites of the software companies.

ABAQUS

ABAQUS FEM software has an extensive set of modelling components for multi-body dynamic analysis. With *ABAQUS Explicit* solver the time integration of a dynamic analysis can be performed quite efficiently although both types of solver, implicit or explicit, can be used. The difference between *ABAQUS* software and other traditional mechanical system simulation tools is that *ABAQUS* uses the same solver for rigid multi-body dynamics and flexible body dynamics. The user can first model the case with all rigid bodies and then switch either some or all of the bodies into flexible description.

According to the material available there is no particular interface to control system simulation tools like *Matlab/Simulink* or *MSC.Easy5*. This is also the case with external hydraulic system simulation tools like *AMESim.* Furthermore, ready-to-use hydraulic modelling components and capability are missing at the moment.

ABAQUS has a CAD-like user interface, *ABAQUS/CAE*, which provides a native interface to several CAD systems. Models can also be imported in SAT, IGES, STEP or VDA-FS format. There is also a geometry modeller so that parts and models can be created from scratch. For more information see: http://www.abaqus.com.

ITI-Sim

Simulation software *ITI-Sim* is a multi-purpose tool for heterogeneous combined system simulation including mechanical, control and hydraulic systems. *ITI-Sim* is available only on *MS Windows* systems. The software includes many different kind of extension mechanisms via external user code (*MS Windows* DLL libraries, Delphi and C++ programming interface) and also via macros and modules. *ITI-Sim* does not include a CAD-like user interface for mechanical system model creation and modification. There is not a reseller of *ITI-Sim* in Finland. For more information see: http://www.iti.de/news.

LMS DADS and LMS Virtual.Lab

LMS Virtual.Lab is a framework to offer a unified interface for different kind of simulation and analysis tools and CAD/CAE systems. The mechanical system simulation module of the *LMS* package is called *LMS DADS*. The mechanical system simulation module *LMS DADS* has a graphical, CAD-like user interface for model creation and modification.

LMS Virtual.Lab offers the advantage of using the same familiar interface for different modelling, analysis and simulation tasks. According to the marketing material, geometry data exchange is seamless between leading CAD systems on the market and *LMS Virtual.Lab*. One accessory feature of *LMS Virtual.Lab* software is its connection to test results analysis tools. *LMS* does not have a reseller in Finland. The nearest office is located in Leuven, Belgium. For more information see: http://www.lmsintl.com.

Lumeo Motion

Lumeo Software's Lumeo Motion is a light, easy to use simulation tool that integrates into *Pro/Engineer* CAD environment. The key benefits of the software are its ease of use and simulation speed.

There are some hydraulic components, such as like hydraulic cylinders, available in the component palette but no interface to external hydraulic system simulation tools. *Lumeo* also provides a *Control Interface* product which implements a connection between Lumeo Motion model and a real world control system.

Lumeo Software, Inc. is a Finnish company. For more information see: http://www.lumeo.com. Note: At the time of writing this publication the status of the company has become uncertain.

Matlab/SimMechanics

Matlab/SimMechanics is a mechanical system simulation and analysis module in the *Matlab/Simulink* environment. It has all the necessary components for basic mechanical system simulation and there is a natural connection to control system simulation. A hydraulic sub-system module is not available at the moment.

Matlab/SimMechanics lacks a CAD-like 3-D graphical modelling environment but simulation results can be visualised using either the *Virtual Reality Toolbox* or *Matlab* graphics. *Matlab* has a reseller in Finland, Comsol Oy. For more information see: http://www.mathworks.com.

Modelica Modelling Language, Dymola and MathModelica

Modelica is an object-oriented modelling language for large, complex and heterogeneous system modelling. It is developed and maintained by a non-profit organization. *Modelica* itself is not a tool for system simulation but a standard-like way to describe systems in mathematical format. The Modelica language is quite new and there are only two commercial modelling and simulation tools that support it.

Dymola is a multi-engineering modelling and simulation software from *Dynasim AB*, Sweden. *Dymola* is one of the first simulation packages that supported the Modelica simulation language.

MathModelica is a simulation environment by *MathCore AB*, Sweden. The environment includes a graphical model editor (based on *Microsoft Visio*), the *Dymola* simulation engine, a visualisation tool, model libraries and a notebook tool. *MathModelica* can use either *Modelica* or *Mathematica* (Wolfram Research, Inc.) syntax for model description. Because of the *Modelica* connection all the same modelling capabilities which are available in *MathModelica* are also in *Dymola*. *MathModelica* model editor is a graphical tool to create diagram style model representations. There is no CAD-like 3-D graphical modelling tool available at the moment. It looks like there are no links to control or hydraulic system simulation software in *MathModelica*. However, *Modelica* object libraries for these simulation tasks do exist.

Dymola and *MathModelica* do not have a reseller in Finland. For more information see: http://www.modelica.org, http://www.dynasim.se and http://www.mathcore.com. Modelling and simulation using a modelling language is discussed in more details in the report *Modeling Methods* [Kortelainen 2003].

MSC.ADAMS

MSC.ADAMS is one of the oldest mechanical simulation software packages on the market. Originally *ADAMS* (owned originally by Mechanical Dynamics, Inc.) was a pure mechanical system simulation tool with a quite open structure. It was possible to simulate systems other than mechanical ones by providing the needed equations to describe the system dynamics. As one of the leading mechanical system simulation tools on the market nowadays, *MSC.ADAMS* has a quite extensible palette of modules for special applications.

MSC.ADAMS has a CAD-like graphical user interface *MSC.ADAMS/View* and sophisticated geometry manipulation capabilities due to its use of Parasolid geometry kernel. *MSC.ADAMS* is nowadays a product of MSC.Software Corporation. *MSC.ADAMS* has a reseller in Finland, MBS Models Oy. For more information see: http://www.adams.com.

Pro/Engineer Mechanical Design Solutions

Pro/Engineer software package is a CAD/CAM/CAE environment including several analysis tools, one of which is a mechanical system simulation module. The advantage of *Pro/Engineer Mechanical Design Solutions* is that it is tightly integrated into the *Pro/Engineer* CAD/CAM/CAE environment. The analysis tool uses the native design geometry and model database of the CAD/CAE environment. The mechanical system model database is also kept up to date automatically. Exchange of data and results between other analysis tools in the same environment is straightforward. With *Pro/Engineer Mechanical Design Solution*s the product designer can use an environment that she or he is familiar with.

According to PTC web pages and other marketing material, Pro/Engineer does not have a link to other simulation tools for combined simulation of mechanical systems and control or hydraulic systems. *Pro/Engineer* has a reseller in Finland, Parametric Technology Finland Oy. For more information see web page: http://www.ptc.com.

SIMPACK

SIMPACK is a mechanical system simulation tool from INTEC GmbH. It has a sophisticated CAD-like 3-D graphical modelling environment. *SIMPACK* does not have a reseller in Finland. For more information see: http://www.simpack.de.

Due to the nature of the material, the research report *Modeling Subsystems* [Kortelainen & Järviluoma 2003] is confidential.

3.5 Simulation of multi-domain systems

A virtual prototype is often a large system which contains many sub-systems from particular domain which may need complex interactions between sub-systems. If all sub-systems are modelled with just one simulation tool the software would be too complex to create, use and maintain. The software should handle several domains of modelling journalism, handle both discrete and continuous systems and have many different kind of graphical user interfaces to deal with 1D-, 2D- and 3D-information. However, in most cases simulations of complex systems are done modelling the sub-systems with some more like general purpose software of with some special purpose software by modelling all circumferential sub-models less accurately. This means that simplifications in most cases demand experience and detailed knowledge of theory that the modeller in most cases does not have. The circumferential sub-models can also have different kind of physical domain than the used simulation tool. The use of simulation tool developed for some totally different kind of environment can be impossible to use.

The best accuracy for all sub-models can be achieved by using special simulation tool for all different sub-systems. Simulations of each sub-system are done in the industry using very different kind of methods and tools, which means that in simulation of complex multi-domain systems several specialised simulation tools have to be used. The disadvantage of using several tools is that usually software is developed for certain domain and complex interactions between other software are ignored. Each software has also specialised user interface which has different characteristics. The link between user interfaces must also be taken into account when using different simulation software. Use of specialised software for each sub-system gives advantages such as encapsulation of details which enables different abstraction levels, ease of making new sub-models and use of specialised integration algorithms for each sub-model to enable efficient computation.

Some examples of specialised simulation tools are *MSC.ADAMS*, *LMS DADS*, *SIMPACK*, *WinSIMU*, and *HOPSAN*, and general purpose simulation software are *Matlab/Simulink*, *ACSL*, and *Dymola*.

The simulation of a multi-domain, heterogeneous system is discussed in more detail in report *Simulation of multi-domain systems* [Hyvönen 2003].

3.6 Modelling methods in computational dynamics of mechanisms

The nonlinearity of mechanical systems can lead to numerical difficulties which usually force one to use computerised techniques when analysing the dynamics of the system. The multi-body dynamics simulation approach can be used to analyse a wide variety of mechanical systems including automobiles, mobile cranes, satellites and robots. Large rotations and large variations of geometric configurations under operation conditions are the common features in these applications.

In Figure 3.3 the principle components of advantaged simulation are presented. Methods used in multi-body simulations can be divided into two broad categories: global and topological formulations. Several commercial software products, such as *MSC.ADAMS*, use natural or Cartesian coordinates and are based on global formulations. In the global methods, systems consisting of open and closed loops are considered in the same manner. By taking advantage of system topology by employing recursive methods with relative coordinates, it is possible to improve the numerical efficiency of the dynamic simulations.

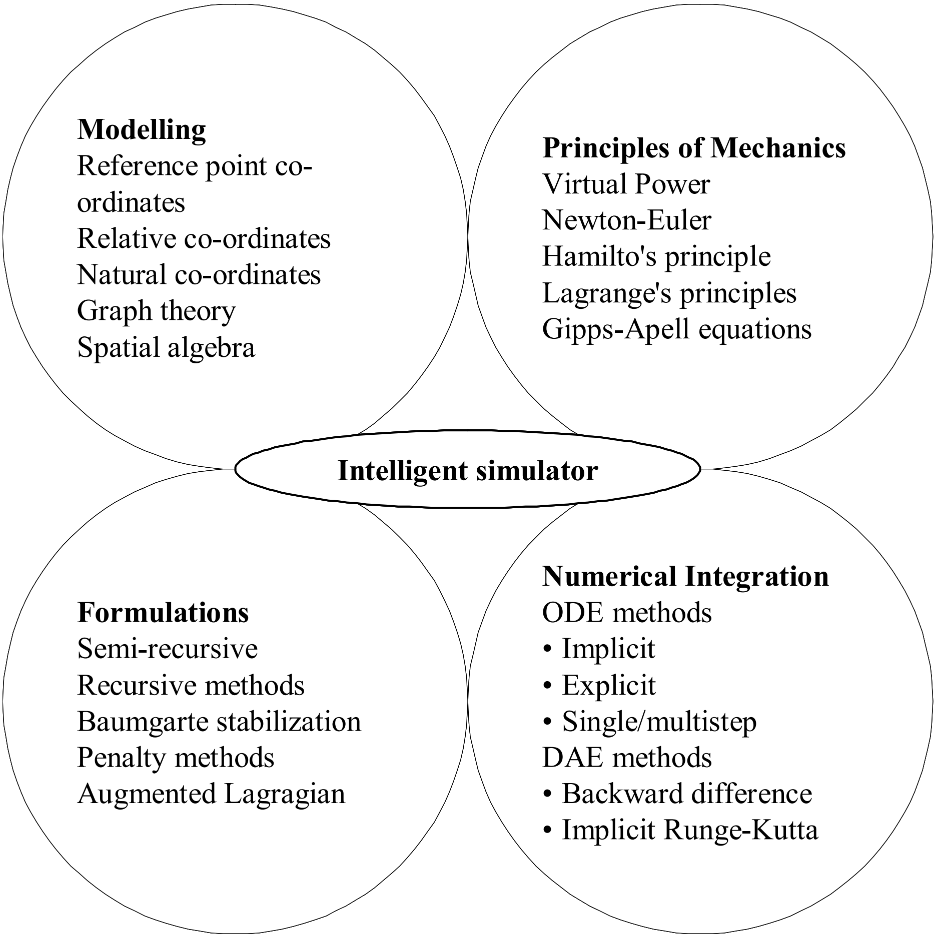


Figure 3.3. Components of advantaged simulation [Korkealaakso & Rouvinen 2003].

Formulations which use both Cartesian and relative coordinates with velocity transformation between these coordinate systems are often called semi-recursive methods. In these formulations, the equations of motion may take a simpler form.

To ensure the correctness of the numerical solution, a stabilisation method is required to confirm the fulfilment of constraints and energy balance. Baumgarte stabilisation and penalty methods can be used with both the Newton-Euler method or Lagrange’s equation, while augmented Lagrangian is an iterative method.

The numerical solution method depends on the formulation of the equations of the motion. ODE methods can be used if the equations of motion can be formed so that they include the constraint equations. If the constraint equations are added to the group of equations to be solved, DAE methods are required.

In report *Modelling Methods in Computational Dynamics of Mechanisms* [Korkealaakso & Rouvinen 2003] the mathematical and numerical formulation of a mechanical system is discussed more deeply from the point of view of implementation simplicity and numerical efficiency.

3.7 Modelling of structural flexibility of mechanisms utilizing floating frame of reference method

Study of structural flexibility within simulation of multibody systems (MBS) has increased recently. Structural flexibility is the deformation of the structure due to loads affecting to it. The increase of the interest in structural flexibility is due to increase of available computational power, more efficient modelling methods and the fact, that structures have become more slender and thus more prone to vibrations. A relatively new method for representing flexible structures in mechanical system simulation models is presented and discussed in more detail in report *Mekanismien rakenteellisen joustavuuden mallinnus kelluvan koordinaatiston menetelmällä* [Rouvinen 2003]; the report is in Finnish.

Usually multibody system analysis is based on the assumption that particles of a body can’t move relative to each others, so bodies are rigid. When structural flexibility is taken into account, the particles of a body can move relative to each others and a force affecting to a body doesn’t necessarily cause an equivalent state of motion to the body. In the mathematical point of view, every body of a mechanism is flexible. In practical modelling work the structural flexibility is often omitted. If the mechanism is modelled using rigid bodies it is necessary to verify that the structural frequencies of the bodies are not in the range of operational frequencies.

The modelling of the structural flexibility is essential in several types of dynamics analysis, for example:

- vibration analysis
- analysis of control systems
- computation of loads for FE analysis
- fatigue life analysis
- slender structure analysis.

The modelling if the structural flexibility is a challenging task. The numerical solution of the models is usually complicated and requires a lot of computational power. Most of commercial MBS solvers have extensions for structural flexibility analysis, such as: *MSC.ADAMS/Flex*, *LMS Virtual.Lab Structures* and *SIMPACK/SIMBEAM*.

In most of the cases the structural flexibility is modelled using the floating frame of reference method. The features typical to method are the following:

- The flexibility and the reference motion are separated.
- The reference motion is defined in coordinate system that can move relative to flexible body.
- The flexibility is defined utilising assumed modes and modal coordinates.

The motion of the flexible body is a combination of reference motion and elastic deformation. The reference motion can be close to rigid body motion while the elastic deformation can be seen as vibration relative to reference motion.

3.8 Modular modelling and simulation of mechanical systems

In the product development process, simulation can be seen as a decision making tool (see Figure 3.4). Applied from the beginning of the process it first helps to decide the overall structure and boundaries of the concept. Later in the process it can be used for evaluating component selection and parameter definition, to get information for other analyses such as FEM, for performance evaluation and test planning. To be able to fulfil all these different tasks the simulation tool, all the simulation models, and the actual simulation process must be quite flexible and adaptive. The advantage of simulation is always judged by the benefits achieved using it and the effort that is needed to get them.

A modular mechanical system simulation model of an industrial vehicle was designed and modelled. The overall simulation model was built from independent sub-models using a building system made of simple *MSC.ADAMS/View* command files. The building system was designed so that the independent sub-models could be modelled and simulated without connection to other sub-models and new or modified versions of sub-models could be saved without any manual editing of the text formatted model files. The interface between the sub-models was designed so that different versions of sub-systems could be used in the overall simulation model. The simulation model building system makes it possible to build 27 variations of the basic model and additionally some minor variations of the model.

The modelling and simulation work done during the project proved that the principles of modular modelling and simulation are justified, regardless of the limitations of the modelling and simulation tool used in the project. The analogy between modular modelling and simulation, and object-oriented programming in software development was discussed.

Due to the nature of the material the research report *Modular Modelling and Simulation of Mechanical Systems* [Kortelainen 2006b] is also confidential.

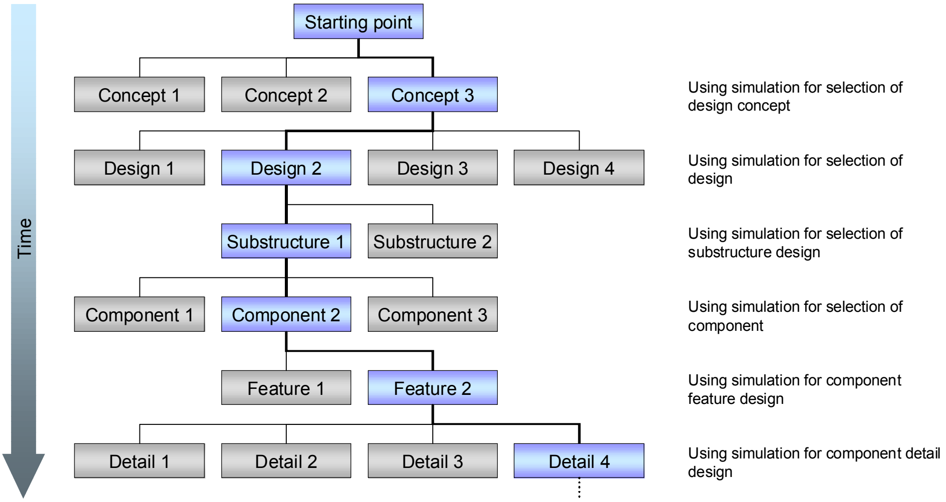


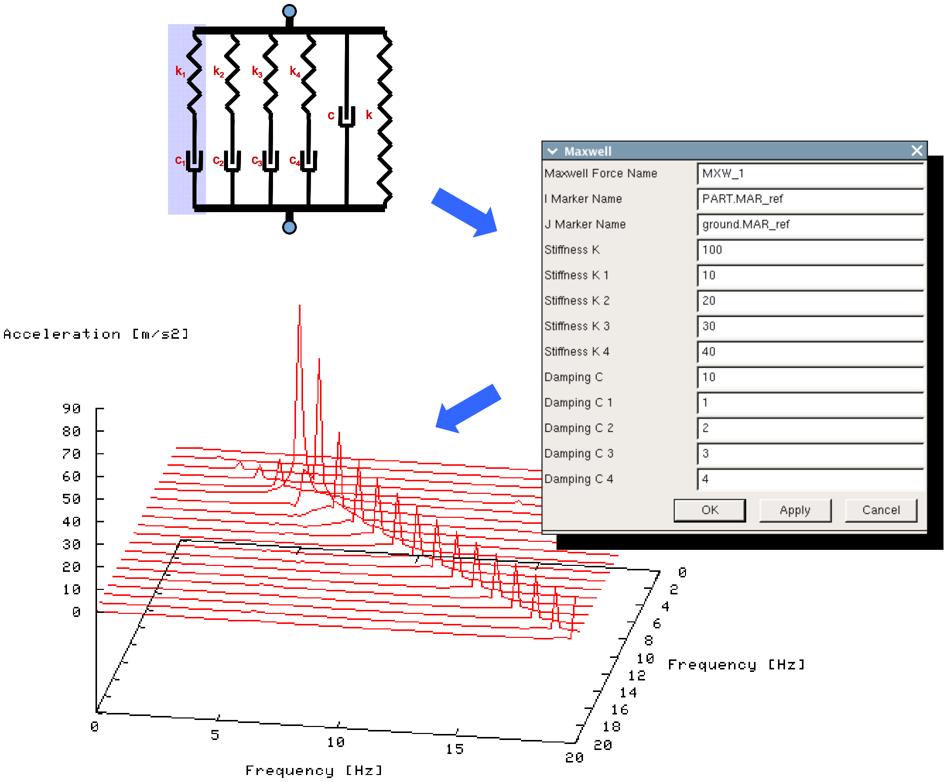
Figure 3.4. Simulation used as a decision making tool in a product development project, seen from the point of view of one detail [Kortelainen 2006b].

3.9 Implementation of isolator component models in MSC.ADAMS/View

It is a quite common practice to drastically idealise flexible components such as vibration isolators and different kinds of springs in a mechanical system simulation model. The usual way is to use linearised representation for both the stiffness and the damping. In most cases this is an acceptable idealisation. However, simulation of more complicated loads and more optimised designs needs more accurate models.

The formulation of two different kinds of progressive vibration and shock isolators used in industrial and vehicle applications is presented in the report *Implementation of Isolator Component Models in MSC.ADAMS/View* [Kortelainen et al. 2006]. In addition, the implementations of these models into the selected mechanical system simulation software, *MSC.ADAMS*, are presented including the actual, ready-to-use macro for modelling (see Figure 3.5). The two isolator components, a rubber and a wire rope isolator, are different in nature, the former being strongly vibration frequency dependent and the latter dependent on isolator component local amplitude.

The mathematical formulation of the two isolators is based on a relatively simple approach: using idealised primitive elements like linear springs, viscous and friction dampers, Maxwell and friction-spring elements. By combining these primitive elements, both serially and in parallel, the dynamic properties of the isolator components can be approximated accurately enough for most engineering requirements.



Maxwell Force Name	MXW_1
I Marker Name	PART.MAR_ref
J Marker Name	ground.MAR_ref
Stiffness K	100
Stiffness K 1	10
Stiffness K 2	20
Stiffness K 3	30
Stiffness K 4	40
Damping C	10
Damping C 1	1
Damping C 2	2
Damping C 3	3
Damping C 4	4

Figure 3.5. A schematic presentation of how the non-linear vibration isolator components were developed and implemented [Kortelainen et al. 2006].

In the implementation of these mathematical representations into the selected simulation environment, the usability and numerical efficiency have been one of the main concerns. The developed components and their implementation in the selected mechanical system simulation software, *MSC.ADAMS,* and the simulation results and the experiences on using the components have shown that the objectives have been attained.

3.10 Influence of scuff and ageing on the response of a mechanical system

Mechanical system responses are strongly dependent on the force and vibration path in structures. Discontinuities like clearances and vibration isolators may change the system characteristics which must be taken into account in simulations in order to gain realistic results, when the vibration responses are in focus. Figure 3.6 presents an example of force (one component) acting on a wheel support structure of a industrial vehicle. The location of the virtual measurement is such that it cannot be measured practically on a real system.

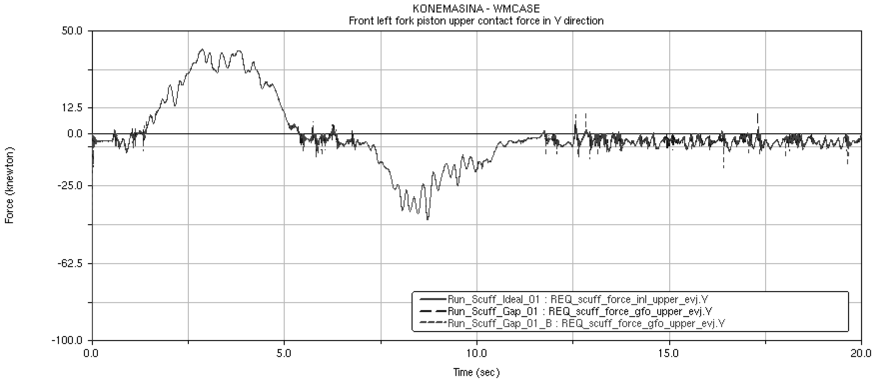


Figure 3.6. By modelling some nonidealities into the simulation model useful information can be obtained from details that cannot be measured from the real product [Kortelainen 2006a].

The report *Influence of Scuff and Ageing on the Responses of a Mechanical System* [Kortelainen 2006a] presents the use of the overall system simulation model of a industrial vehicle for studying the influence of scuff and ageing on the mechanical, vibration responses of the system. The natural choice for the target was the industrial vehicle case of the research project, in which the modelling of clearances in component joints and connections was studied. A free clearance was modelled into one wheel support vertical joint to represent the results of scuff. Test simulations were run, both with and without the modelled clearance, in which the industrial vehicle completed a manoeuvre on a bumpy surface. Force in two places on the selected wheel support was measured and the results were analysed.

One of the main differences when using modelled clearances in simulations is the content of higher frequencies in vibration responses related to the case of ideal constraints. When the simulation objective is to study the vibrations of the system and especially when trying to develop methods to decrease the vibration levels, this difference must be taken into account. If the requirements are strict, the flexibility of the structures and their influence on vibration levels should also be considered.

3.11 Methods to create 3D terrain models

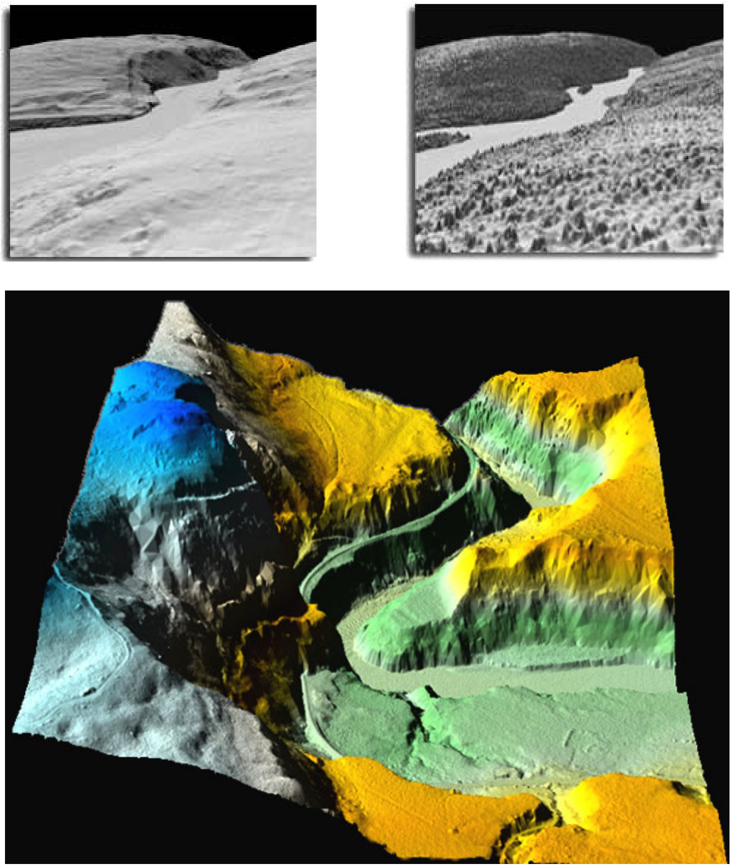


Figure 3.7. LIDAR measurements and generated 3D terrain model.

The interest in 3D mapping and terrain modelling is growing all the time along with development of methods and sensors. A 3D terrain model is useful when driving simulators, planning paths for robots, researching terrain-tyre interaction and within many other applications. In the past these models were created by artists from a library of pre-constructed primitives. Nowadays it is possible to directly acquire 3D models from real world environments, in other words to “digitise reality”.

The report *Methods to create 3D Terrain Models* [Kauppi 2006] gives an overview of different methods and equipment which can be used to build 3D terrain models. The report gives a description of DEM (Digital Elevation Model) and explains such methods as LIDAR, InSAR, Stereo Imagery, Road Surface Monitoring vehicles and 3D and 2D laser scanners and their usage. Facts to be considered when building a 3D terrain model are also handled. Such facts, among others, include required accuracy, shadowing effect, snow, rain and grass.

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4. Real-time simulation

4.1 Introduction

Virtual technologies are used to produce of computer model of a product. These models can be used to simulate the behaviour, manufacturing or production of the product before its physical existence. Real-time simulation is a simulation method where computer time and real world time are synchronized. The time in simulated process progresses simultaneously with the system under investigation and the rate of change of system parameters is similar.

Real-time simulation and virtual technologies present interesting possibilities in many areas. Presently virtual technologies are used in reasonable level but real-time simulation is mainly used in research and training purposes. The main problem in exploiting real-time simulation is the lack of commercial tool suitable for systematic forming models suitable for real-time simulation. The present training simulator technology is mostly based on kinematics and visualization, the dynamics modelling of the systems has been modest.

Multibody simulation approach is nowadays used to study the dynamical behaviour of machine systems. While demands to dynamical properties of machine systems increase the control systems required to fulfil them become more complicated. Real-time simulation enables the effective use of control design tools in conjunction with operator of the studied system in earlier phase of design process.

The goal of the project was to develop methods and tools suitable for the use of real-time simulators and virtual technologies in

- product development process
- condition monitoring
- operator training
- determination of customer’s needs considering new procedures and products.

To achieve the presented goals the plan was that the following actions were taken:

- survey of real time simulation methods, environments and tools

- development of real-time simulation models with different grades for different needs
    - quickly built, light parametric model
        - early stage of product development
    - accurate physical model
        - research and development, condition monitoring
    - realistic virtual surroundings and accurate physical model
        - research and development, operator training
- survey of verification methods and their accuracy for simulators
- development of demonstration simulators and general simulator platforms

4.2 Realization of the project

The project realized as a study of possibilities of utilization of real-time simulation and the development of an open, general and modular real-time simulation environment. This became the main task since there were not available efficient commercial solutions for real-time simulation of mechatronic systems. Present commercial soft/hardware is expensive and usually aimed to the general simulation purposes so the construction of simulation models is difficult and case sensitive.

A major problem in using general purpose simulation software is that the existing models build using some design software, can not be used directly. This is a serious problem, since companies have already a certain design environment, to which the real-time simulation must be connected in a reasonable way. If the connection is not fluent, the use of real-time simulation can become too complicated. For this reason one task was to find a general way to take advantage of existing models, Figure 4.1.

The numerical solver is is the core of an entire real-time simulation environment. The solver consists of modules of several separate modelling- and numerical methods, which enable fast and straightforward study of methods. The core connects other modules either in pre- or postprocessing phase or during the computation utilizing distributed computation. The communication between distributed components is implemented through standard network sockets, the blue arrows in Figure 4.1.

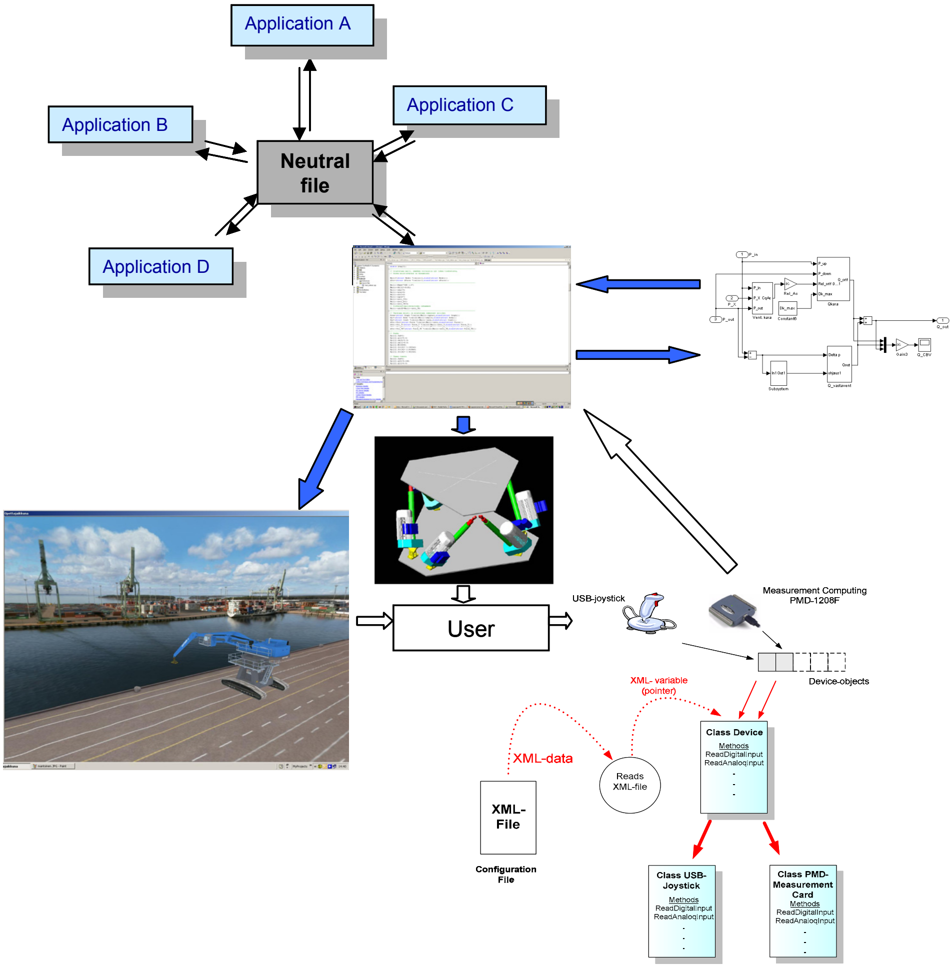


Figure 4.1. Tasks of the project.

HIL simulator consists of a real-time simulator and experimental hardware. HIL simulation has been used in most cases for testing existing control hardware with a virtual process model. The method has rarely been proposed in the form in which part of the process is simulated while rest of the process is real physical. Some examples in the fields of high speed trains, vehicle suspensions and spacecraft dockings are documented. In this project the hydromechanical system is interfaced by means of pressures and flows instead of forces and motions. The method is based on a real-time simulation model of hydraulics, which is simulated while running the physical prototype. The simulation model inputs are the measured pressures and it calculates the virtual flows that are transformed into real flows by means of flow feedback control systems that use high bandwidth flow transducers, PID-controllers and real high performance servo solenoid control valves.

The motion platform is used to increase the immerse in the real-time simulation environment and is a part of visualization environment. From control point of view, the motion platform is a passive node in environment. The chosen platform structure is a Stewart platform, which is suitable for many different cases. The first platform is hydraulic driven and the second one consists of electric servo motors and ball-race screws. Transitory acceleration and neutral settling in operating area is obtained by manipulating the simulated acceleration signal by means of washout filtering. An inverse kinematical model with inverters, analogical filters and PI controllers are applied in controlling. The achieved servo system can be driven with either speed or position trajectory.

Real-time simulation models of hydraulic components are needed in HIL simulation as well as in traditional real-time simulation of mechatronic machines. Since models used in off-line simulation often include high frequencies and numerical discontinuities the study of more effective models and modeling methods is necessary.

Real-time simulators have often a case sensitive user interface. Easy and cheap user interface can be formed using commercial game controllers, anyhow the parameters of controllers must be specified each time. This can be done using separate user interface library that enables the use of special dialogs instead of compiling the complete software, thus enabling on-line changes in controllers' behavior.

To verify the correct functionality and to compare the amount of work in forming simulation models a comparison model must be built. The environment used in comparison is Simulink with Real-Time workshop.

4.3 Integrating real-time simulation in product development

The use of numerical simulation in different stages of the product process is steadily increasing. As the accuracy and reliability of the results obtained by simulating improve and are combined with high quality virtual reality-based interfaces, physical testing can be replaced by virtual prototypes. The obvious driving forces behind this development are the anticipated savings in development time and cost and eventually the improved quality of the finished products. In addition to optimising the end product from a functionality and cost perspective, simulation is used to optimise the production process both through designing for manufacturability (DFM) and assembly (DFA) and through simulation of the production process itself. To achieve these benefits methods, algorithms and software platforms need to be further developed and new standards and working procedures need to be adopted so that reliable results can be produced with reasonable effort. This becomes even more critical in a business environment where the design and production of components is distributed to increasing numbers of subcontractors at the same time as practices of concurrent engineering are being adopted.

Setting up a simulation always requires that an optimal balance between different design goals of the simulation system itself is achieved. These options have to do with matters such as simulation objectives, physical design, user interfaces, required accuracy and reliability etc. and are steered by normal business restraints such as time and cost, but also by more pragmatic things such as availability of skilled personnel and suitable software models, maturity of technology and understanding of theory behind the phenomena. Requiring real-time performance usually comes at a cost by limiting the selection of suitable mathematical models, solvers or parameters, thus forcing to accept some loss of accuracy.

Because of the trade-off between the requirement of real-time performance and other important goals real-time simulation should not be used without good reasons and considering the consequences. Generally speaking real-time simulation is required only when the simulation needs to be synchronised with an external system, whose performance depends on universal time and whose time reference cannot be artificially altered. In practice this limits the use of real-time simulation to specific integrated applications where part of the system is replaced with a simulation module such as in hardware-in-the-loop and software-in-the-loop systems and to interactive simulations involving human beings e.g. training simulators.

In the following typical use of real-time simulation in some design stages is described.

4.4 Concept design

Real-time simulators can be used early in the design process to help to define various physical properties, functional characteristics and process requirements of the product in virtual world. In the product definition phase and in concept design accurate behaviour is usually less important. Instead, so called virtual mock-ups with simplified functionality may be used.

4.5 Testing and refinement

In testing and refinement phase real-time simulators can be used for example to test software and hardware modules of the product. During this phase testing, validation and final adjustments of the design are done. This usually requires higher accuracy simulations than is needed in concept design. In some cases parts of the system is available as physical prototypes or actual components, which makes it possible to build partially virtual prototypes.

In partially virtual prototypes part of the simulation model is some real component or system. The most common partially virtual prototypes are so called Hardware-in-the-Loop (HIL) or Software-in-the-loop (SIL) systems. In HIL simulation part of the real system is replaced by high-fidelity simulation model executed on a real-time computer system. The idea of the SIL simulation is the same except the target hardware is simulated and the software under development runs on that simulated hardware. SIL approach may be cheaper for testing the embedded software because there is no need for physical test beds as in HIL simulation but it may be difficult to simulate the target hardware. And if the physical hardware is readily available and it can be connected to the simulation model fairly easy it will probably give better results than a simulation model of that same hardware.

4.6 User training

Probably the most traditional application for real time simulators is user training. It is particularly useful if the real device, vehicle etc. is too expensive to use it for training purposes. Or if the training is not possible before the real action for example some maintenance operation in nuclear power plant during maintenance breaks. Besides in virtual world it is safe to train dangerous operations or situations, which are not possible in the real world.

4.7 Integrating simulation systems with the design loop

One of the challenges with using real-time simulation as part of the design process is to produce the necessary systems set-ups fast enough so that the process is not delayed. The simulation results need to be available well in time before important design decisions must be made. Difficulties to keep in pace with the design process is mainly due to two factors:

1. the complexity and diversity of real-time simulation systems in general
2. the lack of support for available digital design data.

The first issue has to do with the uniqueness of dedicated and often custom-built systems. The setting up of a real-time simulation system usually involve extensive time consuming development work and testing.

The second issue is an expression of the well known difficulty of exchanging information between unrelated software.

4.7.1 Rapid real-time simulation

In order to speed up the simulator development and application process the concept of “rapid real-time simulation” was introduced. This includes initiatives to minimize the time it takes to get useful simulation results to feed back to the design team and to minimize efforts required to transfer information from design tools to simulation. Changes to the design should be quickly and correctly reflected in the corresponding simulations.

The approach in this project was to focus on mechanisms for transferring information between different systems and software. This can basically be done in two different ways:

- by developing software tools and libraries to support the different file formats used
- by agreeing on a single file format that include all necessary aspects of the system required for the real-time simulation. These approaches can be illustrated as in Figure 4.2.

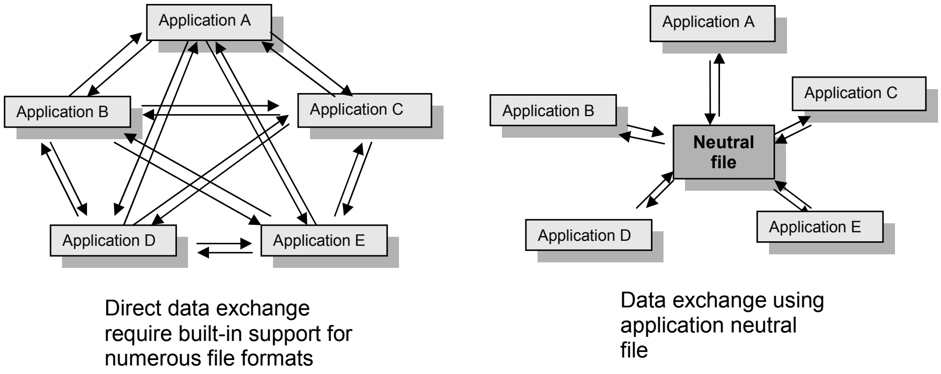


Figure 4.2. Data exchange between separate applications.

Direct file exchange require support for a number of file formats for each application. This is difficult because detailed and comprehensive descriptions of supported file formats are often hard to find and in some cases format descriptions are not disclosed at all. Sometimes version support becomes an obstacle as different versions of the same format may be incompatible.

The idea with an application neutral file format is that one export filter and one import filter per application is needed. Because the file description is public writing these filters is easier.

4.7.2 Considerations for defining a neutral file format

Because the neutral file should support a variety of different software tools the design of the file structure deserves careful attention. If the file is not to be used as a data storage within a single application all features of every application need not be included. In this project, for the purpose of multi-body dynamics simulations the most important elements are descriptions of individual parts of the design, the connections between these parts and forces acting on the system. Things to be agreed on include

- coordinate system orientation
- definitions of positive rotation directions
- supported joint types and constraints
- units and dimensions to be used.

Finally, a structure for the file has to be designed. For a neutral file format it is a great benefit if the file is human readable and if new features can be added later without disturbing downward compatibility. For this reasons a format based on the eXtesible Markup Language XML was chosen.

4.7.3 MechXML

MechXML is an XML-based language for the description of rigid and flexible multibody systems, developed in the Technical University of Madrid. Instead of creating a similar format definition for this project it was decided to adopt the MechXML description. Tools already exist to transform MSC Adams solver files to MechXML.

To use MechXML in a software project such as a RT simulation program require that a file parser is implemented. Because the file is based on XML writing such a parser is relatively simple. To demonstrate how this can be done a function library for a real-time simulation system developed for this project at the Technical University of Lappeenranta was crated. The library functions operate directly with data structures used in the simulation program and thus provide easy access to the MechXML file.

The test case model is made in MSC Adams. The final objective is to show that the Adams model can be used as input data for rapid creation of a real-time interactive simulation using the MechXML file and developed parser tools. Due to performance issues some manual simplification of the model may be necessary although the conversion and parsing of model files can be made automatic. Such simplifications will be made in the Adams environment before the model is exported.

4.8 Real-time simulation environment

4.8.1 Introduction

Real-time simulation environments are complicated systems that consist of several subsystems from different engineering disciplines. Aspects, such as modelling and numerical methods, computer science and programming, control- and automation engineering need to be taken into account in the development of such systems. The development of the real-time simulation environment at the IMVe has been under investigation since 2002. The main goal of the research is to develop an open, modular and easily expandable environment that enables the research and testing of different modelling methods and separate modules, such as motion platforms, visualisation environments and the addition of computational nodes, in a systematic and efficient way.

4.8.2 Simulation environment

The environment consists of subsystems that enable the modular development of the system, Figure 4.3a. Each grey shade block represents a separate computer node in distributed computing while black arrows describe communication paths. Each subsystem can be divided into exchangeable modules as shown in Figure 4.3b in the case of the solver module. This modular approach enables fast and straightforward implementation of new integrators or solution methods as each module level utilizes the same interface.

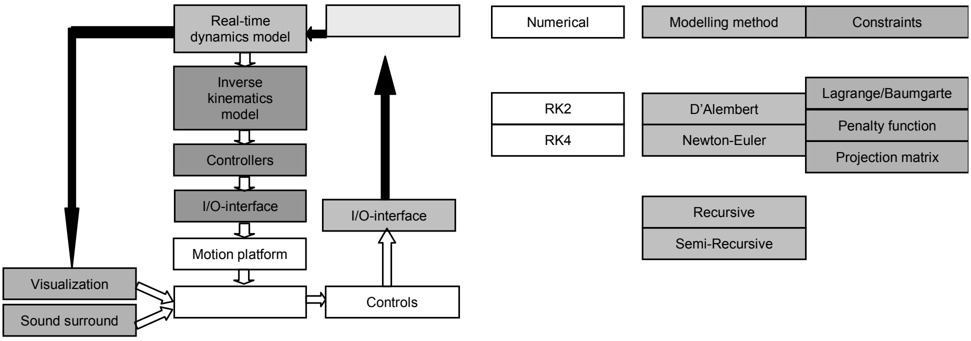


Figure 4.3. a) The subsystems of the real-time environment. b) The modular structure of the solver.

Similar modular design has been applied throughout the entire software architecture. The core of the real-time dynamics solver consists of three static libraries: the solver library of numerical algorithms, the modelling library of the formulations of dynamics equations and the communication library for distribution of computational tasks.

The rigid body motion can be analyzed employing both Newton-Euler equations and D'Alembert/Lagrange formulation with second time derivatives of the Euler parameters. However, the Newton-Euler equations are preferable in order to reduce the number of velocities and accelerations of generalized coordinates. In addition, the equations of motion can be simplified and a constant mass matrix can be obtained, resulting in a more efficient solution. Kinematic constraints are included to the differential equations using either Lagrange multipliers or penalty functions. Utilizing the partitioning of the generalized coordinates, the projection matrix from the independent generalized coordinates to the dependent ones can be solved in order to describe the system with the minimum set of differential equations. The topology of the system can be used in two formulations. One formulation is based on the recursive Newton-Euler solution of the inverse dynamics problem while the other utilizes semi-recursive approach. These methods are straightforward to apply for open kinematic chains.

The use of distributed computing enables the division of the environment into independent computational parts, e.g. separation of the user interface, motion platform etc. from the solver. In addition to clarifying the system architecture, more computational resources are available for the solver, as it is running on an independent processor. Parallelization of the components of the solver allows faster iterations, thus enabling real-time processing of highly complex models. Presently the environment consists of two computers, one for the graphics engine and the other for the solver core. The graphics engine is implemented on Windows operating system while the solver core is portable to Windows and Linux operating systems. The communication between these components is implemented through standard network sockets. The same approach can be used for distributing more subsystems of the simulator into additional nodes. This approach demands that the subsystems must be independent of each other. In addition, the processing power required by the subsystems dictates whether multiple nodes can be used effectively. On the other hand, parallelization can be used to compute a single module using multiple threads inside a multiprocessor node, or using multiple processors on a number of nodes. Currently, each module is lightweight, and, for this reason, only the multiprocessor approach is considered for parallelization.

The graphics engine for the real-time simulation environment is implemented using C++ with Windows MFC libraries, which allows flexible addition of features, Figures 4.4a and 4.4b. The engine is based on OpenGL library and OpenAL library for the audio environment. OpenGL Glut library simplifies the use of projection matrices and the positioning of the camera. The stereoscopic view uses the OpenGL quad buffer feature. The graphics are imported using 3ds-format, which enables the efficient preprocessing of the graphics objects in external software. Another important feature of the 3ds-format is it’s structure, consisting of object related meshes that are based on triangle polygons. A single object can have several meshes. This enables the utilization of the structure in collision detection by using the separate meshes in forming the collision tree and the triangle polygons in the leaf level collision detection. Taking into account the collision detection while creating the 3ds graphics, a very efficient collision detection tree can be obtained and some of the non-colliding features can be eliminated already at the trunk level of the collision detection tree.

Figure 4.4. a) A tailor made user interface. b) A user's view. c) 2D-visualisation environment.

The physical visualization environment includes two separate projection systems. A three screen 2D-system, Figure 4.4c, and a 3D-system with one screen. Both systems utilize PC-hardware and Windows operating system. This enables reasonable update costs and the use of generally available software, for example when viewing CAD-based presentations. The motion platform is currently under testing and will be added to the visualization environment. From the control point of view, the motion platform is a passive node in the environment. The chosen platform structure is a Stewart platform, which is suitable for several purposes. The platform consists of inverter driven electric servomotors and ball-race screws. Transitory acceleration and neutral settling in the operating area is obtained by manipulating the input acceleration signal by means of washout filtering.

4.9 Hardware-in-the-loop simulation

Usually, a hydraulically driven machine can be constructed by using alternative hydraulic components and systems. The effects of alternative components on the behaviour of machine are normally difficult to observe because it is laborious and time-consuming to install and replace the components in construction. By using a simulation model of the entire construction it is very easy to study the effects of component variations. If however, the construction is complex, it is often time-consuming to build a simulation model of the entire machine system.

The present study deals with hardware-in-the-loop (HIL) simulation of hydraulic components and systems. The main idea is to develop hydraulics by using a simulation model of it as a part of the machine. The idea makes it possible to test a variety of design parameters of a hydraulic system or single component on-line while running the practical experimental machine. By using the existing construction, less modelling work is required. Also, properties like flexibility, gaps and friction are automatically included.

In the previous studies the proposed R&D method has been studied mostly for testing different kind of directional valves for controlling physical mechanical prototypes. In this study the method is utilized for a study of pressure relief valves (PRV) in existing hydraulic circuit. The method is valid since the modeling accuracy and bandwidth of the interface is sufficient compared with the dynamics of simulated component.

Figure 4.5 shows the schematic construction of the experimental rig used. In the present system the cylinder is controlled by using the directional valve *v1*. Valve *v4* is used to select the active valve: either the PRV *v3* or the HIL simulator with high bandwidth servo solenoid valve *v2*. Released flow is measured by flow transducer *a1* and pressure by pressure sensor *a2*. It is important to notice that the dynamical properties like bulk modulus and volumes of pipes *p1* and *p2* must be equal.

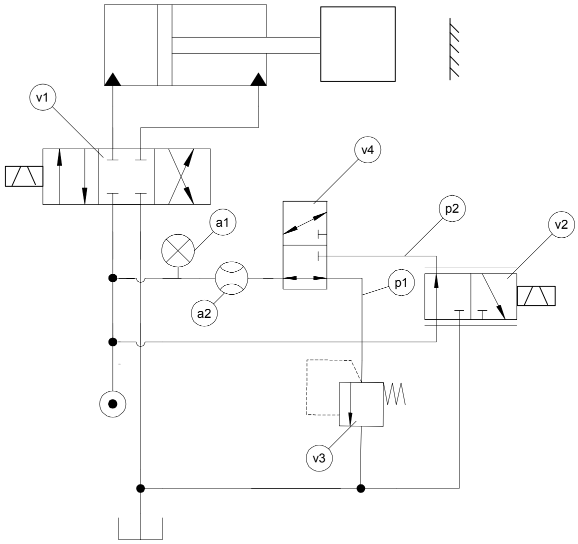


Figure 4.5. Schematic representation of the used test rig.

The natural behavior of PRV can be seen when the oil pressure is suddenly increased. In this study this was done by driving the cylinder at the end of its stroke. At first this was done by using the real PRV in action. During the first work cycle two points of measured pressure and flow were taken and used to solve the empirical constants of the used PRV model. After parameter settings similar work cycles were done by using the HIL simulator with the defined models.

The defined simulation models of the present study were modeled first in Matlab/Simulink environment and then converted to c code by using Simulink/RTW. After this the code is compiled and loaded into a dSPACE processor card. The bandwidth of servo solenoid valve used is 35 Hz, the reaction time of the flow transducer is less than 2 ms, the bandwidth of the pressure sensor is 2 kHz and the used sample-time is 1 ms.

Two different simulation models of PRV are used. The functionality of the HIL simulator can be reviewed by comparing the measured flows and pressures of both cases etc. by using the original PRV and by using the HIL simulator. In Figures 4.6 and 4.7, three oil flows are compared. Q_{Model} is the output flow of the simulation model, Q_{HIL} is the output flow of the HIL simulator's interface and Q_{Real} is the output flow of the real PRV. The measured pressures are compared in Figures 4.8 and 4.9.

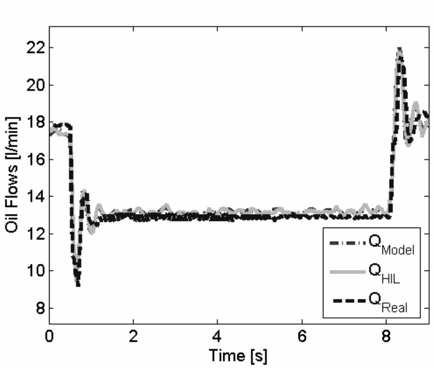


Figure 4.6. Flows by using 1^{st} order model.

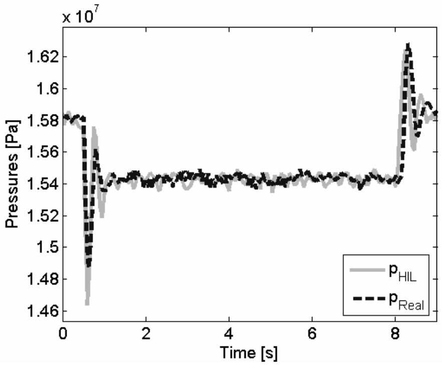


Figure 4.7. Pressures by using 1^{st} order model.

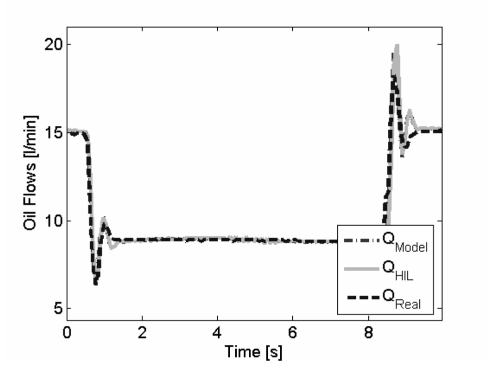


Figure 4.8. Flows by using 2nd order model.

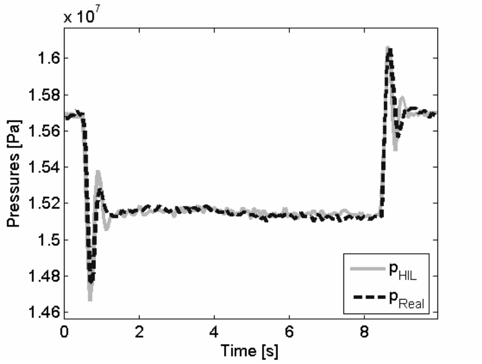


Figure 4.9. Pressures by using 2nd order model.

4.10 Motion platform

The motion platform is used to increase the immerse in the real-time simulation environment and is a part of visualization environment. From control point of view, the motion platform is a passive node in environment. The chosen platform structure is a Stewart platform, which is suitable for many different cases. The first platform is hydraulic driven (Figure 4.10) and the second one consists of electric servo motors and ball-race screws (Figure 4.10). Transitory acceleration and neutral settling in operating area is obtained by manipulating the simulated acceleration signal by means of washout filtering. An inverse kinematical model with inverters, analogical filters and PI controllers are applied in controlling. The achieved servo system can be driven with either speed or position trajectory.

Figure 4.10. Hydraulic driven motion platform.

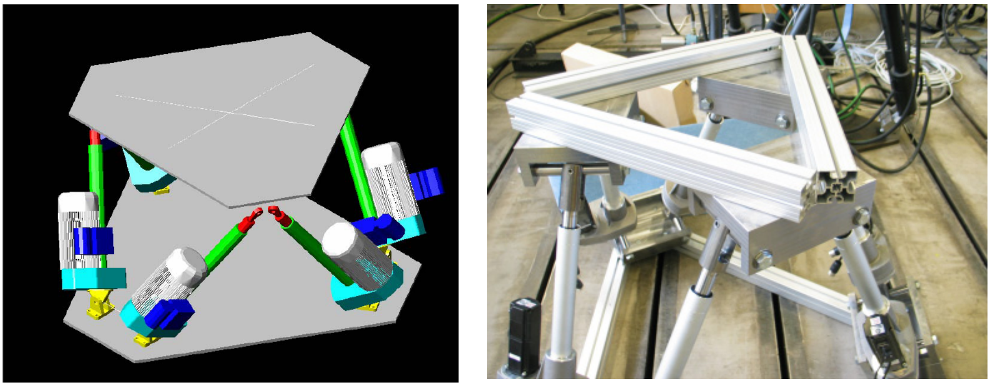


Figure 4.11. Electric driven motion platform.

4.11 Real-time simulation of hydraulics

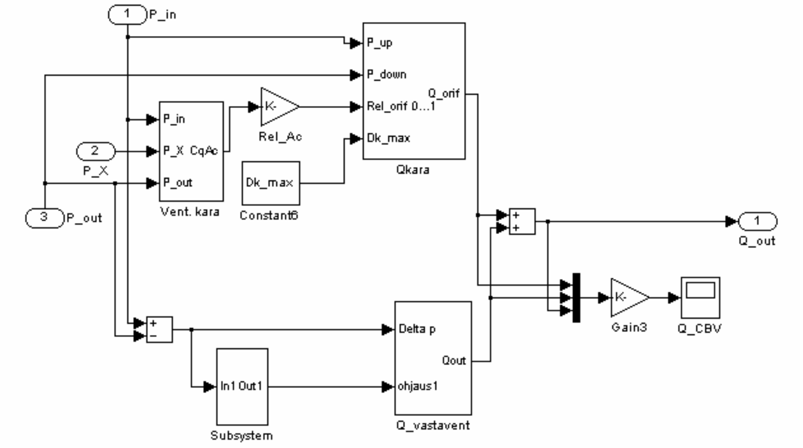


Figure 4.12. Schematic view of counter balance valve Simulink model.

The real-time simulation of hydraulics is utilised using Matlab-environment and C-programming language. The modified Heun method is used as a basis for the real-time simulation model of a conter balance valve. The results are compared to results obtained using traditional modeling methods and Simulink-environment. (Figure 4.12.) The reference models are numerically solved using ode23s, ode23t and ode23ts algorithms and Runge-Kutta and Heun algorithms. The results show that the modified Heun method provides as accurate results as comparision methods but also offers greater computational efficiency.

4.12 Connecting user interface equipment to real-time simulation environment

A typical problem with a conventional user interface design is that even a slight change in the user interface might imply large modifications in the application code, especially if the code for the user interface is scattered all over the application. The application also has to be compiled after every change in the code. To improve usability of the IO-interface in real-time simulators the IO-interface class library was developed to study its utilization as a part of a real-time simulator, Figure 4.13.

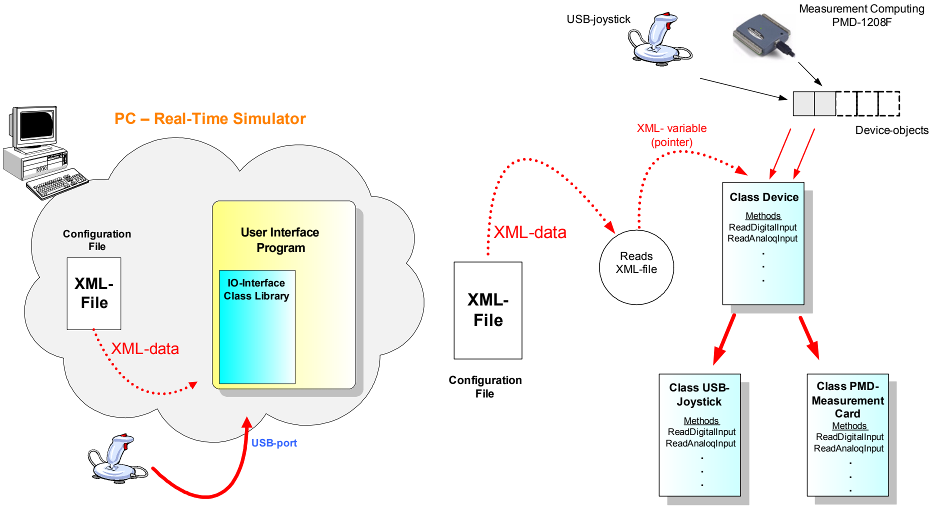


Figure 4.13. The principle of IO-interface class library and Class diagram.

The IO-interface class library includes a set of methods for reading and writing signals to devices. After the class library has been linked to the user interface program and class objects have been created, all these methods are available in the program. The IO-interface class library reads all the needed information on devices from the configuration file, Figure 4.14. This XML (Extensible Markup Language) based configuration file allows user to define separate configuration for each IO-channel. The user can determine the devices (ID number, name and type) and select the digital and analog channels that are used in real-time simulator. For each selected channel the user can configure the following options:

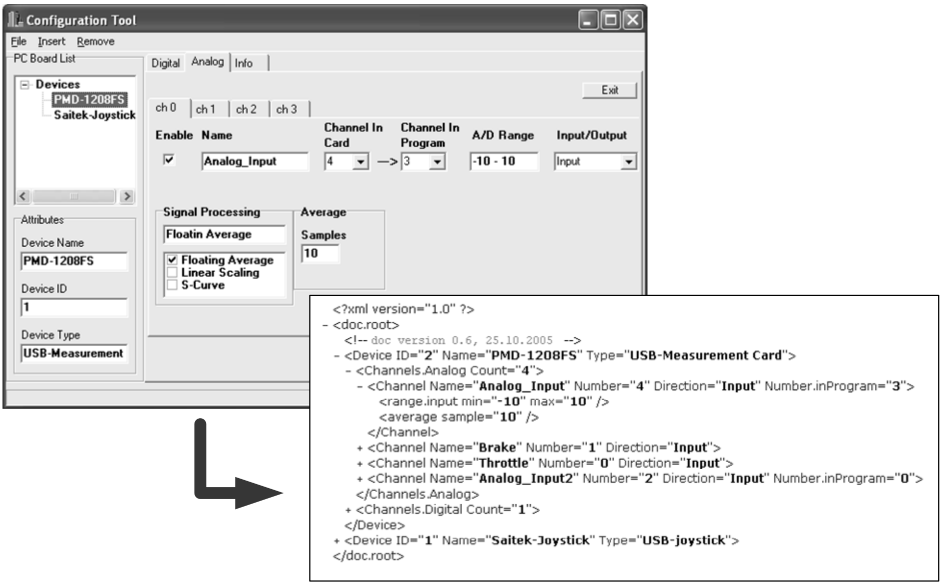
- Name of the channel. The name can be symbolic like throttle, brake, wheel etc.
- Physical channel number.
- Direction of digital I/O channel (input or output).
- Input range for analog channels. Measurement cards need this information when reading analog channels.
- To give a new number for any physical channel used in the user interface program.

The following signal processing methods can be also configured separately for each analog channel:

- Average – calculates floating average values of input signals.
- S-curve – generates output signals using STEP function got from ADAMS definition.
- Linear Scaling – calculates output value according to the definition of two points.
- Dead Zone – generates defined output value within a specified dead zone region.

All these configurations can be done without compiling the application and actual C++ programming, and is thus easy and efficient way for the user to maintain and modify an IO-interface. The IO-interface class is designed and programmed so that its implementation and use would be as easy as possible. The use of methods for reading and writing signals are always the same independent of what USB-based devices are connected to the computer. Currently the IO-interface class library supports only low-cost commercial USB joysticks and one certain USB-based measurement card. To add support for new measurement cards, a new class for this card has to be programmed. The IO-interface class library was written in ANSI C/C++ language. Thus it can be used with any modern compiler and also in other operation system like Linux, QNX etc.

Figure 4.14 illustrates a view from the developed configuration tool. The program generates XML-based configuration file according to the user-defined rules and settings.



Enable: ☑
Name: Analog_Input
Channel In Card: 4 —> Channel In Program: 3
A/D Range: -10 - 10
Input/Output: Input

Signal Processing: Floatin Average
☑ Floating Average
☐ Linear Scaling
☐ S-Curve

Average Samples: 10

Device Name: PMD-1208FS
Device ID: 1
Device Type: USB-Measurement

```
  <?xml version="1.0" ?>
- <doc.root>
   <!-- doc version 0.6, 25.10.2005  -->
 - <Device ID="2" Name="PMD-1208FS" Type="USB-Measurement Card">
   - <Channels.Analog Count="4">
     - <Channel Name="Analog_Input" Number="4" Direction="Input" Number.inProgram="3">
         <range.input min="-10" max="10" />
         <average sample="10" />
       </Channel>
     + <Channel Name="Brake" Number="1" Direction="Input">
     + <Channel Name="Throttle" Number="0" Direction="Input">
     + <Channel Name="Analog_Input2" Number="2" Direction="Input" Number.inProgram="0">
     </Channels.Analog>
   + <Channels.Digital Count="1">
   </Device>
 + <Device ID="1" Name="Saitek-Joystick" Type="USB-joystick">
  </doc.root>
```

Figure 4.14. The configuration tool and generated XML-document.

4.13 Comparison model in Simulink

The objective of this work was to create a vehicle and tire model with Simulink software. Vehicle should model a industrial vehicle with possibility to include 8 tires and there should be a possibility to control the steering and velocity of the vehicle. The one of the most important tasks in this work was the tire modelling.

4.13.1 Industrial vehicle model

The vehicle was modelled in three-dimensional space with Simulink to consist the following parts: body, hoist and 4 or 8 tires. The body of the vehicle was modelled as a one piece rigid body and it has 6 degrees of freedom. Hoist is also modelled as a one rigid body and it has 1 degree of freedom, which will allow the up/down movement of the hoist. The hoist is connected to the body with 4 ropes. Ropes between the hoist and the body were modelled as forces based on motor models. All the main dimensions for the vehicle were taken from the industrial vehicle case Adams model. Handling of the vehicle is possible with joystick connected to the computer's USB port.

Simulation model is based on Lagrange's equation of motion. From this equation of motion it is possible to solve the acceleration vector of generalized coordinates and the vector of Lagrange multipliers. When a set of initial conditions is substituted to the equation of motion, the numerical integration of the acceleration vector and the solution of velocities and the generalized coordinates are enabled. From this equation the solution of required information of vehicle's positions and rotations is possible. The equation of motion can be written as

$$\begin{bmatrix} \mathbf{M} & \mathbf{C}_q{}^T \\ \mathbf{C}_q & 0 \end{bmatrix} \cdot \begin{bmatrix} \ddot{\mathbf{q}} \\ \lambda \end{bmatrix} = \begin{bmatrix} \mathbf{Q}_e + \mathbf{Q}_v \\ \mathbf{Q}_c \end{bmatrix} \tag{4.1}$$

where $\mathbf{M}$ is the mass matrix, $\mathbf{C}_q$ is the Jacobian matrix of constraints, $\ddot{\mathbf{q}}$ is the vector of generalized coordinates of acceleration, λ includes Lagrange multipliers, $\mathbf{Q}_e$ is the vector of generalized forces, $\mathbf{Q}_v$ is the quadratic velocity vector and $\mathbf{Q}_c$ is the vector that includes second derivatives of constraints.

4.13.2 Tire model

Tires were modelled based on Pacejka's Magic formula tire model. Tire forces are affecting to the body of the vehicle with four components: forces in *z, y* and *z*- axis directions and torque around the *z*-axis. The coordinate system was chosen the way that the *x*-axis is the vehicles longitudinal axis and positive direction of the axis is forward. The *y*-axis is chosen to be the lateral axis of the vehicle, positive direction is left and *z*-axis is the third axis with positive direction upwards.

The Magic Formula tire force calculations are based on force curves, where in the horizontal axis there is either longitudinal slip or sideslip angle and in the vertical axis there is either tire force or self aligning torque. The Magic Formula needs several parameters which describe the features of the tire. With these parameters calculated force and torque curves will be fitted to correspond the results achieved by measuring. In addition to these parameters there is also need of several variables: normal force, longitudinal slip of the tire, deflection of the tire, deflection velocity, rolling speed of the tire, sideslip angle and camber angle.

Normal force

When the vehicle is on the flat ground there will be a normal force acting on z-axis direction which can be defined as a linear spring and damper system as follows:

$$F_Z = k \cdot \delta z - C \cdot \dot{z} \tag{4.2}$$

where k is the stiffness, δz is the deflection of the tire, $\dot{z}$ is the deflection velocity and C is the damping constant. The road contact can be found out with deflection and deflection velocity. If these will become zero, the normal force becomes zero and contact to the road is lost.

Longitudinal slip

The longitudinal slip, κ, which creates the longitudinal tire force, can be defined with the following equation:

$$\kappa = -\frac{V_r - V_x}{|V_r|} \tag{4.3}$$

where V_r is the linear speed of rolling and V_x is the velocity of the tire. The linear speed of rolling of the tire can be calculated by multiplying the effective rolling radius by the angular speed of rolling.

Sideslip angle

When the tire is turned, there will be a sideslip angle, which can be calculated with the following equation:

$$\tan\alpha = \frac{V_{Sy}}{|V_x|} \tag{4.4}$$

where V_{Sy} is the lateral slip speed.

Tire forces

The general form of the Pacejka's Magic Formula tire model is defined as follows:

$$F = (D \cdot \sin(C \cdot \tan^{-1}(B \cdot X_1 - E \cdot (B \cdot X_1 - \tan^{-1}(B \cdot X_1))))) + S_v \qquad (4.5)$$

The longitudinal (F_x) and the lateral (F_y) tire forces and also the self aligning torque (M) can be calculated with this same formula. The calculation of the coefficients B, C, D and X_1 will make the difference in each of these cases. The output variable F stands for either F_x, F_y, M depending on the case. Coefficient C is called the shape factor and it represents the shape of the resulting curve. Coefficient D is the peak factor and BCD affects to the slope of the curve at the origin and in longitudinal force calculations it represents longitudinal stiffness of the tire. In lateral tire force and self aligning torque calculations it represents the cornering stiffness. Coefficient B is called stiffness factor. Coefficient E is the curvature factor and influences to the curvature near the peak of the curve. The factor X_1, is the sum of the offset coefficient S_h and longitudinal slip in the longitudinal force calculations and sideslip angle in the lateral force and the self aligning torque calculations. Coefficient S_h is horizontal shift, which represents conicity forces, which appear because tire may look a bit like a cone. Coefficient S_v is vertical shift offset, which represents plysteer forces, which appear because of the direction and method with which the plies are manufactured into the tire. Formulas for the calculation of these coefficients are presented in the book: Tyre Models for Vehicle Dynamics Analysis. To calculate these coefficients there will a need of several parameters that will describe the features of the tires. For the longitudinal tire force there is a need of 14 parameters ($b_0 \ldots b_{13}$), for the lateral tire force there is a need of 18 parameters ($a_0 \ldots a_{17}$) and for the self aligning torque there is a need of 21 parameters ($c_0 \ldots c_{20}$). Values for those parameters should be determined the way that curve we will get from the Magic Formula corresponds to the measured curve. This will mean that with these parameters the force of torque curves will be fitted to correspond to the measured cases.

Forces F_X and F_Y are only applicable when there is only one of them, F_X is valid, when $F_Y = 0$ and vice versa. A tire can only generate a certain amount of force so if the both forces are applied we have to combine the longitudinal and lateral tire force so that the combined force won't exceed the maximum force the tire can generate. This can be calculated with the friction circle, which is actually based on ellipse equation. With this approach we will cut down force F_Y so that vector (Fx,Fy) doesn't exceed the maximum magnitude, as follows:

$$F_Y = F_{y0} \cdot \sqrt{1 - \left(\frac{F_X}{F_{X0}} \right)^2} \tag{4.6}$$

where F_Y is the new lateral tire force, F_{Y0} is lateral force calculated with the Magic Formula. F_X is longitudinal tire force calculated with Magic Formula and F_{X0} is the maximum value of the longitudinal force, which can be calculated with $D+S_V$ using Pacejka's formulas.

4.13.3 Results

As results of this work, a functional 4 or 8 tire vehicle Simulink-model was created. In the following figures there are presented the results of the curve fittings for the tire modelling process. Figure 4.15 shows the longitudinal tire force curves, left one is calculated with Pacejka formulas and the right one is achieved with industrial vehicle case Adams model.

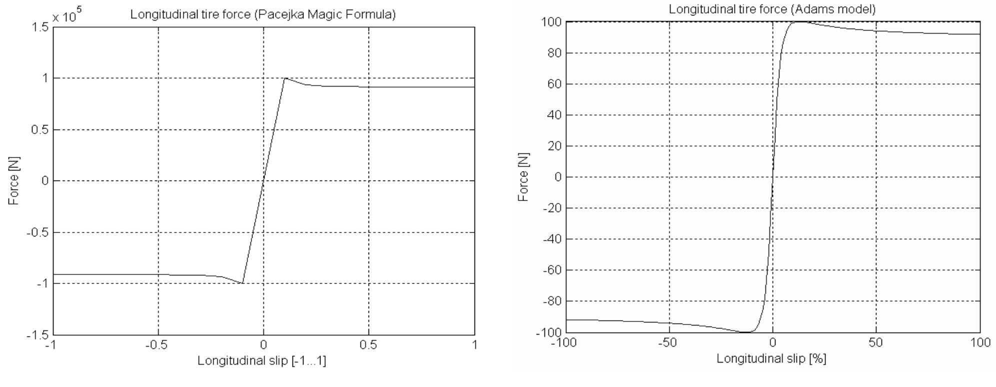


Figure 4.15. Longitudinal tire force curves.

In Figure 4.16 there are presented lateral tire force curves calculated both with Pacejka formulas and with Adams model.

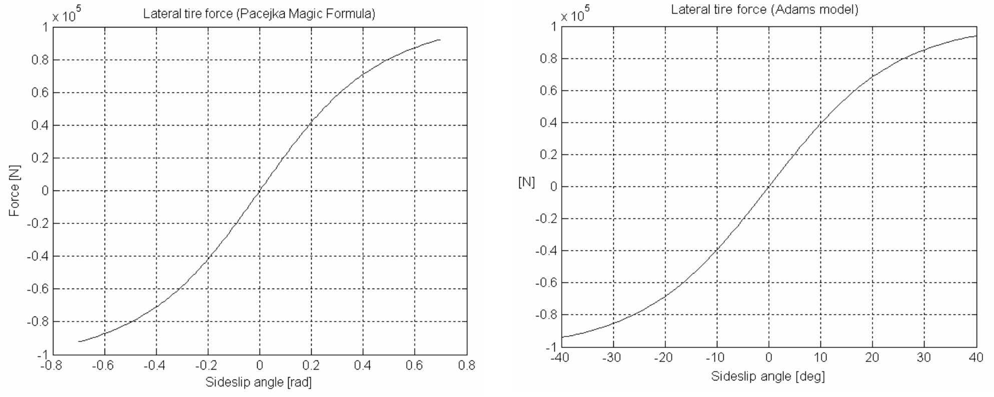


Figure 4.16. Lateral tire force curves.

In Figure 4.17 there's a self aligning torque curve calculated with Pacejka's Magic formula. It is fitted to correspond the general form of the self aligning torque, since the Adams model, which was used as a reference for these curve fitting procedures, didn't included the self aligning torque feature.

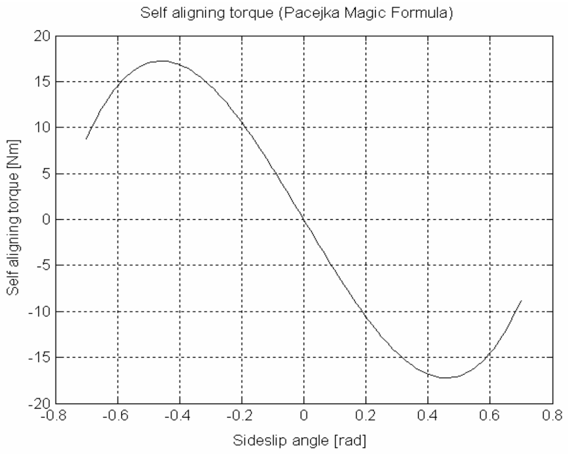


Figure 4.17. Selfaligning torque curves.

4.14 Conclusions

The development of the real-time simulation environment continues in the aforementioned areas. The solver module and graphics engine are connected using network sockets, which is the first phase towards a distributed computing approach. Currently the physical visualization environment is set up while the motion platform is under controller design development. The modular design of the environment enables parallel and independent development of each module and thus accelerates the development of the entire environment. The future work within the solver module includes the study of recursive methods in the case of closed kinematic chains, collision detection and the use of advanced features of distributed computing. Modern numerical solvers will be used to improve the energy balance preservation as well as increasing the stability of solution. The motion platform development concentrates on more sophisticated control design. Graphics engine updates include modular design of user interfaces utilizing object based graphical primitives, such as gauges, warning lights and switches.

The study of hardware-in-the-loop (HIL) concentrates to the simulation of hydraulic components and systems. The main idea is to develop hydraulic systems or individual components by using their simulation model or models as a part of the physical machine. The interface between the real and simulated parts is defined by means of pressures and flow. A simple test rig was built and promising results achieved. From the results it can be concluded that the studied HIL simulation based method is valid for R&D of hydraulically driven machines. The method needs further investigations to determine the constraints in applicability. The method may appear to be a novel powerful R&D tool for hydraulic machines.

The use of the IO-interface class library was tested by connecting to the test simulator the low-cost devices via USB-port and using them for manual control of the simulator. The IO-interface class library worked well giving flexibility in the definition of IO-interface. The configuration file could be easily and fast modified especially by using the configuration tool mentioned above. The main limitation for using the IO-interface class library is that it can be utilized only in the user interface programs written in C++.

One of the most important challenges connected with the use of real-time simulation in product development is to stay in phase with the design process. Development, configuration, validation and running real-time simulations will always take its time. However, simulation results need to be available at the right time in order to make an optimal contribution to the design process and, eventually, to the quality of the final design. Naturally the simulations must also be up to date with current design solutions and relevant design data must be transferred correctly between design tools and the simulation environment. In order to overcome delays and errors connected with manual model configuration a neutral file format for description of multi-body systems is suggested. Instead of creating yet another file format MechXML, an XML-based file structure developed at the Technical University of Madrid specifically for this purpose is adopted. In this project a software library is created for easy parsing of the MechXML file to the simulation program developed at the Technical University of Lappeenranta. The objective is to show that model designs created in the MSC Adams environment can be used as input to the real-time simulation environment and thus help bridge the gap between off-line and interactive simulation.

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5. Future operating place

Human interaction with their work and everyday environment are increasingly shaped by the ICT. During the past decade the development of the information and communication technology (ICT) has been fast and it has been applied in many products including also mobile machines. Novel user interface appliances with intelligent functions will increase in the upcoming years. The mobile machine industry will implement new technological inventions, but prudently to the actual, practical demand of the customers.

This study aims to enhanced simulation model with adequate methods and tools focused on interactive human machine system. It highlights issues that are relevant in the industrial domain on the design phase, especially on how to utilise simulation in the case of the future operating places of intelligent machines. An approach with example of feasible procedure, methods, and tools is described.

5.1 Interactive human machine system

The rapid change in people's work and ways of interaction with their environment has put forward the criteria of good design, e.g. the functionality and safety of the products and environments and also the usability and ease of use. Awareness and comprehension of various factors influencing on a human and mediated as part of an activity system are essential because of theirs high influence on product design, too (Figure 5.1). The activity system passes various interactions and different contradiction within the system and other corresponding external systems, producing activities with different integrative factors, and shaping the outcome and the system self [Engeström 1987]. Internal and external factors such as subjective value formation, mental information processing, psychological mechanisms, physiologic functions and anatomic properties of human and human work operating a product have to be considered equally as design matters with technical ones [Rasmussen 1986, Engeström 1987, Noro & Imada 1991, Järvilehto 1994, Wilson & Haines 1997, Vicente 1999, Sinkkonen et al. 2002, Väyrynen et al. 2004].

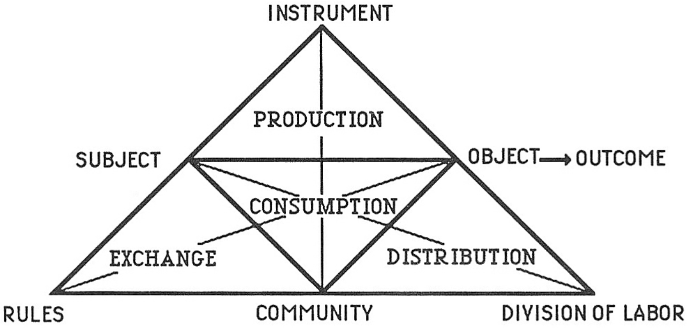


Figure 5.1. A diagram presenting common structure of human activity [Engeström 1987].

Increasingly the need state challenges have been tackled by a developing research area of human-technology interaction (HTI). The contributions to the good design approach are e.g. a human-centred design and development process, a more consistent system specification in developing the product to include also enabling instruments for work. Also the visualisation of results and solutions has been an essential approach to support participatory approach of design and development e.g. by using digital human models [Kuusisto et al. 1986, Mattila & Karwowski 1992, Järvinen et al. 1996].

5.1.1 Operating environment, job and work site

Operating place is in continuous interaction with the environment (indoor and outdoor) and human operator. Main interest of future operating place is focused on cabins. However, cabins have plenty of variations (Figure 5.2) concerning purpose of use and such other properties e.g. a) cabin *placing* e.g. in a vehicle, in the tower crane or in closeness to production machine, b) cabin *interfaces* e.g. seat, controlling equipments, information and communication devices or monitoring apparatus, c) cabin *conditions* e.g. illumination, visibility, heat, humidity, ventilation, or noise, d) cabin *functionality* e.g. tasks to be supported such as drive, control, operate, supervise or follow-up.

Figure 5.2. Cabins with specific purposes of use, e.g. controlling an agricultural machine or manoeuvring a forklift, require specific but diverse properties and features.

Operating environment facilitates interaction of a task between human and machine. Introducing work site, a real or scenario based, is a necessity to comprehend and investigate the efficiency, performance, comfortableness and to identify weaknesses, lacks, errors or contradictions between human (a subject), machine (an instrument) and job (an object). Especially the safety, human factors, indoor conditions and physical and communicative interfaces are potential target issues in human machine system level simulation, evaluation and development, from early phase of design. The technical facilities of operating environment are usually selected or designed; if designed, first based on the information obtained from the purpose of intended usage and job, and later iteratively developed further exploiting the entire model of human machine system. The need to use entire system structure for modelling is that the matters of rules, communities, and divisions of labour have influences on various design factors e.g. linguistic terms or manners of representation in visuals, and therefore neglecting by simplistic means has no sense or makes only temporary advantage.

5.1.2 Design of Human Machine Interaction and Human Role

The common principle way [Pahl & Beitz 1977, Rasmussen 1986, Mattila & Karwowski 1992, Vicente 1999, Ulrich & Eppinger 2000, Leppänen 2000, Sinkkonen et al. 2002, Väyrynen et al. 2004] is that the design is set in motion to take more exact shape according the need state analysis by the steps of specification from early conceptual design to preliminary and detailed design. First specification step aims to define the desired expectation outcome, and iteratively in steps of concurrent design phases, pursue to keep the specifications of systemic plans consistent, and valid against the modified, particularised requirements, and assessments done. Hence system requirements and specifications are crucial in obtaining a successful and feasible operational system as an output. System specification is an output of process creating and developing operational requirements where the functionality and activities of system are analysed using e.g. scenario based approach.

The system functions are decomposed and allocated as lower level technical system functions and human actions, forming tasks, which are analysed in such terms as controllability, performance, comfort, and usability of interfaces, equipment, and other facilities of workplaces, in this especially operating place. Simulations and virtual prototyping are applied as methods and tools, and are the means for ensuring and visualising the consistence, competence and validity of specifications against the requirements. Moreover they are documentation of verification process for design and development done, and are help in validation, too.

Basically, the approach studied, is trying to get rid of the weaknesses of normative type of design which is commonly based on recognised scenarios.

5.2 Human technology interaction based design

Conventionally the focus in the design processes has been on technical matters of planning since technical system typically is sharing the most portion of cost. Sad to say but in design the traditional convention too often has been just copying old plans and improving a bit of technical matters, and mostly neglecting complicated operation and work situations. Resistance to work out required laborious changes is quite a normal character for human beings. However growing challenge and aim in design is towards the balanced design taking account more thoroughly all design areas and aspects concurrently; e.g. in relation to workplaces it is to make workplace, not only healthy and safe to a use, but more comfortable and attractive, too. Comfort, safety, and various other human technology interaction (HTI) matters have become remarkable competitive advantages. Thus, in design more attention it is ought to be paid on balancing subjects and besides also on various human factor aspects and on usability of the workplace, and on the work that workplace is enabling. Nowadays mobile machine as a system technically is made of complicated sub-systems. Concurrent design, exploiting virtual prototypes, modelling, and simulation, has effectively enabled design process to be able to manage not only the design of components but also the design of various systems and sub-systems, e.g. mechanics, hydraulics and control systems. Obviously the HTI design could be integrated more tightly to design process.

Creating future machines and future operating places, the engineers and designers should have courage more often to start from scratch to enable visioning of novel ideas, and abandoning restrictive fixations and past plans. Besides of being more creative, there should be even more discuss who should take part in designing a workplace and the entire human machine system. It is obvious that from the basis of intended purpose of use for a machine, the specifications and concept for a machine including operation scenarios for working processes, should be composed broadmindedly not only by the designers but all involved persons. In practice the product design process already necessitates that solution ideas must be harmonised, taking account the feedback from end users, the boundaries of technology level, and the business, too.

A clear starting point is in improving the comprehension between the requirements given for the ideal machine and its functionality, and the demands of end users considering performance for each action needed to control the versatility of machine functionality. A path towards enhanced design process to manage HTI aspects would be exploiting approaches from user centred design, and participatory design methods.

5.2.1 Integration of design methods and tools

In user centred design (UCD) the work and workplace done by a human as a design target is the starting point. Therefore, if applying UCD, having the foremost criteria, it has to be equal compared to other objects of planning, and even somehow facilitating the concurrent design process. Thus, future machine design when including workplaces should be based not only on technology centred design but on human centred design, too (Figure 5.3).

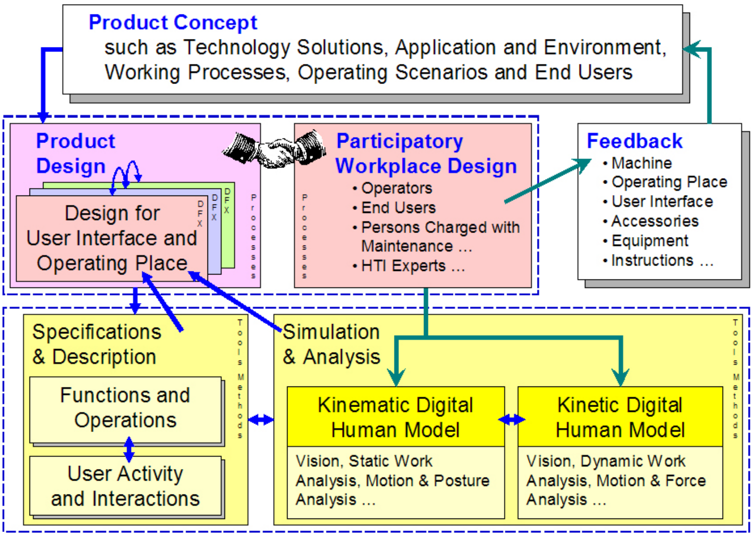


Figure 5.3. A simulation based design process.

Process focus is on the integration of product design and human work and workplace as equal design targets of the entire design process. To boost participatory workplace design, tools and methods utilising digital human models are applied to exploit and collect information into the user interface and operating place design and development. Obviously, concurrent design process may be enhanced in such a way that it can have various holistically working design area centres embedded to entire design process. Development of new methods and tools has been the basis to carry out the philosophy of designing HTI friendly machines. A traditional way getting feedback from end users has been marketing research. However, the end users should involve more thoroughly into the design process, not only through marketing research. One way would be participating into the design of operating place, and work, from the very beginning of the entire design process.

Participatory design is a method in which end users and HTI experts do design tasks together interactively, supported by other design experts. Participatory design is an iterative process, and to be effective it requires sufficient concurrence with all other machine design processes. Supportive 3D models and simulation of functionality are in essential role in this iterative process because they are enabling clarification of design concepts and schemes. Visualisation of the plans and kinematic simulation by using 3D geometry models makes the things alive. Besides end users may immerse into the virtual environment, the operating place and test its performance and properties before actually manufacturing any physical objects.

Dynamics simulation enables kinetic, functional, and physical study of human machine system enabling more exact analysis than exploiting only kinematic simulation. Furthermore digital human models are tools for simulation and analysis of human performance and visualisation of e.g. impacts caused by machine movements, and human operator motions, and also in creation clear coupled scene of the operator in work.

Process for future operating place design is based on exploitation of HTI simulation. At the beginning of simulation focus is on specification and description of the system functions and operations, and continues towards specification and description of human activity and interactions. Concurrently are exploited two kinds of simulation and analysis tools and methods. The process is worked out iteratively.

By utilising the participatory workplace design approach to support the process the end user feedback is took into account. Participatory design group and design engineers define and describe system functions to qualify intended purpose of operations, allocate these in balance for machinery and humans in the system. Participatory design then especially ensures proper chances for end user by developing human activity, actions and interaction between a human and a machine. Thus simulations using technical system models, and human models are exploited in iterative user centred design process, which includes problem definition from contradictory practices of the need state, creation of alternative solution ideas, testing, assessment and evaluation of scenario based simulations giving finally acceptable solutions for the problem. Subsequent stage is the system details design, which is applying the obtained information in working out sufficiently with the entire human machine system based models and simulations to get finalised specifications and plans.

5.2.2 Operating condition, interaction and interface design

Operating place is in continuous interaction with the environment (indoor and outdoor) and human operator and thus is multidisciplinary design challenge. This means a great need considering modelling, simulation and visualisation. Time to time during design process plans should be collected together for ensuring the validity of specifications and achieved results.

The method should be capable of modelling the virtual space, e.g. walls, furniture, equipment and humans in this environment. It should also be capable of running functionality simulation and elucidating the simulation and calculations results, illustrating also the various phenomena influencing to the operators actions such as noise, illumination, temperature, air flow or draught. Moreover the user had to be able of choosing combinations of the elements to be illustrated, to run functionality simulation and to navigate freely in the virtual space, too. Also some dynamic and steady state situations should be visualised with e.g. iso-curves and -surfaces, vector representations in points, and coloured contours or different combinations of these.

The implementation of the method was done based on using VRML format models to import calculation results of environment conditions in a co-operative study to demonstrate the principles of this method [Viitaniemi et al. 2006]. However the present VRML formats will be replaced in short time with X3D. Therefore it would be useful to continue the study and further development of the method to take into account the properties, features and possibilities of X3D format, especially when the standard will now begin to stabilise. Now the focus was more on human actions.

5.3 Future work place design tools

The designing process of mobile machines is calling for tools to analyse the user friendliness of the different designs and to find out where more attention should be paid. In the design process of future work place, virtual simulation eases this work. Two different human models (Figure 5.4) were further developed for this purpose: the kinematic human model OSKU and the kinetic human model HEMMO.

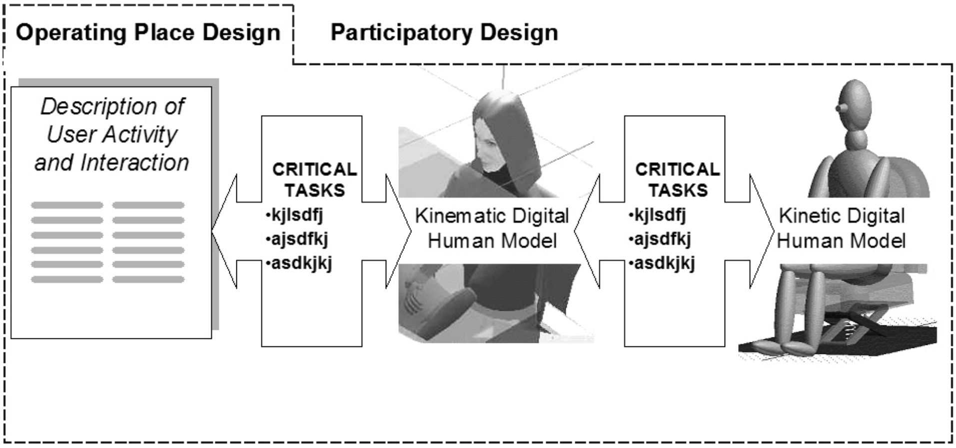


Figure 5.4. A flow diagram that describes the use of digital human models, OSKU and HEMMO, in the design of the operating place.

5.3.1 OSKU kinematic digital human model

OSKU is developed to kinematic work analysis. OSKU is a kinematics simulation tool for easy work task design and analysis. In kinematic simulation human posture, visual range, etc. can be analysed without taking dynamics forces into account. Motion of the human model can be generated by choosing pre-recorded motion clips from a list. Motion clips have been recorded using electromagnetic motion capture system and real human operator.

OSKU calculates automatically postures and motion paths which comply with the given boundary conditions. OSKU tool is suited to conceptual design of the operator's work place and operational work tasks. With the OSKU-tool, critical tasks can be recognized for dynamic analysis with kinetic human model tool (Figure 5.5).

Figure 5.5. OSKU is a digital human model that performs the recorded kinematical behaviour of a human composed from the separate short basic motions.

5.3.2 HEMMO kinetic digital human model

HEMMO helps to virtually test effects of machine design and parameters on human operator. Effective tools are needed to ease the analysis of the dynamic interaction between the machine and the human operator to satisfy the growing requirements for the user friendliness of the mobile machines. When developing the kinetic human model called HEMMO, the initial goal has been to build up an easy-to-use, computationally feasible 3D simulation model of the human body which could be applied in various studies of the vibration transmission and the human exposure to vibration during mobile machine operation. The latest development of HEMMO has been focused on 1) to improve the reliability and the usability of the human model, 2) to improve the automated parameter tuning for different sized human model, 3) to find ways to include the stochastic human behaviour into the virtual simulations and 4) to test different ways to describe the muscular action.

The human model is designed to be applied in a virtual prototype of any mobile machine (Figure 5.6) with minimised modifications in MSC.Adams simulation environment.

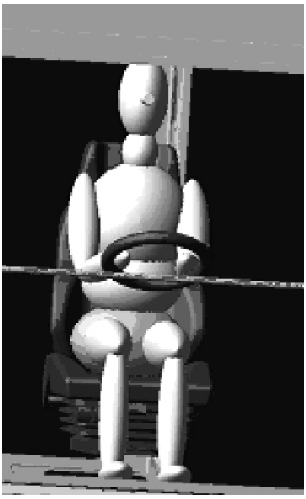
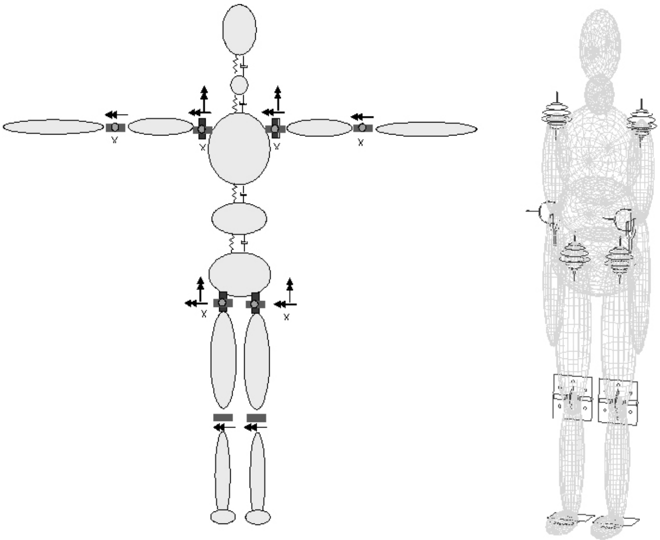


Figure 5.6. HEMMO human model seated in the cabin of a mobile machine.



a) *b)*

Figure 5.7. a) The lumped parameter representation of HEMMO b) An isometric view of the HEMMO modelled in MSC.Adams.

HEMMO – biomechanical multibody object

HEMMO is designed to be a kind of dynamic lumped parameter model of the human body (such as described in Figure 5.7 a by Launis et al. 2006). Here (Figure 5.7 b) the human body is described with a 46 degrees-of-freedom multibody model, in which 13 moving parts are constrained with different kind of rigid, playless joints with some simplifications compared to the real human body. The degrees of freedom provided by the shoulder blades and the collar bones are not taken into account in the HEMMO model. One hand and one arm form one rigid body as well as one foot and one lower leg.

The skeletal system of the torso and hip (spinal column, pelvis, and chest) and the head are discreted to 5 separate parts, which are: the head, the neck, the upper torso, the middle torso, and the lower torso. These parts are held together by spring-damper -type forces so that the translational degrees of freedom describe the elasticity of the spinal column. The spring and damping constants are defined by the mechanical behaviour of human body: For example, in the literature [Chaffin et al. 1999] of the human biomechanics there are available data of the natural frequencies of human body parts. From this data and the known mass data of human body parts we can determine the corresponding spring constants. The viscous-type damping may be chosen to be critical. A Mathcad document has been created to help the calculation of the parameter values. The mass parameter values from MSC.Adams program are entered to the Mathcad document which then calculates the elasticity and damping factors. These values have to be again manually input to MSC.Adams model.

Description of muscular action

There are numerous ways to predict the active human motion. In our case, the dynamic response is the simple outcome of trying to remain a stable, seated posture in the driving situation. Current HEMMO model is not designed for such simulation where conscious moving of body parts is necessary. The posture retention is completed by applying torques to the different joints of HEMMO in order to describe the muscular action. In other words, the torque values are input variables for the HEMMO model. Different ways to control the torques have been tested with the angular and translational displacements, velocities and accelerations as output variables. The controllers are described shortly in the following.

PD controlled torques

As the first approximation, the torque values are PD controlled (a controller, that consists of a differentiator with proportional gain) to maintain the initial posture of the human body relative to the seat. Input variables for the controller are the angular displacements and velocities, and the outputs are the torques. The PD controlled torque behaves actually similarly as linear torsional spring-damper (viscous damping) combinations. This kind of control system is valid for HEMMO who experience relatively small amplitude vibration and no significant muscle work is needed to maintain the posture.

When the excitation includes larger swinging motion i.e. the human model undergoes shock loads, the traditional PD controlled torque can't produce motion that corresponds very well to the real human response. For this reason the torque equation was modified by adding a delay term in the control law [Leino et al. 2002]. It has shown to be possible to tune the PD controller with the delay term up to get quite good comparison with the measured results.

Neuro-fuzzy forces

Another possibility to take the active human muscular action into account is to use soft computing methods like the neural network-driven fuzzy reasoning and utilize field or test bench measurements to create a neural network [Leino et al. 2002]. There exist advanced tools for example in Matlab product family (Fuzzy Logic Toolbox) to build up fuzzy inference systems which allows the fuzzy systems to learn from the data they are modelling.

In the case of simulating the working inside a mobile machine, the input/output data set for teaching the fuzzy inference system of HEMMO should be gained by field measurements. A Simulink model (Figure 5.8) has been constructed to combine the MSC.Adams plant of HEMMO model and the neuro-fuzzy control for the HEMMO's neck joint torque.

Some experimental tests were accomplished in a laboratory test bench, which simulated the vibration excitation that human operator undergoes in heavy mobile machinery. The measured 3D motion data of the different marker points on the body is used as the data for building up a neuro-fuzzy control for HEMMO.

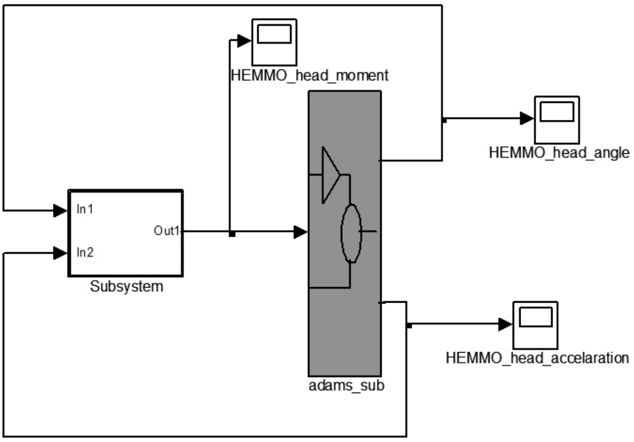


Figure 5.8. A flow diagram of application in Simulink for HEMMO head motion control.

5.3.3 Stochastic human behaviour

The problem with the control systems presented in the previous is that, in reality, the human parameters vary a lot inside the large operator group. Parameters of the controllers, however, may be tuned to correspond only to the response of a single human being.

The stochastic human response and action may be taken into account by Monte Carlo simulations [Anon. wp5-1 2005, Anon. wp5-2 2005] to choose the parameter values for HEMMO simulations from test data and experimentally defined distributions. By definition, Monte Carlo method is a method of generating values from a known distribution for the purposes of experimentation [Anon wp5-2 2005]. This is accomplished by generating uniform random variables and using them in an inverse reliability equation to produce failure times that would conform to the desired input distribution. So actually, what we can do in the case of HEMMO simulations, we first simulate with Monte Carlo method a statistically competent group of human operators (the numerical values for such response affecting parameters like the weight, length, reaction time). Then we run the dynamic simulation with same excitation to the chosen human operators with the virtual model. The problem with this is the time taken by the repetitive dynamic simulations (Figure 5.9).

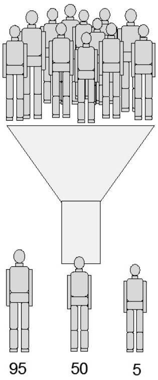


Figure 5.9. Parameters of a human may vary a lot, which is a simulation problem.

5.3.4 Application of HEMMO – simulation example

In order to tune and verify the human model, laboratory measurements[4] were accomplished on VTT's motion platform (Figure 5.10 a), which physically simulated the vibration excitation that operator undergoes in heavy mobile machine. The test excitations were based on field measurements. Vibration response of 23 test persons was measured by four tri-axial accelerometers and

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[4] The human vibration exposure measurements with mobile platform were carried out in collaboration with the TEKES project TÄRSKY (2004−2006), "Human Body Vibration Control in Future", of Technology Programme MASINA. TÄRSKY focuses on limiting vibration exposure in mobile working machinery by means of new product development tools and improved active and semiactive vibration damping methods. Important part of the project has been to develop techniques for measuring personal vibration dosage accordant to EU directive 2002/44/EC and methods to assess safety and comfort in real world or virtual environment. Related to HEMMO, the contact between the human model and the seat of the work place is studied in detail in TÄRSKY.

the tests were recorded by two video cameras. Result of the video analysis was the 3D motion data of the different marker points on the body, which was then synchronized with the other measurement data for further analysis.

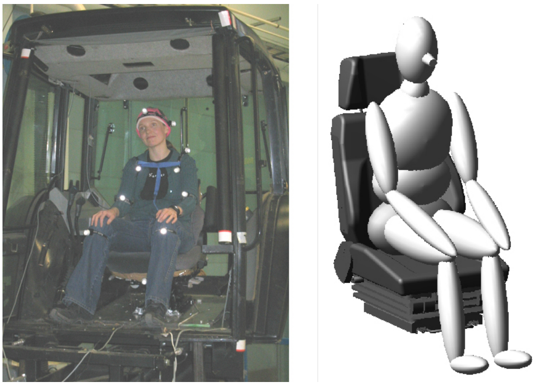
a) b)

Figure 5.10. a) Test persons were equipped with LED-lights and accelerometers, b) Hemmo in the test case posture.

A selection of the test cases was virtually simulated with HEMMO, whose muscular action was described with the PD type controllers. In the simulation model, HEMMO was seated in driving position and attached with rigid joint to the rigid driver seat with hands laid on the thighs as illustrated in Figure 5.10 b. HEMMO's feet were rigidly attached to the floor of the cabin. The measured xz-motion (the front plane of the driver) of the experimental seat was forced on the model seat.

Some values of interesting simulation parameters and HEMMO's key parameters are listed in table (Table 5.1).

In the figures (Figures 5.11 and 5.12) are plotted the measured and simulated human head and shoulder motion in xz-plane, respectively. From these results it can be deduced that the HEMMO model predicts the human response reasonably well for the kind of excitation applied in the tests, although there are clear lacks that can be pointed out when comparing the measured and simulated data.

Table 5.1. List of simulation and measurement parameters.

HEMMO parameter	**Value**
Mass (head, neck, upper torso, middle torso, lower torso, upper leg, lower leg+foot, upper arm, lower arm+hand, total) (kg)	(4.33, 1.03, 17.1, 8.41, 9.49, 7.08, 3.85, 2.19, 2.07, 70.7)
Spring constants of torso* (head-neck, neck-upper torso, upper torso-middle torso, middle torso-lower torso) (N/m)	(107700, 1017, 72010,47810)
Damping coefficients of torso* (head-neck, neck-upper torso, upper torso-middle torso, middle torso-lower torso) (Ns/m)	(1372, 64.74, 2865, 1268)
Proportional gains in muscular torques (head-neck, neck-upper torso, upper torso-middle torso, middle torso-lower torso, upper arm- upper torso, lower arm., upper arm) (Nm/deg)	(50.0, 50.0, 500, 500, 3000, 1000)
Derivative gains in muscular torques between torso parts (head-neck, neck-upper torso, upper torso-middle torso, middle torso-lower torso, upper arm- upper torso, lower arm., upper arm) (Nms/deg)	(1.0, 1.0, 1.0, 1.0, 100, 100)

Test person parameter	**Value**
Mass (kg)	70
Length (m)	1,76

Simulation parameter	**Value**
Simulation time (s)	15
MSC.Adams Integrator	GSTIFF
Static equilibrium	STATIC

* x-,y-, z- directions have the same values.

In the measured horizontal motion there seems to be a delay that the PD controlled torques are not able to predict, at least not with the parameter values used in this simulation. Considering the HEMMO models and human topology, it is obvious that the active muscular action has more to do with the horizontal motion than with the vertical motion of the human torso. So the delay in the measured data is probably at least partly due to the known fact that there is a delay in the human muscles' reaction.

Another possible reason for this difference between measured and simulated horizontal motion is that in the simulation model the seat had no cushion and human pelvis was rigidly attached to the seat i.e. the seat and the pelvis behaved as a single rigid body whereas the real seat had soft cushion on it. Moreover, the tuning of the PD parameters was done in a highly coarse level in order to see how effectively HEMMO could be implemented to a system level model with satisfying results. So if more precise imitation of real person was needed, there are possibilities to gain them by putting more effort in tuning the PD parameters.

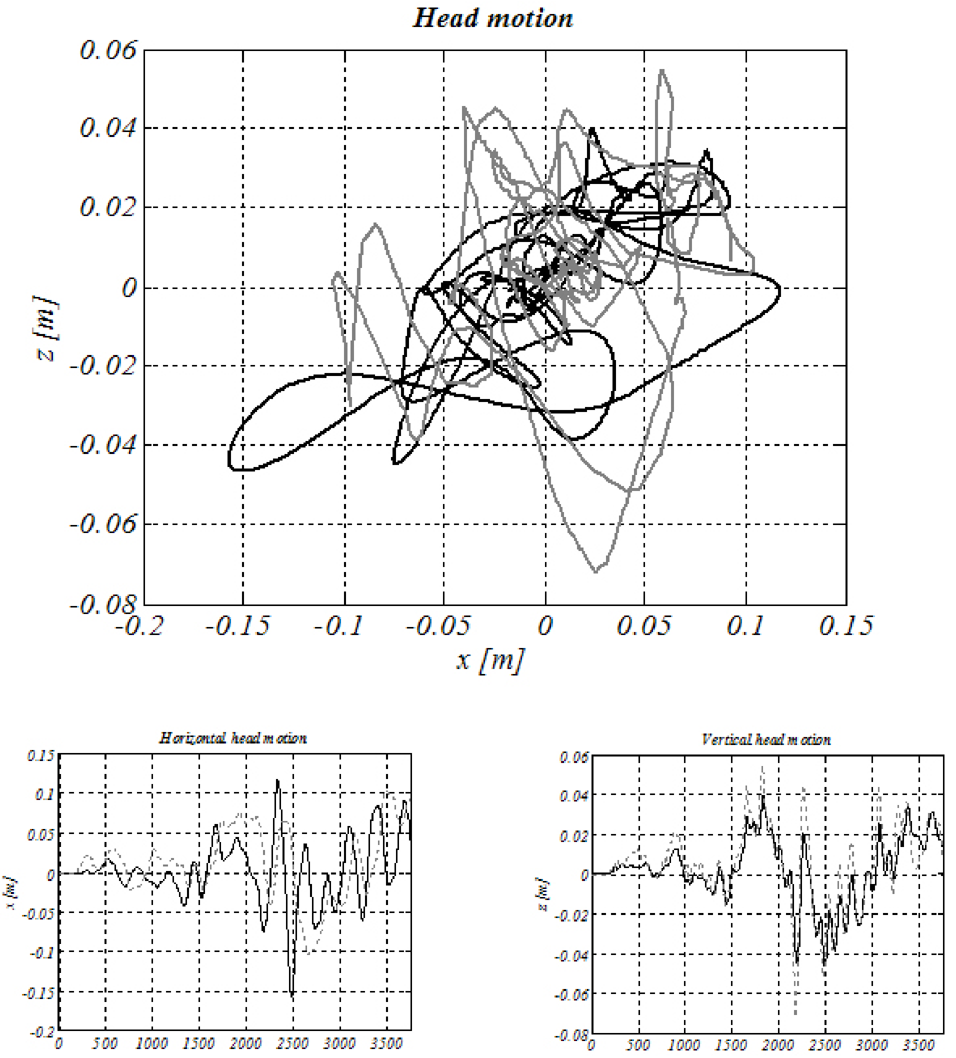

Figure 5.11. The measured (dotted line) and simulated (solid line) head motion.

Another possible reason for this difference between measured and simulated horizontal motion is that in the simulation model the seat had no cushion and human pelvis was rigidly attached to the seat i.e. the seat and the pelvis behaved as a single ridid body whereas the real seat had soft cushion on it. Moreover, the tuning of the PD parameters was done in a highly coarse level in order to see how effectively HEMMO could be implemented to a system level model with satisfying results. So if more precise imitation of real person was needed, there are possibilities to gain them by putting more effort in tuning the PD parameters.

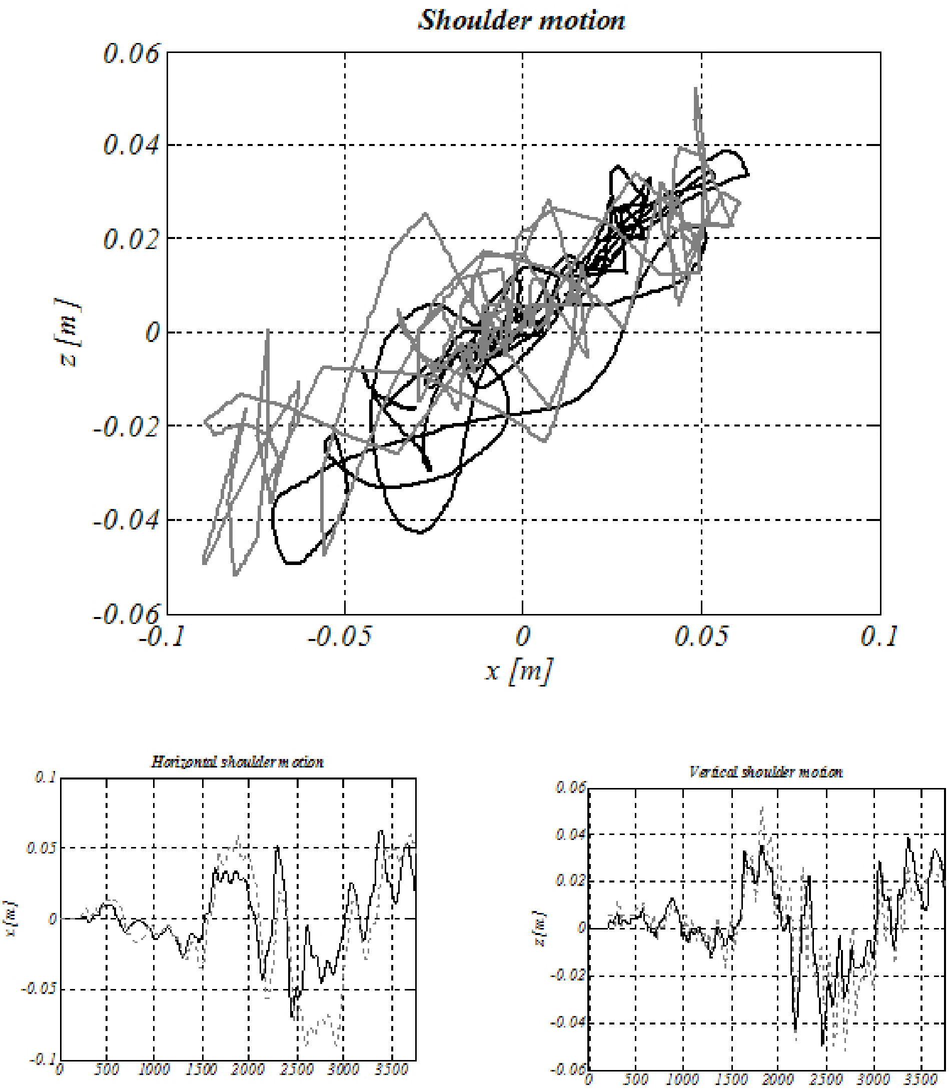

Figure 5.12. The measured (dotted line) and simulated (solid line) motion of right shoulder.

In the vertical direction, the measured and simulated motion seems to be, more or less, in the same phase. There are differences between the amplitudes of the motions. The real system seems to be more flexible than the model which is partly due to the non-existent seat cushion and the contact model between human and seat.

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6. Component dynamic properties

6.1 Introduction

Modelling and numerical simulation is often efficient to do on the basis of modular design. By designing the final full system with separate independently designed modules and components it is possible to gain various advantages during design phase. The design work is more flexible as modifications can be done to smaller parts without working with the whole large product model. In addition, concurrent design process is possible with modern networked co-operation of subcontractors. However, in order to be able to do reliable system level simulation one has to have good numerical models of the used substructures, their connections and boundary conditions.

In many applications small simple parts and connecting elements have strongly nonlinear properties with high level damping. These innocent looking components may cause the results of a large and otherwise detailed simulation model to be unreliable. With severe loading conditions these parts and components have essential role to the overall system response. Unfortunately, the complicated dynamic properties are often difficult and laborious to model very accurately. In this work a generalized but practical process for producing dynamical models for components is presented. In addition, examples of practical real life product cases of shock and vibration isolators, damping materials and vehicle tires are discussed.

6.2 Simulation and modular product design

Today computer simulation is an essential part of product development for many industrial areas. Increased computer capabilities with advanced and user friendly computer codes make the design work increasingly efficient. In principle, with simulation it is possible to optimize products better and, thus, to get the needed edge in the markets. However, there are still problems with the use of simulation for more complicated products. Typically, expert knowledge is needed for large computer codes and the needed investments in the simulation tools and personnel make the companies evaluate the costs and benefits carefully. It is seen, that more standardized principles for modelling and data transfer would make simulation easier and more cost effective. In addition, it is important to note, that solely computer simulation of a product is never enough and the obtained results have to be verified experimentally. Nevertheless, simulation is already widely in use and clearly the future for many product development teams. It is more a question of how to implement it into your design work. Here, the principles of modular product design give various benefits also in the simulation work. In addition, modular design approach is well suited for the efficient use of high level component models.

With separate independently developed modules and components it is possible to gain various advantages during design phase. The design is more flexible and modifications can be done to smaller parts without working with the whole complete product model. In addition, concurrent design process is possible with modern networked co-operation with subcontractors. With modular computer simulation only information of the modules need to be transferred without any physical transportation of product parts or personnel.

The use of modules and substructures has already long history in dynamic analysis of structures e.g. with the use of finite element method. Today, also several simulation codes originally concentrated on rigid body and mechanism dynamics have extended to the use of flexible parts and structures. However, in order to be able to do reliable system level simulation one has to have good models of the used substructures. In addition, the connections of the product parts and modules to the final product have to be well defined – physically and mathematically. In this presentation mainly smaller parts and components with well defined boundary conditions are discussed. Larger modules and substructures can be built on the basis of the component information discussed here.

6.3 The process of developing component models

A nonlinear and highly energy dissipating characteristics are often wanted for e.g. for efficient shock and vibration protection. Shock and vibration isolators, damping materials and vehicle tires have typically such properties. Thus, these components may have essential role to the overall system response especially with more severe loading conditions. More common linear dynamic analysis is not valid and the response is more difficult and laborious to predict accurately. What is needed is a strategy and process for the development of the more advanced component models. These models should be compatible with the used complete product simulation process. In optimal case, the simulation tools are well integrated to the company's product development processes.

It is seen that there is a need for flexible processes with various levels of testing, modelling and verification tools. In practice one mathematical model or one test machine for dynamic properties is not enough even for a one component. Different levels of models are needed at different phases of product design. In addition, larger variation of test frequencies and static and dynamic excitation forces require different testing machines.

In the conducted research work the needs of practical design work was emphasised and requirements for the model development work was set:

- The parameters of the models can be quantified by commonly available testing and measurement equipment.
- The analysis is based on well established, preferably standardized, principles.
- The models can be implemented to the most common computer simulation codes.
- The models are simple enough for practical analysis work.
- The models are needed for both time and frequency space analysis.

The principle of the process for determining the dynamic properties of components is presented in Figure 6.1. The process is inherently iterative and in practice some of the given stages have to be repeated before the results are satisfactory.

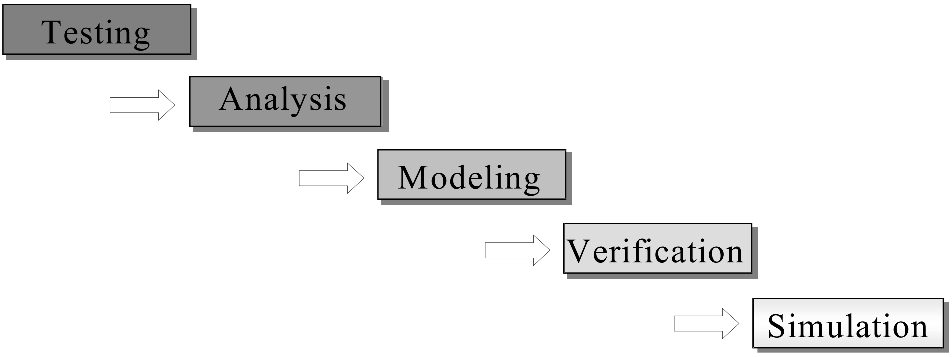

Figure 6.1. The principle of the process for determining the dynamic properties of components.

Both testing and mathematical methods may be used for component modelling. Sometimes a kind of “black box” approach gives good practical results directly on the basis of the tests. Thus, no knowledge of the physical and mechanical principles of the object is needed in order to produce the needed dynamic characteristics. However, sometimes it is more efficient to use numerical methods such as finite element method for the study of the dynamic behaviour of components. Nevertheless, whatever is the basis of the developed model typically experimental verification is needed to ensure reliable results. It is usually good idea to study a component once in more detail with the variation of test object size, geometry and materials. Thus, if the component is somewhat modified the needed change in the model parameters is known without extra tests. Furthermore, after detailed studies simplified tests may be developed for quality control and model parameter determination in a manufacture’s production line.

6.4 Examples of testing and modelling

In the presented work various testing and compatible analysis methods suitable for component modelling were studied. Shock and vibration isolators, isolating materials and vehicle tires were chosen for the case studies of strongly nonlinear components with high level damping. The studied isolator types included various elastomer based isolators, heavily loaded steel spring sets and wire rope isolators. In addition, a new type of "combined" isolator was developed and its dynamic properties were studied. In the study of tires the comparison of various computer codes producing tire models was emphasised. The modular design approach was used as a basis for the work and was also studied separately.

The static and dynamic properties of shock and vibration isolators were studied with hydraulic test frames and with electromagnetic shakers. The usually varied excitation parameters were pre-load, excitation amplitude and frequency. Typically, standardized definition of dynamic stiffness and loss factor were used as basis for the modelling. Nevertheless, analysis was made in frequency and time domain with the use of different modelling approach. The laboratory test results were always used as a basis for component modelling. Examples of the conducted laboratory test results of a wire rope isolator with hydraulic testing equipment and electromagnetic shaker are presented in Figures 6.2–6.4 [Keinänen & Juntunen 2003, 2005]. An example of a wire rope model is given in Figure 6.5. A corresponding simulated dynamic response in a virtual test situation is given in Figure 6.6 [Keinänen et al. 2005].

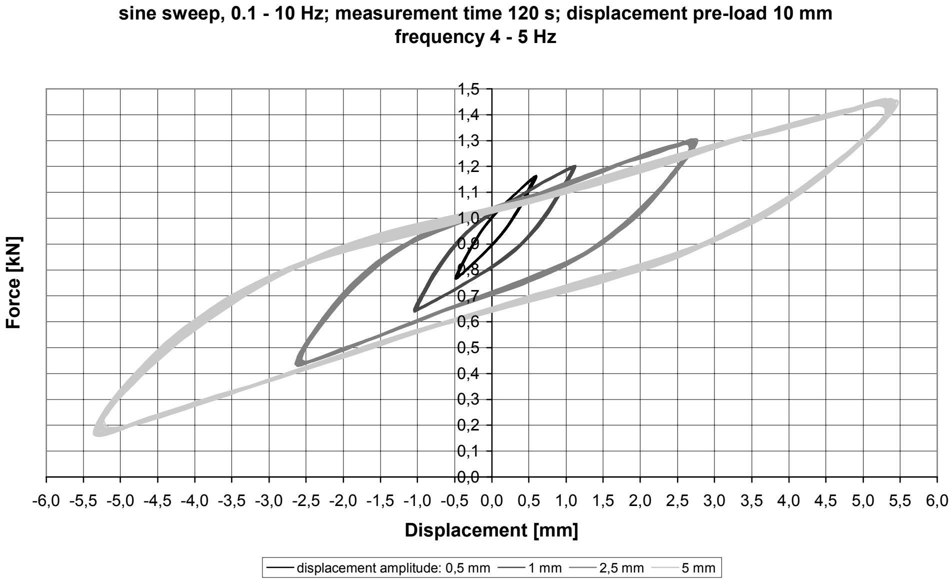

Figure 6.2. Example of a response of a wire rope isolator in time domain during a test with a hydraulic test frame.

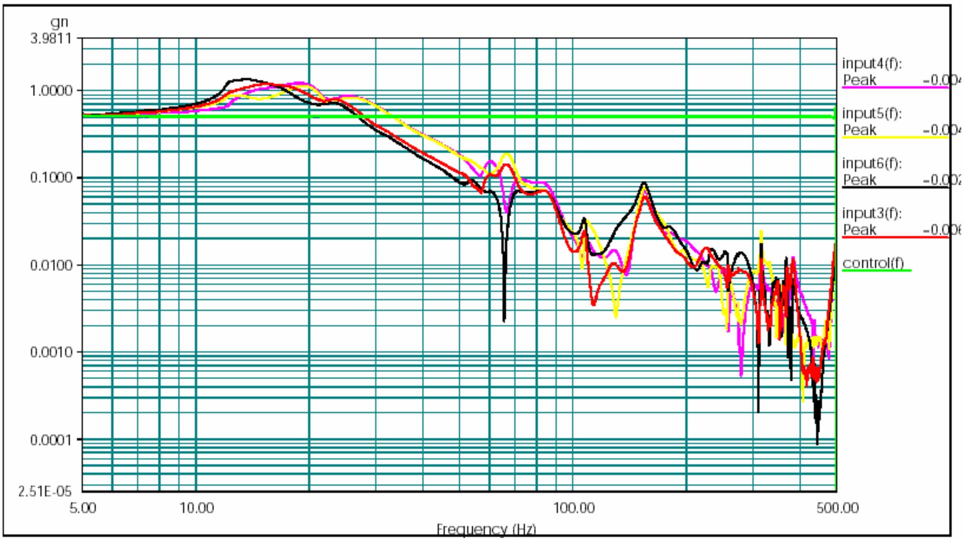

Figure 6.3. Example of test results with an electromagnetic shaker.

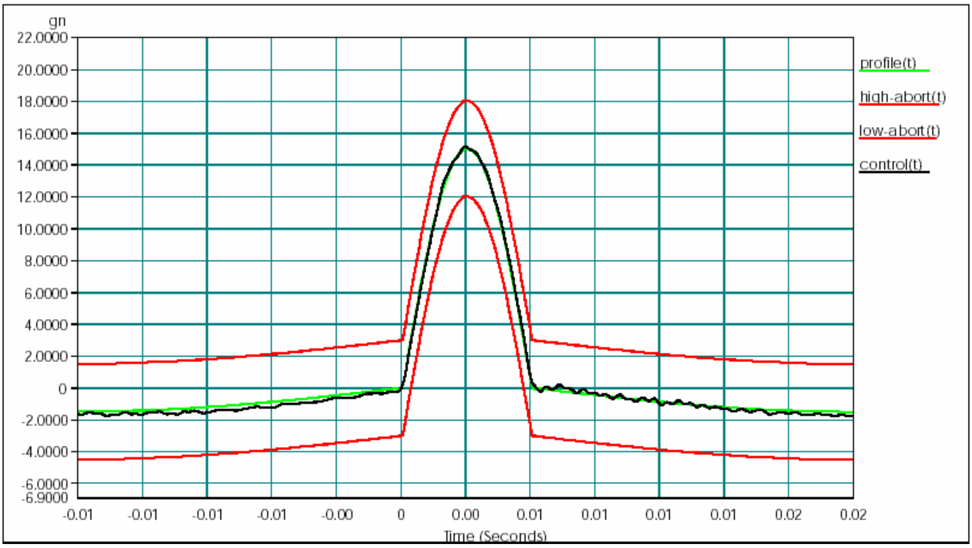

Figure 6.4. Example of a shock test with an electromagnetic shaker.

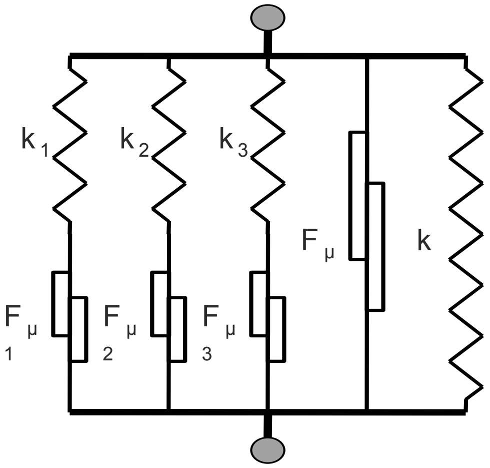

Figure 6.5. Principle of a wire rope isolator model (8 variables).

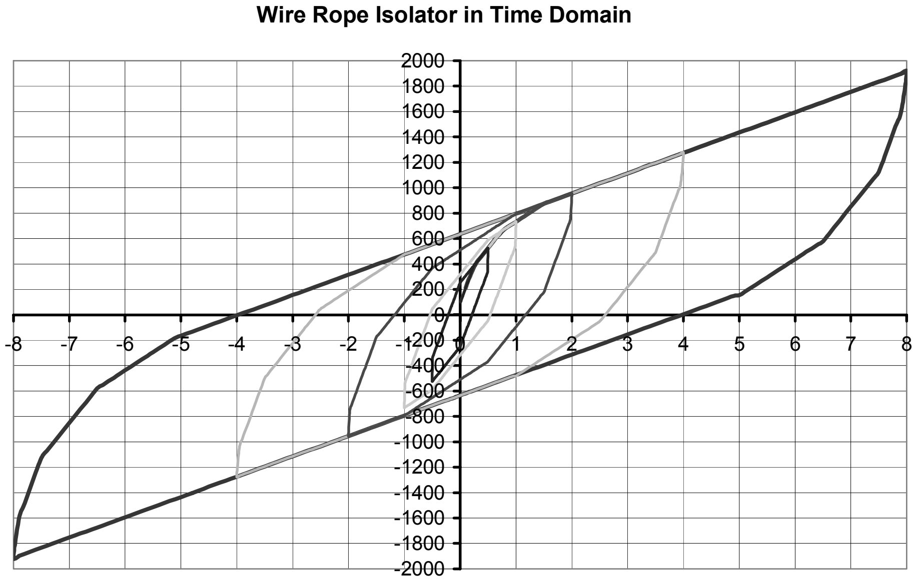

Figure 6.6. Wire rope isolator model in time domain. Five different dynamic amplitudes presented in force-displacement graph.

In addition to the laboratory tests results, full scale field tests were used to verify the behaviour of the developed models. In Figure 6.7 the results of a measured field test and corresponding simulated response to a high level shock are presented. The responses are very similar for the studied case.

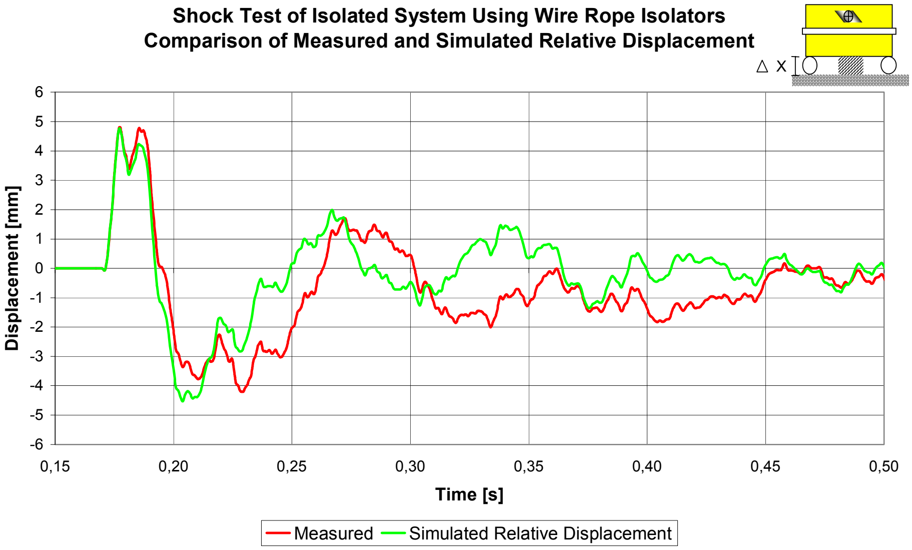

Figure 6.7. Comparison of measured and simulated relative displacement of an isolated system in a high level shock from a full scale field test.

The simulation of Figure 6.7 was conducted with the use of MSC.ADAMS-simulation code. In order to study and demonstrate the possibilities of the efficient use of component models an interface [Kortelainen et al. 2006] was built for MSC.ADAMS in order to have an easy to use data input for a component model. With the input interface one can give the parameters obtained from the tests to the simulation code and obtain directly a component model shown in Figure 6.5. Thus, the user of the simulation code does not need to analyze the test results and to build a complicated component model separately. The component models can be quite complicated and, thus, a user friendly interface to generate component model enable efficient simulation without special knowledge of the measurement and analysis of the laboratory tests.

The Figures 6.5 to 6.7 shows a one line of studies and applications of a wire rope isolator. The model type presented in Figure 6.5 was based on a kind of “black box” approach to the component model. With this approach, in principle, one does not need to know too much about the physical dimensions of the component. However, also different wire-rope isolator models and scaling of the dynamic characteristics on the basis of the variation physical dimensions of the component were studied [Kantola 2003, 2004, 2005]. In addition, rubber and new combined isolator types were studied. Furthermore, some studies of the ultimate strength of real life isolators were studied in order to know the limit loads for the component models.

In addition to the isolator study the machine and vehicle tire dynamic properties [Weckman 2004, Kaijalainen 2005] was an important part of the conducted work. Tire dynamic behaviour is essential to know for reliable vehicle simulation. Interesting results were obtained from the comparison of some of the most popular computer codes. Furthermore, studies of the experimental dynamic testing of joints and material properties [Juntunen & Ojala 2005] were conducted with a close connection to the studies of modular design approach and requirement management for shock loaded structures [Juntunen 2006]. The emphasis was on simple and efficient test development giving the essential dynamic characteristics of the studied objects.

Typically, the research of the various studied components included test and analysis development in addition to the mathematical model studies and development. The test equipment, measurement and analysis procedure development required significant part of the available research resources. The building various test frames with different attachments for each test directions and test objects needed a lot of work. The variation of mean load, dynamic load amplitude and frequency need several tests. If different translation directions, rotations and cross coupling effects are included the combined number of required tests is even larger. Furthermore, high frequencies, temperature effects and requirements of high level shocks increase the test, measurement and analysis difficulties. Therefore, one test set-up is not usually enough and several testing machines are needed for more complete studies. Finally, after all laboratory studies and numerical analysis, the results should be verified in real life applications in actual field conditions. In spite of the above mentioned difficulties it is seen that the conducted research succeeded in covering and demonstrating the most important aspects of the required component model development.

As a framework of the determination of component dynamic properties modular design approach is seen essential for successful simulation in today's networked product development processes. As an example, a subcontractor may provide different level of models depending on the costs and the needed level of accuracy. However, modules and component models need well defined boundary conditions and commonly agreed methods for determination of the dynamic properties. In addition, the definition of the used boundary conditions is essential in order to have compatible models while doing system level simulation. It is worthwhile to note, that in addition to the component model development, these module and boundary definitions and agreements may serve as a basis for successful verification, reliability testing and requirement management.

6.5 Summary

Increasing demand for more accurate and reliable computer simulation needs good models. In order to create reliable mathematical models for numerical shock and vibration simulation the dynamical properties of the used parts and components have to be well known. However, well-defined models for mechanical components with strong nonlinear dynamic properties and high level damping are not often available.

In the presented work a practical process of determining dynamic properties of components for simulation work was developed. As research cases shock and vibration isolators, machine and vehicle tires, joint and material properties were studied. Laboratory and field test results were used to characterize the dynamical properties and to verify the developed simulation models. Computer codes producing tire models for simulation purposes were compared. As a framework for the component model development the use of modular design approach was discussed.

Although many questions were answered and new results were obtained there is still room for improvement. However, the developed approach, a process for determining the dynamic properties of components, was found to be flexible and suitable for real life design and product development work. As a result of the conducted research work there is now available a networked component model development process. These facilities may be used for various electronic equipment, machine and building applications. Simplified component modelling processes may be developed for individual manufactures practical needs. Finally, the obtained vision for further development is quite clear: the conducted work seems to have been on the right track and this was supported by the raised international interest in the results. For the future the developed type of capabilities might give the high technology advantage for efficient simulation and product development work needed in the competitive international markets.

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7. Control of machine reliability and operability

7.1 Introduction

The operational reliability and expected remaining lifetime of a machine can vary depending on several features. Condition monitoring and prognostics methods are used to prevent sudden, unpredicted breakage or shut downs, which can lead to unacceptable economical losses. In addition to monitoring and prognostics, the main reasons for failure need to be clarified. In many cases excessive, unknown loading conditions may trigger the deterioration progress. The detection at a sufficiently early stage and the control of the deterioration process, requires properly realised monitoring of load, operational stages and other condition related features and measurements. The control of the lifetime optimised performance of the system can be further enhanced by utilising statistical tools for reliability and probability calculations in addition to diagnostics suitable for immediate detection in the focused applications.

Condition monitoring

The most typical measurements used for condition monitoring and diagnosis are temperature and vibration acceleration. Vibration measurements are typically used for detecting and predicting failures in rotating machines. Failures typically occur as a consequence of excessive load and reaction forces due to unbalance, misalignment or discontinuities in dynamic systems. About 40 percent of excessive load arise from unbalance, 30 percent from misalignment and 20 percent from resonance in general [Wowk 1991]. Data acquisition is carried out by using sensors mounted onto monitored machines close to the points where the failures are expected to originate. Detection probabilities and costs of the failures as well as failure frequencies and consequences (both technical and financial) should be assessed and are all indeed very case dependent. In addition to external measurements, condition analysis can be based on monitoring operational parameters such as rotation, load, power, pressure, control current and so on. Both on-line and off-line solutions are available. In general, condition based maintenance (operational state and failure detection and predictions) and proper inspections actions can be used to increase the reliability and, if properly managed, the life expectancy of a machine.

Loading history

Every mechanical and dynamic system needs to carry loads whose magnitude and type depends on the machine construction, operational constraints and dynamic forces and changes arising from several sources. The most used sensor types are strain gauges. They are low cost, small and robust and they can estimate both static and dynamic forces quite accurately. Sensors are normally attached onto the most critical points of the monitored machine in order to monitor load where it causes the highest stress. Excessive stress can lead to direct breakage or fatigue failures. It can also cause wear between sliding parts if the lubrication and material pairs at contact points are not adequate enough.

Each measured stress-time history is unique and contains effects of external loads on the structure and the dynamic response of the structure. The simplest load-time history is a sine wave with a constant amplitude and constant frequency over time, which determines the number of load cycles per time unit. These are normally documented in stress-life curves (SN curves). In condition monitoring of machines, however, operating loads and stresses vary randomly, in both amplitude and frequency. The measurements of stresses, loads, acceleration, and other loading parameters at specific points on the structure under real operating conditions are the basis of every lifetime prediction. By generating a cumulative database format where these measurements as well as a diverse collection of operating conditions are stored, a comprehensive knowledge of the machine condition can be formed for system analysis.

Load measurements are measurements of time-based signals and contain information according to the operational stage and monitored phenomena and sampling frequency and accuracy. Before data is used for life testing or dynamic simulations, the most relevant features are normally extracted from the data by using, for example, statistical methods. In this way the entire history is described by a few parameters instead of a large memory burden of data. Using statistical parameters instead of actual measurements for establishing stress levels reduces the number of calculations required to analyse load distribution during monitoring time. If all combinations of materials and operating conditions are included, the obtained fatigue life is sufficiently reliable.

Remaining lifetime

In general, comprehensive lifetime estimation is only possible for components whose criteria and models are available for the assessment of residual lifetime of the component on the basis of condition related measurements. The models used must be able to address considerations such as small crack behaviour, crack propagation under variable loading, influence of surface residual stresses, interaction between multiple cracks, variable fatigue loading and stochastic aspects of fatigue crack initiation and early growth. Uncertainty under operation load conditions arises both from the statistical characteristics under constant amplitude load and from random variable amplitude load. Moreover, the data-link and its format between condition monitoring measurements and the remaining life estimation scheme is an important element of practical implementation. In practice the implementation can be installed in analysis devices using on-board processors. The analyses are charged with continuous updating of damage and comparison with fault growth rate estimates, along with evolving estimates of remaining life. These estimates may be presented in terms of statistical boundaries that reflect stochastic aspect of fault growth behaviour. A series of distributed microprocessors could be used to track, for example, hot spot damage or flaws for each critical component, or a single processor for each component could be applied by using distributed sensor and/or algorithms which sweep across the critical components [McDowel et al. 2003]. Sweeping methods are based on component-specific stress and frequency response analyses between component (excitation) and sensor (response) locations. As an example, acoustic energy excited by a crack propagation can be monitored and located by using correlation techniques and construction knowledge as well as sensor location knowledge.

Report focus

The goal was to study and demonstrate a new concept for model and simulation based machine operability and reliability to be further utilised both by the operators and maintenance personnel. A paper reeling system used in a paper mill was used as a common application case for the activities performed. This report represents methods for reliability analysis, real time simulation applications as well as load monitoring application and solutions for estimating remaining lifetime.

7.2 Methods for diagnostic detection and lifetime estimations

7.2.1 Noise attenuation

Methods for condition monitoring and life-time estimation of industrial machines and processes require reliable and noiseless measurements of the stresses on the machine parts and on the process conditions. In industrial settings there are many sources of disturbance that may cause noise in the measurements. It is advisable to avoid measurement errors by careful design and implementation of the measurement processes and instruments [Aumala et al. 1998]:

- removal of noise sources
- preventing the spread of the noise
- better noise screening and noise tolerance of the measurement devices
- use of stable components, methods and devices
- usage of fast enough measurement devices considering the speed of the measured phenomena.

When one has not been able to eliminate the noise sources well enough the stored signals will contain disturbances. There are many methods for correcting the measurements e.g. by filtering them. In [Hiirsalmi 2005] we have concentrated on reviewing and experimenting with such digital signal processing methods. In this overview we shall present some of the most common types of measurement errors and then we shall present a data mining based process for data preparation in order to detect noise and errors in the raw signals and to attenuate the noise level when possible. The described methods are better described and demonstrated in the project report [Hiirsalmi 2005].

One of the most common types of measurement error is noise. It is called white noise if it is totally random and its spectrum is even. It typically affects the signal all over the time and frequency domain. It may be caused by poor quality of electrical components and by changes in the temperature and by thermal radiation. The latter may be reduced with cooling. In the low frequency range there is additional noise called 1/f noise whose amplitude is reversely proportional to the frequency and therefore largest in the low frequency area. [Aumala et al. 1998.]

Another error type is cyclic noise. For example, 50Hz mains voltage may affect the measurement signal either inductively or capacitively. Also radio transmissions may cause electromagnetic noise. [Aumala et al. 1998.]

Short term disturbances can be impulsive or stepwise. Impulsive errors (also transients or interference peaks) may be caused by ignition systems, radio frequency devices, lightning, electric discharges and contact disturbances (caused by poor connectors or junctions, dirt and moisture). Fast stepwise errors are less common. The noise source may cause drift in the signal. When the noise source disappears, the signal level may suffer a fast change. A change in the measurement range or contact disturbances may also cause a sudden change in the signal level. Another short term disturbance is caused by saturation caused by the limited measurement range of a sensor. When the signal crosses over the boundary of the measurement range it is cut to the boundary value. This causes a constant signal on the boundary value. It is also possible to get stuck with the zero-level due to sensor fault or a cut in the measurement connection. [Aumala et al. 1998.]

Data preparation is a key step in the data mining process. In it one must inspect the raw data to get to know it and must try to detect problematic or noisy areas of the data. Visual plotting, descriptive statistics and frequency domain analysis may be used to learn to know the data. Domain experts are needed to judge whether the found phenomena are noise to be eliminated or actually contain useful information. The purpose of data preparation is to get to know the data and to prepare it for later analysis steps. One aims to make certain that the data is suitable for the selected business problem. [Pyle 1999.]

We can apply the data preparation process to the noise attenuation task in the following way.

At first one should review the raw data by visually examining each signal and its behavior based on the available knowledge about the measurement system and the measured entities. One may also compare the signals with each other. Domain experts may be used to explain the interconnections between the data signals. Control signals are useful to know and the underlying dependencies between the different measurements should be known at least on a qualitative level.

Cyclical noise may be looked for by inspecting the signal data in the frequency domain and by looking for clear peaks in the Fourier spectrum. These peaks are possibly caused by cyclical noise and indicate the cycle frequencies to attenuate. Domain experts should be consulted to confirm the noise hypothesis before applying band-stop filtering to attenuate the detected cyclical noise.

White noise may be attenuated by median filtering which equalizes the time series and therefore effectively eliminates outliers. If the desired signal lies in a specific area of the frequency domain (typically on the low frequency area) one may use low-pass filtering to attenuate high frequency components in the signal.

Outliers or impulses may be detected by statistically determining limits for the normality of a sample. Outliers are candidates for replacement but they should be verified by domain experts so as not to eliminate potentially useful information. Both eliminated outliers and missing data samples may be replaced by a suitable estimate, like the previous legitimate value or an interpolated value.

Long-lasting constant values in the signal are candidates for erroneous samples. They can be caused by the signal getting stuck to the zero level due to a sensor error or by saturation of the measurement signal due to reaching the measurement range of the instrument. Such phenomena should be examined by a domain expert.

7.2.2 Simulation models

Modeling and control of industrial process is based traditionally on analytic system models. The models are built using knowledge based on physical phenomena and assumptions of the system behavior. However, many practical industrial systems are too complex to be defined by global models. In such cases, the models are based on experimental data of various measurements.

The simulation model typically consists of mechanical, electrical and hydraulic subsystems that are coupled together. Based on the response differences between normal and faulty simulations, the required measurements for identifying the faults can be defined and utilized in the design of the fault diagnosis system. The system can be modelled by using commercial simulation software such as ADAMS or the modeling can be accomplished using a general purpose programming software such as ANSI C computer code. The former is suitable for precise offline simulations, the latter for less precise online simulations.

7.2.3 Monitoring

Normally information of the operational states, precise plant and environmental properties, final adjustments and changes etc. are not adequately known in the designing phase of a machine. One consequence of this is a deviation between the planned and real remaining life time of the machine and its parts. Thus it is essential to monitor the relevant information during the total life cycle of the machine. Depended on the possible economical technical impacts this can realised with preventive, scheduled and/or condition based maintenance methods. Normally different approaches are applied with success at the same plant.

Typically direct condition based analysis are needed as well as more statistically oriented remaining lifetime and prognosis analysis. What are the suitable methods to be applied depends on the situation at the case, its reliability and expectations. If the production uncertainties are handled at its best focusing on the structural strength and fatigue, the cumulative loading should be monitored. In larger production machines such as paper mills the economical losses due to fatigue of main structures are easily very expensive and thus there is a clear need for cumulative stress calculation.

7.2.4 Feature extraction with Gabor filtering

Gabor filters have been successfully used to detect motor failures from stator currents [Ilonen et al. 2005]. Gabor filter is an efficient feature extraction method, which extracts both the phase and frequency information from a time-scale signal. By transforming a time scale signal into frequency domain, the periodic fluctuations in the signal are transformed into constant peaks as presented in Figure 7.1. The location of the peaks in frequency domain stay fixed when the machine is in normal condition. Faults and failures in machine are expected to appear in the frequency densities of the measured signals. SOM can be used to cluster the fault situations. Gabor filtered time-scale signal is given as an input vector to the SOM. First the map is taught by running the machine in normal situations. When a new fault situation appears on the machine, the SOM clusters the input vectors on the border of the clusters. The classification is presented in Figure 7.2.

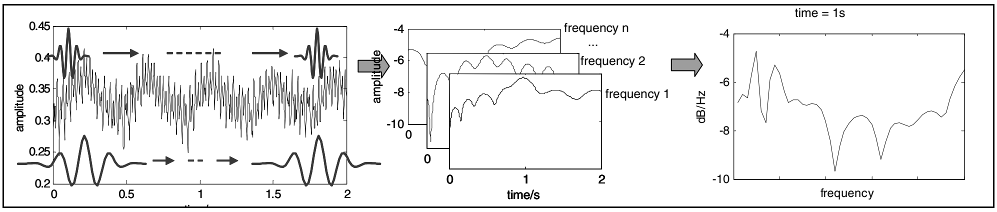


Figure 7.1. Gabor-filter extracts both the phase and frequency information from a time-scale signal. Finally, the periodic fluctuations in the signal are transformed into constant peaks.

7.2.5 Detection using self organizing maps (SOM)

The self-organizing map (SOM) is an effective tool for the visualization of high-dimensional data. It maps a high dimensional distribution onto a regular low-dimensional grid. It converts complex, non-linear statistical relationships between high-dimensional data into simple geometric relationships on a low-dimensional display. The map follows the probability density function of the data and is robust to missing data. The SOM usually consists of a two-dimensional regular grid of nodes. A model of some observation is associated with each node. The SOM algorithm computes the models so that they optimally describe the domain of observations. The models are automatically organized into a two-dimensional order in which similar models are closer to each other in the grid than the more dissimilar ones. In this sense the SOM is a similarity graph, and a clustering diagram. [Johnsson 1985, Jokio 1999, Jorkama 1998, Kohonen 1990, Kohonen 1998.]

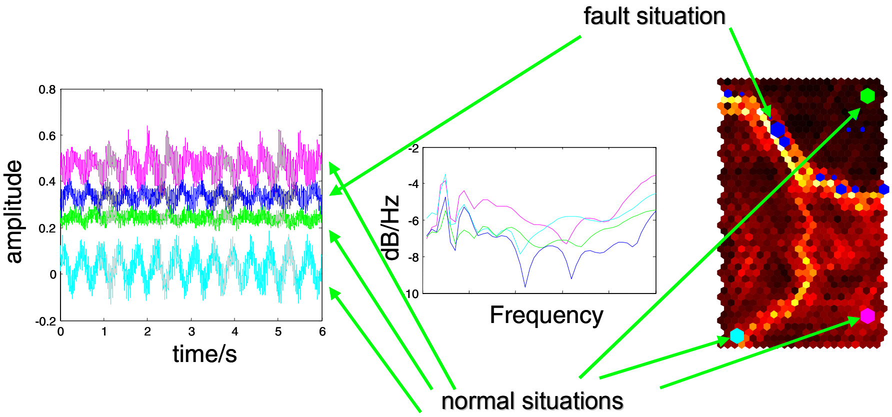


Figure 7.2. Faults and failures in machine are expected to appear in the frequency densities of the measured signals. The classification of densities is made by SOM.

The phases of a basic explorative data analysis process using the SOM can be sketched as follows according to Himberg. Data pre-processing phase contains processing, selection and segmentation. This is an elaborate task involving a lot of knowledge. Erroneous raw data have to be removed. Proper data scaling and representational transformations (e.g., symbolic to numerical values) have to be considered. Clearly inhomogeneous data sets may have to be divided to disjoint subsets according to some criteria in order to avoid problems, which would come up if a global model was applied.

Pre-processed and segmented data are transformed into feature data vectors. The objective in the case is to interpret the data and extract knowledge from it and from the feature variables have to describe the important phenomena in the data in such a way that they are clear in the analysis point of view. This and the previous stages cannot be properly done without knowledge on application domain.

Variables are usually normalized because variables with large relative variance tend to dominate the map organization. The distance measure used in the SOM training has to be chosen in such a way that applying it to data makes sense and usually the Euclidean distance is used.

The training of the SOM is carried out in this phase. The training parameters need to be determined. The basic SOM algorithm seems to be rather robust in this sense. Satisfactory results are usually obtained by following certain basic guidelines. The scaling of feature variables is a sensitive issue.

Visualization and interpretation are the key issues for using SOM in data analysis. These include correlation detection, cluster analysis and novelty detection. The data analysis is usually not a flow-through process, but requires iteration, especially between feature extraction and interpretation phases. [Haug 1989, Himberg et al. 2001.]

7.2.6 Estimation of service life

In most cases, the service load spectra for a component or structure are probabilistic rather than deterministic. Therefore, statistical analysis is often required to obtain the stress distribution. In addition, as discussed in previous sections, the fatigue strength of the component or structure has a statistical distribution due to the many sources of variability. Schematic representations of probability density functions for both service loading and fatigue strength are shown in Figure 7.3. If there were no overlap between the two distributions, failure would not occur. However, there is often an overlap between the two distributions, as shown in Figure 7.3, indicating the possibility of fatigue failure. The overlap can increase as the strength decreases due to accumulation of damage with continued use of the component or structure. Reliability analysis provides an analytical tool to quantify the probability of failure due to the overlapping of the two distributions. The reliability or probability of survival, R, is obtained form

$$R = \int_0^\infty F_1(x) F_2(x) \mathrm{d}x \tag{7.1}$$

where $F_1(x)$ and $F_2(x)$ are the cumulative density functions of the service stress and fatigue strength, respectively. [Stephens 2001.]

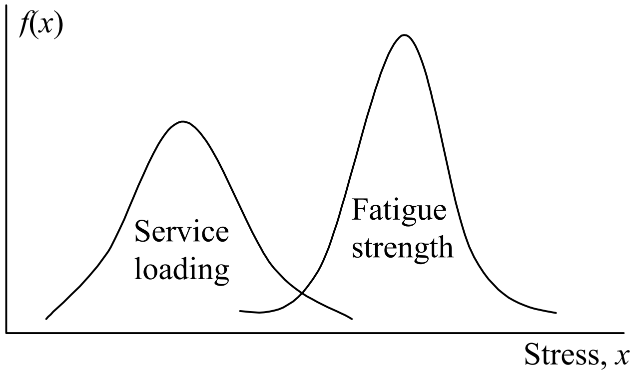


Figure 7.3. Probability distributions for service loading and fatigue strength.

Material strengths can be converted to member resistance R. Then it is possible to determine a probability density function $f_R(\ )$. Both load effect S and resistance R are generally functions of time. Usually the uncertainty of prediction of both S and R increases with time so that the probability density functions $f_S(\ )$ and $f_R(\ )$ become wider and flatter. In addition, the mean values of S and R may also change with time. Loads have a tendency to increase, and resistance to decrease, with time. The general reliability problem can therefore be represented as in Figure 7.4.

The safety limit will be violated whenever, at any time t,

$$R(t) - S(t) < 0 \quad \text{or} \quad \frac{R(t)}{S(t)} < 1 \tag{7.2}$$

The probability that this occurs for any one-load application is the probability of limit state violation, or simply the probability p_f of failure. It is actually equal to, the amount of overlap of the probability density function f_R and f_S in Figure 2. Since this overlap may vary with time.

Fatigue may be defined as a process of cycle by cycle accumulation of damage in a material undergoing fluctuating stresses and strains. The load is not large enough to cause immediate failure. Failure occurs after a certain number of load fluctuations have been experienced. Final failure may occur by basically three mechanisms: brittle fracture, ductile fracture, and plastic collapse, depending on the toughness of the material, temperature, loading rate, plate thickness and constraint. [Berg 1985.]

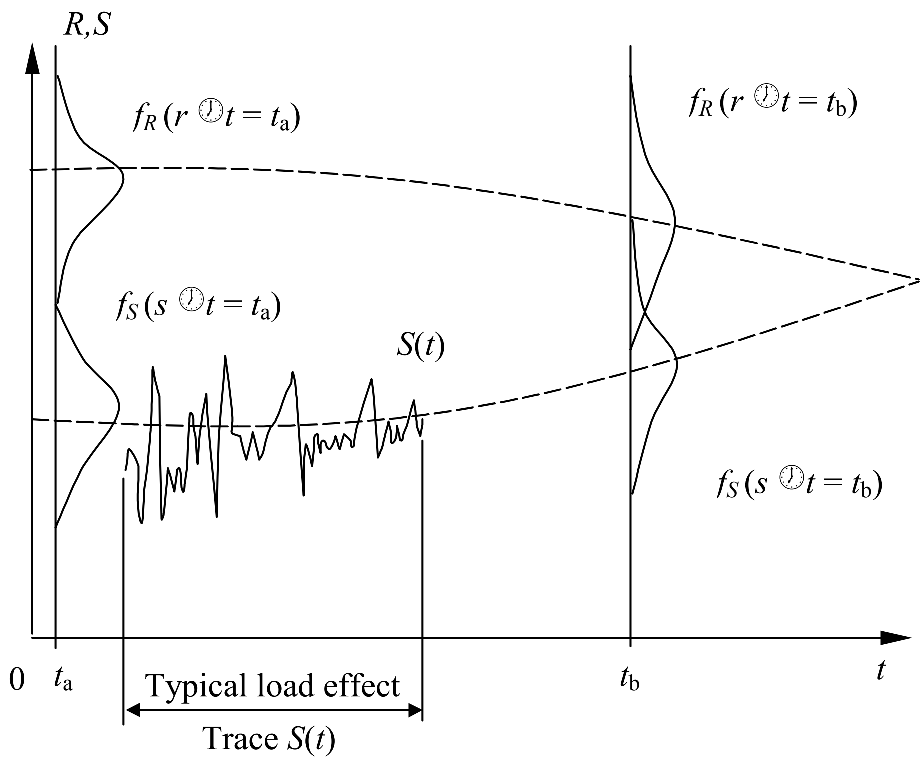


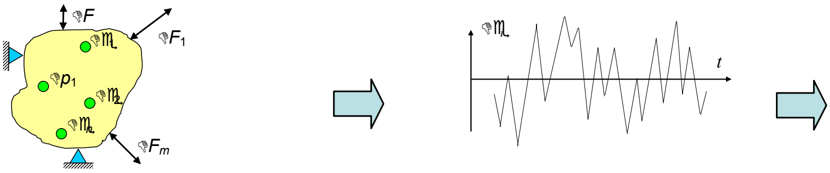
Figure 7.4. Time-dependent reliability problem.

7.2.7 Failure risk analysis

In the case of the reel has been developed a failure risk analysis flow chart with analysis methods. The short measurement is not as reliable as the longer one. That is why the variance of the measurement should not be ignored. The flow chart in Figure 7.5 includes the fitting procedure of the measured data. The measured data is fitted with boot strap method and the result fitting includes the variance with selected confidence level. The distribution of the fitted data can be narrower after long time data collection.

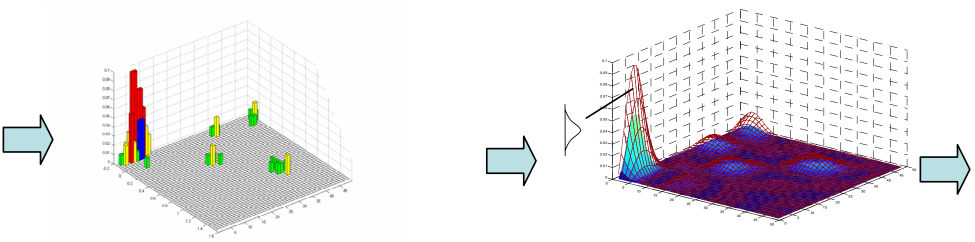
The resistance of the structure or material can be first quite conservative value. Later if the processed detail is critical the resistance of the detail can be determined with better accuracy and the risk of the failure will be lower.

Finally, it is possible to calculate a failure risk for the entire system or part of the system.



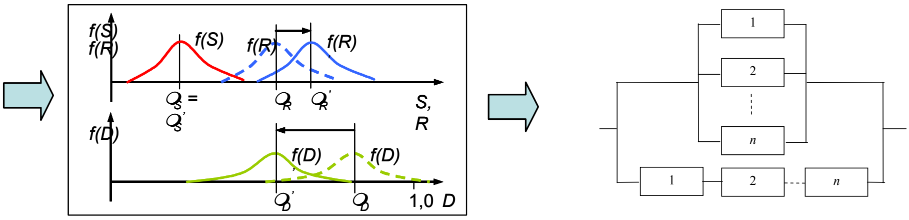
Measurements: strain, pressure, etc.

Signal processing



Classification

Fitting with variance of the uncertainty



Risk of cumulative damage using varinaces of the load and resistance

Risk of failure calculation for the entire system

Figure 7.5. Failure risk analysis of the system.

7.3 Case application – Paper reel

7.3.1 Simulation model

The multibody system simulation approach is applied to the fault diagnosis of the reel. The reeling sequence follows calendering at the end of the papermaking process. When paper comes from the calender, it will be wound around the reel spool. The purpose of this sequence is to produce large diameter rolls of paper called parent reels. The weight of the roll can be from 20,000 to 120,000 kg while the diameter ranges from 2 to 4 meters [Jokio 1999]. The main parts of the reel are depicted in Figure 7.6. The reel spool is attached to the carriages by hydraulically locked arms. Note that the carriages do not hold up the reel spool. Instead, it lies on the sledges which move along the rails on the low friction linear bearings. The reel spool is pressed against the reel drum by pulling the carriages using hydraulic cylinders.

The simulation model consists of mechanical, electrical and hydraulic subsystems that are coupled together. Based on the response differences between normal and faulty simulations, the required measurements for identifying the faults can be defined and utilized in the design of the fault diagnosis system. In the simulation model of a reel, clearances of the mechanical joints and structural flexibility are assumed to be neglectable. However, the flexibility of a hydraulic system is accounted to the reel model.

In the first stage the reel system is modeled using commercial simulation software ADAMS while in the second stage modeling is accomplished using a general purpose ANSI C computer code. Several formulations are introduced in order to achieve better accuracy and shorter solving times. Three well known formulations are studied and used in fault diagnosis purposes. The methods are a method of Lagrange multipliers [Haug 1989, Shabana 2001], the Augmented lagrangian [Bayo et al. 1988, Garcia de Jalon 1994] and the method based on projection matrix **R** [Serna et al. 1982, Wehage & Haug 1982, Shabana 2001]. A comparison of these methods is carried out using a modeled case system. Based on the simulations, the most efficient is chosen, and used in simultaneous simulations of normal and faulty scenarios with several parameter variations.

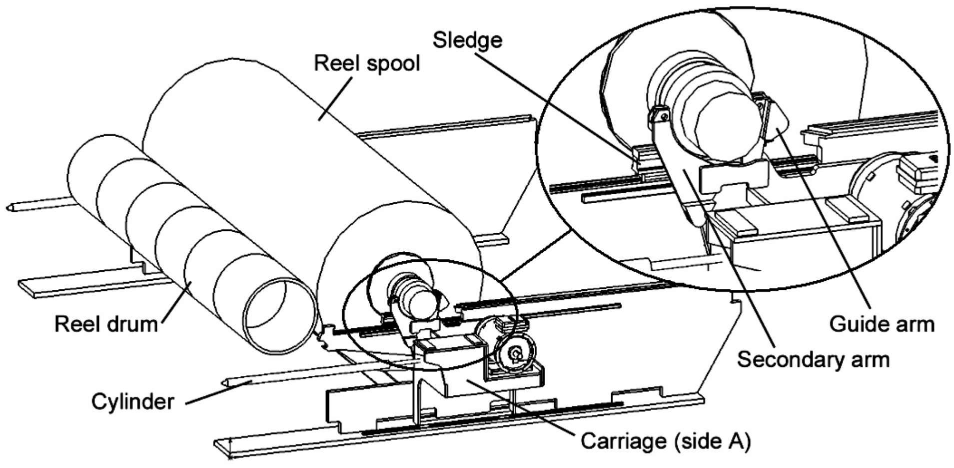


Figure 7.6. The main parts of the reel.

The simulation model of the reel mechanism consists of eleven rigid bodies and it is constrained in such a way that it has eleven degrees of freedom. In Figure 7.7, the topology of the system is described using lines to illustrate kinematic joints and arrows to illustrate applied forces. The contact model between the reel drum and the reel spool is used to describe the nip load. The contact is described using several nonlinear springs between the rolls. The contact parameters are estimated using the Hertz theory of elastic contacts resulting in deformation between a long, linear-elastic, homogenous and isotropic cylinder, and a rigid cylinder, describing the paper roll and drum roll [Jorkama 1998, Johnson 1985]. The force required to produce the appropriate nip load is achieved by pressing the rolls against each other by hydraulic cylinders. The reel considered in this study is driven by motors attached to both the winding roll (reel spool) and the nipped roller (reel drum). The drives are called the secondary center drive used in the torque control of the reel spool and the reel drum drive used in the torque control of the reel drum [Jokio 1999].

7.3.2 Simulation results

Three abnormal operation conditions of the reel are simulated using ADAMS. The simulation model is used in the analysis of the following fault conditions during the working sequence: Excessive friction on the rails, leakage in the servo valve and noise in the force sensor signal. In simulations proceeded with self-written computer code only excessive friction cases are considered.

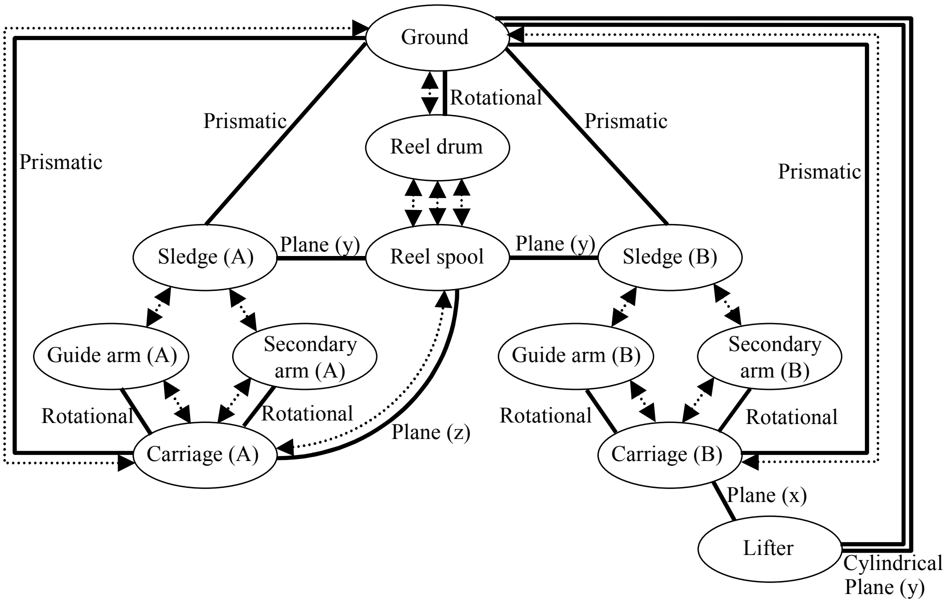


Figure 7.7. The topology of the system. Arrows are applied forces and moments and lines describe kinematic joints.

In the first example, the excessive friction is imposed on the rails of carriage at side A, shown in Figure 7.8. In this example a 500-second cycle of reeling sequence is implemented. When simulation time exceeds 300 s, the static and dynamic friction coefficients are increased from 0.015 to 0.025 and 0.0045 to 0.0145, respectively. Due to the force control, the friction causes an increase in the nip load at side A of the reel, as can be seen in Figure 7.8. This can be observed as a small error in the position of the carriages. However, the position error is only 0.2 mm, making it cumbersome to identify using measurements. To detect excessive friction, it is reasonable to simulate another stage of the working cycle.

When the paper roll is completed, the secondary carriages transfer the parent reel to storage position. 70-second simulation cycle is used to simulate the transfer sequence. During the transfer sequence, the excessive friction can be perceived from the force sensors of the hydraulic actuators or the pressures of the cylinder chambers as shown in Figure 7.9.

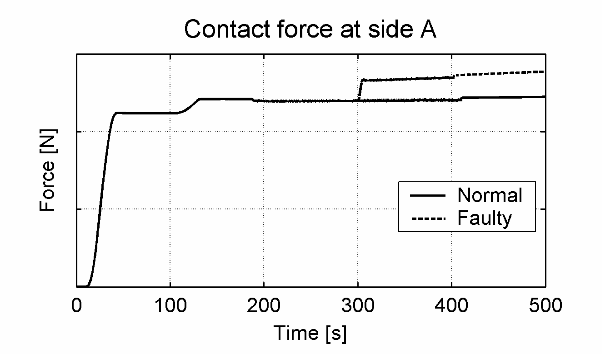


Figure 7.8. Nip load when increased friction applied to rails of carriage at side A during reeling sequence.

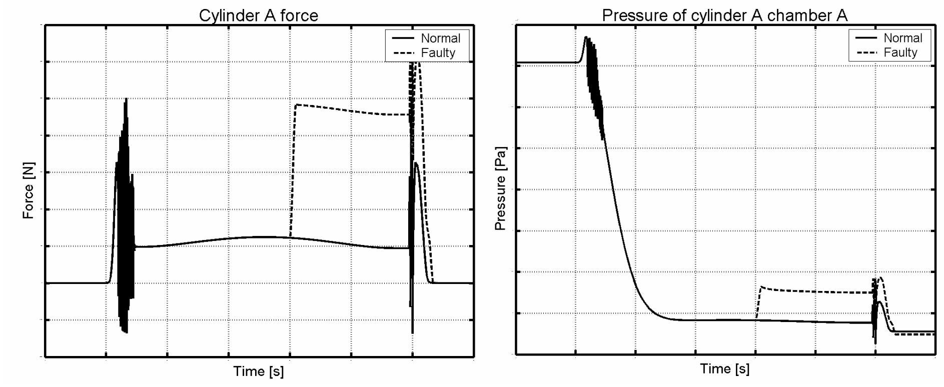


Figure 7.9. Force of cylinder A and pressure of chamber A in Cylinder A during transfer sequence.

In the second case the excessive friction on the rails of sledge A causes an increase in the nip load similarly to excessive friction on the rails of the carriage. In this case, the friction force is a function of the mass of the paper roll and it increases the nip load during reeling. The same friction coefficients as in the first example are used in this case. In this example, a change in the friction coefficient can be perceived from the force sensors of the hydraulic actuators and, in addition, from contact forces between arms and bearing housing as in Figure 7.10.

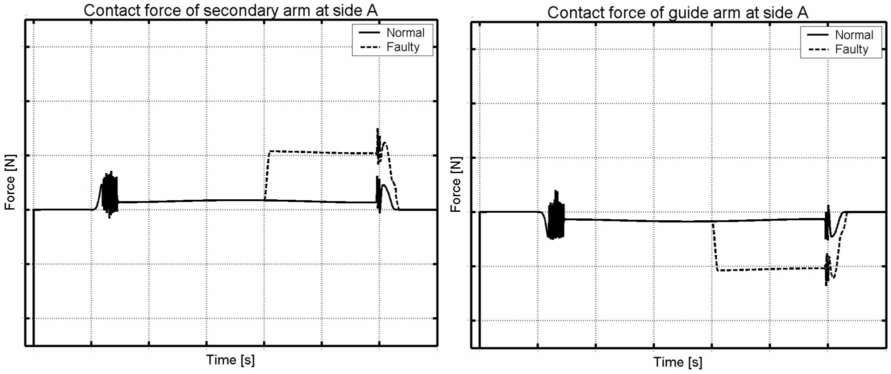


Figure 7.10. Contact forces of secondary and guide arms at side A during transfer sequence.

The reeling operation is considered to be defected when a 5% difference occurs in the nip load. In practice, the nip load is cumbersome to measure and, for this reason, a simulation model can be used for estimating it. Excessive friction on the rails directly increases the nip load. During the reeling it can not be detected from the cylinder pressures or force sensors used to control the nip load. Rail failures can be perceived when the paper roll is transferred to storage position. The faulty rail can be also identified using the force measurements of the arms.

7.3.3 SOM application

In the case of the reel, the SOM is trained with the normal run data (i.e. faults excluded) as presented Figure 7.11. The run data is in this case the Gabor-filtrated frequencies. When the frequencies are changed by the way which is not included to the training data of the SOM. The unified distance matrix (u-matrix) shows the cluster structure on SOM grid visualization. It shows the distances between neighboring units and gives an impression of mountains (long distances) which divide the map into fields (dense parts, i.e., clusters).

The other way is to train the SOM with the fault included data to recognize and categorize fault situation. However this would be difficult and expensive way to generate feature data. Another way is use virtual prototyping to generate feature data for the SOM but virtual prototypes can not yet produce enough accurate input data.

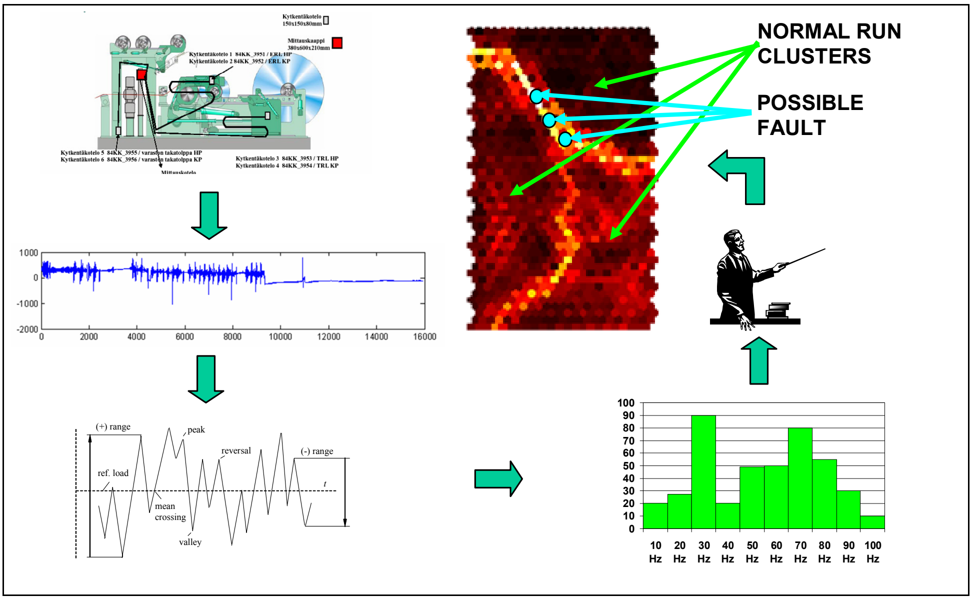


Figure 7.11. The SOM has been trained with fault free situation run.

Kohonen self-organizing maps (SOM) [Kohonen 1990] are used in the purpose of automatic fault detection and isolation. SOM is based on the neural networks that use unsupervised learning algorithm. When the knowledge of classes of the data is added, the network can be supervised to recognize the class in which the given data belongs. Generally, SOM is an effective method for data clustering and widely used in data mining and process monitoring applications. The model is used to simulate faulty and normal conditions and the results are used in learning SOM. The reference simulations are carried out and used to test the applicability of the learned network to classify these simulations.

The network has learned using 18 simulations of each faulty situation which means 18 parameter variations for each situation. Situations are labeled for the learning so that “n” is normal operation condition, “f1” is an excessive friction fault on the rails of carriage at side A, and “f2” is an excessive friction fault on the rails of sledge at side A. Twelve state variables and parameters are chosen to describe the simulated situations, and they form learning data for SOM. Before learning the weights, the network is initialized using random values. When the network has learned, it is tested using 9 simulations of each situation with different parameters from the learning process. The result of classification is shown in Figure 7.12, in which the trained map’s size is 9-by-6.

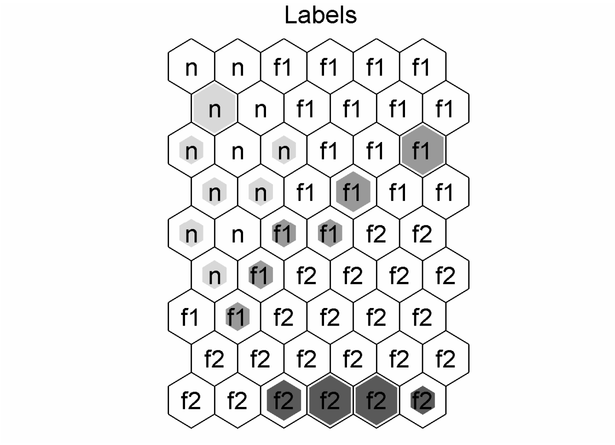


Figure 7.12. Self-organizing feature map after training and classification results of testing data.

The darkest hits describe the testing data from excessive friction on the rails of sledge A and the slightest marks are from the testing data from normal operation condition. In addition to using the testing data, the quality of the network can be estimated with measures called quantization error and topology error. These measures depend on the used data and generally give the best result when the map is overfitted by the data, which is the case when the number of map units is as large, or larger than the number of training samples. In this study, the number of map units and the number of the training samples are chosen to be equal. The values of the error measures can be decreased using more map units. Nonetheless, the resulted map may not necessary produce improved classification.

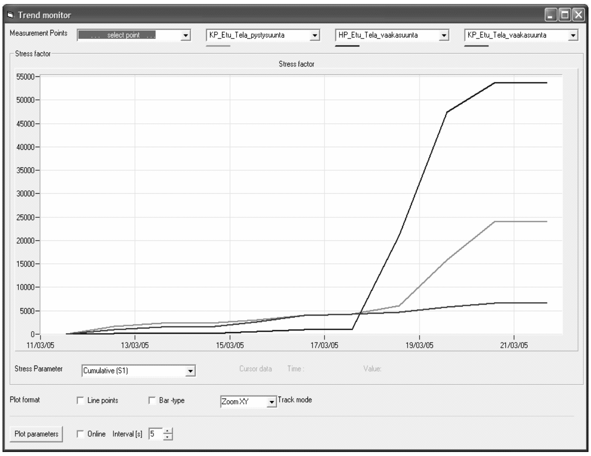
SOM is an applicable method for classifying situations described. It can be seen from Figure 7.12 that SOM managed to classify all the test configurations to the appropriate categories. However, the training must be done with care, or problems in the classification may appear. For example, changing the map size may slightly confuse different classes.

7.3.4 Cumulative stress calculator

The development process was adapted to requirements arising from the reliability of the paper reeling system. The reel system consists of two main arms operated by servo hydraulic cylinders and a reel drum operated by electric motor. The system is normally under heavy and dynamic loading due to its rolling process. These are mostly predictable and thus can already be evaluated in the designing phase. However, uneven operating systems and clearances, different lubrication, friction and wear conditions are not accurately predictable. In addition, the loading can be due to these reasons remarkably different on the both sides of the reel. Hence the loading information during the reeling is essential from both the designing and operation reliability point of view.

The reeling system is instrumented with several strain gages at the critical points of the system. The measurement signal is sampled with a data acquisition system and further processed to form a rain flow matrix classifying the information into hits to mean and maximum classes. The analysis of rain flow matrices are mostly done manually. Methods suitable for automated analysis, extracting the relevant load pattern features without losing any relevancies, are needed. These automated load counters can be used for monitoring load and changes in the reeling system. A method was developed to further process the maximum and mean load class counts stored into the measured rain flow matrices. The method utilises both windowing and integration techniques. By using the developed method different loading properties and points (e.g. welding seams, bolt joints) can be observed individually. Finally, one feature is derived from the rain flow matrix. The feature is stored to the data base. The software solution of the feature extraction is formed by the integration of previously extracted values, with the cumulative stress factor representing the current loading level. Additionally, the velocity of the stress factor is formed. All the derived values can be monitored as a function of time by selecting the measurement point and proper parameter (Figure 7.13).

The condition of the reel can be evaluated by monitoring the calculated parameters. In addition, these values can be used to increase the knowledge of the operation of the reeling process and loading conditions. It is essential for the designers to get feedback from the real conditions and its changes. Furthermore, the process maintenance personnel and, indirectly, process operators need the information at least when the levels are deviating from their allowable paths, or when the levels are properly equal in the responses measured on both sides of the reel. In the developed software solution it is possible to set flexible limits for each measurement point. According to the give mean value and the standard deviation as well as the distribution type (currently the normal distribution), the current reliability stage of the system can be evaluated. The remaining lifetime at each point can be assessed by first modelling the progress equation using linear regression of the last values, and then solving the time from the modelled equation and the equation of the maximum allowable level (normally constant). The result of the current probability stage and remaining lifetime is presented in Figure 7.14.



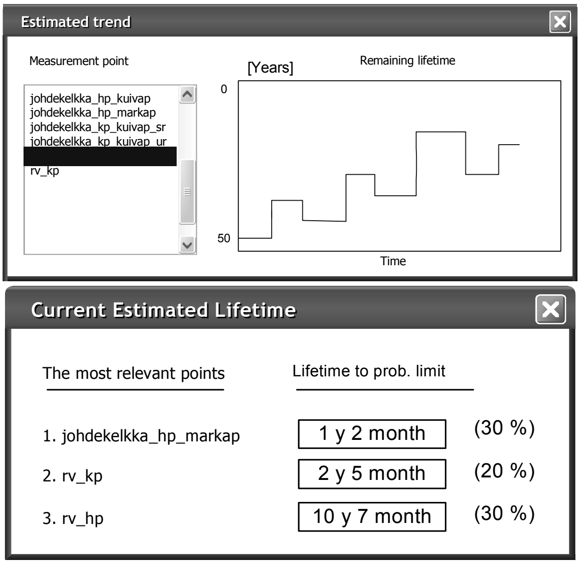
Measurement Points: . . . select point . . . | KP_Etu_Tela_pystysuunta | HP_Etu_Tela_vaakasuunta | KP_Etu_Tela_vaakasuunta

Stress Parameter: Cumulative (S1)

Plot format: ☐ Line points ☐ Bar -type Zoom XY Track mode

☐ Online Interval [s] 5

Figure 7.13. Stress factor software, trend monitoring window.



Measurement point

johdekelkka_hp_kuivap
johdekelkka_hp_markap
johdekelkka_kp_kuivap_sr
johdekelkka_kp_kuivap_ur
rv_kp

The most relevant points	Lifetime to prob. limit	
1. johdekelkka_hp_markap	1 y 2 month	(30 %)
2. rv_kp	2 y 5 month	(20 %)
3. rv_hp	10 y 7 month	(30 %)

Figure 7.14. Current probability stage (bellow) and the remaining lifetime (above).

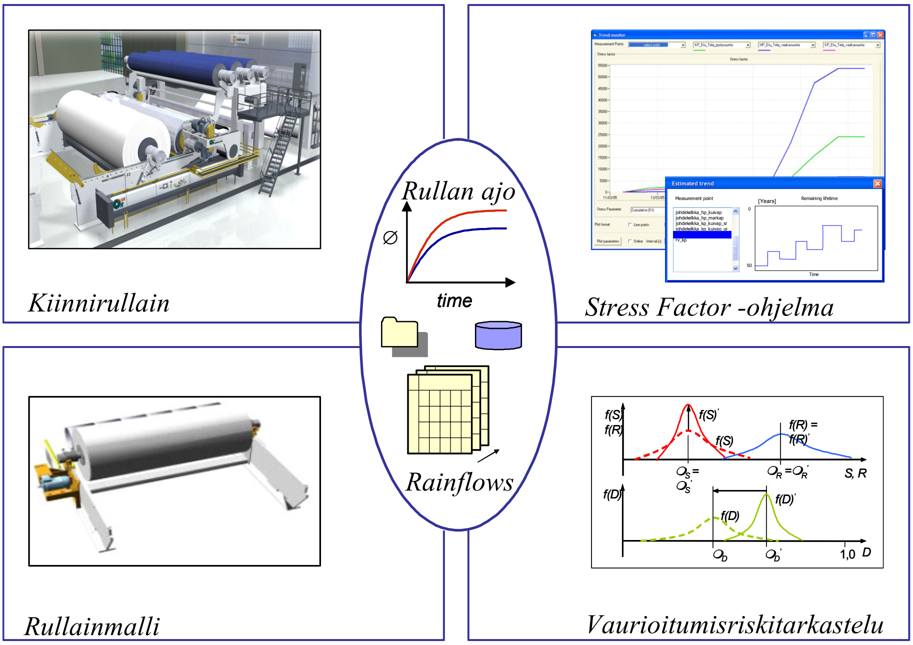


Figure 7.15. Integrated real time simulation models and stress factor concept.

7.3.5 Integrated application

During the project offline and real time simulation models of the reel system were developed. The responses available from the reeling measurement system were forwarded to a remote PC used for analysis. The analysis PC was installed with both real time simulation model and stress factor programs. The real time simulation model which was implemented uses as its input the measured rotational speed and measured load. It calculates according to its model (see chapter on real time modelling) the load on the reel in real time. The derived load results are further processed and the rain flow matrices are formed similar to the results from the measurement system. After each reel has been processed a new output file is formed. A stress factor program reads and further processes these files in the same way as it does with the rain flow files derived from the measurement system on the reel. This way the measurement results and simulated responses can be evaluated in parallel to each other, giving more depth to the monitoring and analysis activities. Changes in either can be used as an indication for further analysis. The simulation models together with the stress factor can be used for the evaluation of the possible novelty stages (e.g. increase in the reel rotation speed) without testing them with the real machine (Figure 7.15). Within the operational area of the real time model it gives essential prior causal performance and loading information from the focused model nodes, all of which can be used for further evaluation. This can even increase the reliability of the reel.

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8. Safety and reliability in product design

8.1 Introduction

The aim of the project was to bring probabilistic design methods aimed at safety and reliability into product development. The approach developed in the project is based on the application of probability-based design to control safety and reliability.

In the report Survey of probabilistic component degradation methods [Ahlroos et al. 2004a], both design methods and methods used in component failure analysis and remaining lifetime modeling were surveyed, and their characteristics were studied. With these methods, the failure mechanisms and faults affecting reliability can be taken into account in the early stages of product design. The survey covers friction, wear, lubrication, fatigue, corrosion, and defects in terms of their effect and the faults they cause and methods of controlling uncertainty.

The probability based modeling of degradation of structural components necessitates a thorough knowledge of structural properties, loads, the relevant degradation mechanisms and prevailing environmental conditions. Several time dependent degradation mechanisms exist which can shorten the lifetime of components. In addition, two or more of these can affect a component simultaneously. The report Survey of probabilistic component degradation methods [Ahlroos et al. 2004a] includes an overview of various relevant component degradation mechanisms.

Degradation or ageing can be observed in a variety of changes in physical properties of metals, concrete and other materials. These materials may undergo changes in their dimensions, ductility, fatigue capacity, mechanical or dielectric strength. Degradation results from a variety of degradation mechanisms, physical or chemical processes such as fatigue, cracking, embrittlement, wear, erosion, corrosion and oxidation. These degradation mechanisms act on components due to environmental loads, such temperature changes, pressure, radiation, reactive chemicals and synergistic effects. Various degradation mechanisms may also act simultaneously, like for example fatigue and creep.

In the report Applicability of probabilistic component degradation analysis methods [Ahlroos et al. 2004b] the methods were evaluated and their applicability to modeling of degradation was reviewed. The computational methods for load history analysis were also discussed. Due to the stochastic nature of many of the properties or phenomena, probabilistic modeling methods are deemed suitable for the degradation analyses. In general, the nature of degradation models of structural components can be deterministic, probabilistic or a combination of these two types. An important example of a combined approach is probabilistic fracture mechanics (PFM), in which one or more of the physical model parameters are considered to be random. In practice, degradation analyses are usually performed with a suitable analysis tool, i.e. with analysis software.

8.2 Tribology

Tribology is, according to OECD, ‘the science and technology of surfaces acting upon one another in relative movement and of the problems associated therewith’. Tribology connects know-how in the areas of mechanical, lubrication, and material engineering in an effort to control friction and wear so as to improve the reliability of machines. The aim of tribological design is to optimize the reliability, performance, life, and efficiency of sliding and rolling contacts of machines when special tribological circumstances are considered. The initial data used in tribological construction are based partly on properties of the construction materials but mostly on the behavior of these materials in the tribosystem in which all the mechanical, hydromechanical, thermal, and chemical factors act. Tribology is highly multidisciplinary, and therefore the generally empirical information needed in tribological design is very troublesome to extrapolate or even to transfer from one case to another. Through experimental tribological simulations, the influence of single factors on friction and wear processes can be analyzed. From the tribological performance reliability point of view, the best construction is achieved by considering the experimental laboratory data and information from the field tests. Laboratory methods used in tribology simulation are for example: pin-on-disk test, twin disk test, scratch adhesion test, ball cratering test, reciprocating sliding test, film thickness measurement, and rolling bearing test [Ahlroos et al. 2004a].

In the statistical design of experiments, the test design and analysis techniques based on mathematical statistics and rigorous quality standards are chosen. Characteristic to this approach is the departure from the commonly used ‘best guess’ or ‘change one parameter at a time’ strategy in favor of a statistical test planning method, in which several test parameter values are systematically changed. With the latter approach, money and time can be saved, allowing more information to be gained from the tests. In particular, the interaction of different parameters can usually be seen more clearly.

Wear is defined as the loss of material as a result of mechanical contact between two solid surfaces in relative motion to each other. Wear can be due to adhesion between the solid surfaces, abrasion from hard asperities or particles, fatigue at the surface or tribochemical mechanisms. Wear is commonly inhibited by lubrication. Wear and tribology related aspects were discussed in Chapter 2 of the report Survey of probabilistic component degradation methods [Ahlroos et al. 2004a].

Several wear models exist, but their applicability and scope are very limited. This is because tribology is an extremely complicated topic and models can be easily misleading. In realistic wear modeling, the analysis must include the complete system, both triboelements, and several problems must be treated simultaneously: dynamic behavior of the tribosystem, load distribution, temperature fields, tribomechanisms (wear debris) and material response. In FEM modeling usually only one of the two contacting surfaces is considered and inevitably some of the parameters, which are needed for realistic modeling, are lacking. A generally accepted standard wear test is missing and that causes also problems. The apparatus used in testing has major effects on the wear results, and also the specimen geometry is significant. Thus, general and practical models are still missing.

As a consequence of the lack of good general and practical models, in practical applications a lot of friction and wear related problems exist, which result in high warranty costs. The other problem is that designers use poor models if good models do not exist. The benefits of useful models for friction and wear would be undisputable.

The rolling contact bearing manufacturers have done extensive work in the field of providing design information for the designers. Prediction of the life of rolling contact bearings is based on probability calculus, of which the essential element is empirically and experimentally generated correction factors. The object of the calculations is the rolling contact fatigue resistance of the bearing. Statistical signal processing is used in the vibration measurements employed in condition monitoring. A possible fault in the bearing can be detected via several statistical parameters or by a single parameter, such as the amplitude at a fault or rotational frequency in the spectrum.

Water is one of the most important factors that cause premature damage of bearings and gears, see an example in Figure 8.1. However, the service life calculation instructions issued by bearing manufacturers do not provide a factor that would take the effect of water contained in the lubricant into consideration. Water causes corrosion on metal surfaces, it reduces the efficiency of the elastohydrodynamic (EHD) lubrication capacity of the lubricant, and it may additionally cause sludge formation.

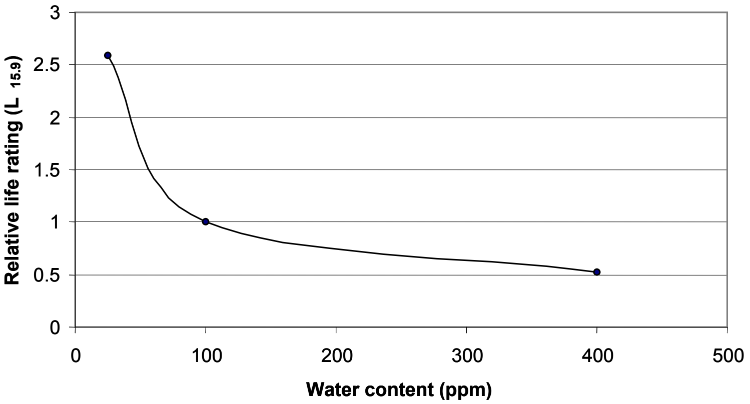


Figure 8.1. Relative life rating of a rolling contact bearings function of the water content of the lubricating oil, according to Cantley [1977]. The graph refers to tests with a contact pressure of 2.03 GPa and a rotational speed of 2700 rpm.

Water in lubricating oil has also been found to increase the wear of bearing surfaces. Some experiments have shown that, depending on the grade of oil, the proportion of abrasive wear may increase by up to two orders of magnitude, when the water content of a lubricant rises to 500 ppm. The dramatic change has been found to occur due to changes in the additives caused by the presence of water, which changes the wear-reducing properties of the lubricant. Water acts on the metal surfaces of the bearings, by causing corrosion. Occasional corrosion pits may act as nucleation points for fatigue cracks, and hence promote the formation of fatigue damage [Ahlroos et al. 2004b].

8.3 The control of uncertainty in design process

The features of a manufactured product are always uncertain to some extend, due to manufacturing tolerances, material property variations, in-service degradation, etc. The variability that is inherent in manufacturing of components and assembling parts produces a consequent variability for example in the dynamic responses [Lee et al. 2003]. Moreover, the operational conditions in service may vary and the product can experience unpredictable environmental loads.

The design process for new products should include tools for the control of various uncertainties. These tools consist of traditional calculation methods, but they should be understood, as a broader sense, to include also systematic ways of controlling and measuring the uncertainties. The control of uncertainties culminates at the design decision points. It is at these process phases where the uncertainties should be taken into account in a proper manner.

When virtual prototyping and simulation are used in the design process, two different needs for the application of such models can be identified. If entirely new structure is in question, then the reality is in our models and uncertainties exist in at that moment non-existing structures and we want the make good design decisions for something that is in the future. Secondly, we might have an existing structure and we want to make it better or it is not working desirable. In this case the reality is in the structure and theoretically we have all information available. The uncertainty is in this case in our models and the key objective is on the proper accuracy of our models.

8.3.1 Characterization and evaluation of uncertainty

To control the uncertainties the designer needs to identify the causes and consequences. In the beginning a qualitative review can be conducted. This includes survey of all the possible uncertainties and subsequent classification. In general the uncertainty can be classified into two categories. Epistemic uncertainty is characterized as lack of knowledge. Aleatory uncertainty is true randomness and it is described with random processes [Oberkampf et al. 2002, Tonon 2004]. Aleatory uncertainty describes the inherent variation associated with the physical system or the environment. It is generally quantified by a probability distribution, when sufficient information is available to estimate the distribution.

Epistemic uncertainty is also called subjective uncertainty. The key feature of it is that its fundamental cause is incomplete information. Sources of uncertainty in mathematical models generally include those in system parameters as well as in the boundary and initial conditions. These are always present in engineering applications and are often modeled as random variables or processes. Traditional approaches to uncertainty quantification include the Monte Carlo method and its variants which generate ensembles of random realizations for the prescribed random inputs and use repetitive deterministic solvers for each realization. The convergence rate of these methods can be relatively slow. To overcome this problem other non-sampling methods are available and these include perturbation methods and second-moment analysis [Xiu et al. 2005]. If no probabilities are known but bounds are given for the uncertain parameters, then a set of possible parameter values represent the uncertainty [Shuller 1997, Elishakoff 1995, Qiu et al. 1996 a, Qiu et al. 1996 b].

In the absence of empirical data the judgement of experts may be used. This is the case especially when new concepts and arrangements are designed with little or no experience of similar concepts [Apeland et al. 2002]. Since the information is non-validated, the selection, framing and bias of experts becomes dominant. Sometimes consensus may be important, in some cases diversity may be important and retained [Richards & Rowe 1999]. In producing expert judgements, some principles should be followed. Firstly, the experts should be educated to make probabilistic judgements in a calibrated way. Secondly, the expert judgement process should be documented in a transparent way: the sources of information used in the process and the experts' argumentation should be traced. If several experts are used, the way to combine the judgements should be described.

One source of information is the historical data of similar products, especially if epistemic uncertainty is in question.

8.3.2 Use of models

Engineering design makes use of symbolic or mathematical models in various phases of the design process. In order to do design, the designer wants to predict the behavior of the product beforehand. This can be done only through the use of models. The designer must predict system behavior prior to making design decisions and data cannot be obtained from physical tests prior to the construction of the product. On the other hand the product cannot be constructed until the design decisions are made. Thus all the models that are used in support of engineering design are forecasting and predictive in nature. Consequently it must be realized that such models cannot predict the future with perfect precision and certainty. Thus the most important aspect of models is the validity of such models with respect to their use in design decision making processes [Hazelrigg 2003].

Usually the models that are used in engineering design are predictive in their nature. The information obtained with these models is used to aid the design decision making. It can be stated that a model provides perfect information if, using the model, the decision maker is guaranteed of choosing the alternative that would prove to be the best meaning that the alternative gives the most desired possible outcome. When mathematical models are used in the design process one should evaluate, what are really the questions that the analysis tries to give answers to, and which uncertainty does the analysis remove or diminish.

Models are the basis for all prediction of system behavior and hence form an important platform for the engineering design process. A key concern is the validity of such models. It has been stated that predictive models, such that those used in engineering design, cannot be validated objectively. That is, the validation of a predictive model can be accomplished only in the context of a specific decision and only in the context of subjective input from a decision maker, including preferences [Hazelrigg 2003].

A model is a simplified representation of a real world system [Apeland et al. 2002]. The general objective of developing and applying models is to acquire more information of real world phenomena. This information is then used in design decision making. Detailed modeling is required to be able to identify critical factors. The simplified form makes models suitable for analysis. In model construction this property is traded off against the needs for complexity required for producing sufficiently credible results. Typical factors governing the selection of models are the form in which and what level of detail input information is available, the economical and human resources available in the specific study and whether the focus is on the accuracy or merely comparing decision alternatives.

8.3.3 Design decisions under uncertainty

A decision is a commitment to an action taken by the decision maker. The commitment involves making a choice between alternative courses of action. All decisions involve commitments made in the present with the intent of a preferred outcome in the future. The future can never be predicted with absolute certainty. Consequently, all decisions involve uncertainty and risk. All decisions involve three elements. The first element is the existence of alternative courses of action available to the decision maker (*decision alternatives*). The second element is the decision maker's perceptions relative to these alternatives (*expectations*). The final element is the *preferences* over possible results of the various alternatives (*outcomes*) [Hazelrigg 2003]. In design process the uncertainty is controlled in decision points. The decision points should be clearly identified in the process. Moreover the quality and availability of the information should be assured to the decision maker. In many practical cases it is important to make the interface between the various experts and designers as well working as possible. In complicated technical issues the lack of good communication between these groups can be a great obstacle in the control of uncertainties.

The tendency is to incorporate more intelligence in the products. This combined with the increasing use of virtual prototyping in the design puts new demands on the design process. As new technologies are exploited and fewer physical prototypes are made the requirements for the control of uncertainties in the design process becomes predominantly important. That is why the design process should comprise of methodology for the control of uncertainties. The design process should indeed contain tools for the control over product design requirements in order to assure that the final product fulfils optimally these requirements with respect to functionality and economy.

Figure 8.2 shows schematically the idea of combining the uncertainty analysis into the design process. At some design phase it is realized that a need for a separate uncertainty analysis is apparent. In order to conduct such analysis a separate decision is required to guide the design process. The main purpose of the separate uncertainty analysis is to acquire information for the decision maker. What kind of decision is in question depends on at what level in the design process we are. At the very beginning it might be question of choosing between different concepts and at later phases design decision concerning product details.

The risk or uncertainty analysis can be conducted according to the flow chart that is shown in Figure 8.3. The first task is to identify the design phase by naming and describing it. The description of the phase includes defining the purpose as well as the inputs and outputs. Moreover the different parties involved in the design phases are listed. The parties might include designers, manufactures, experts, etc. The third step is to identify and classify all the uncertainties in the design phase including causes and possible outcomes. In the fourth step the results obtained in the third step are analyzed and decisions are made on the needs and possibilities to diminish or remove uncertainties. Decision might also be to make a more detailed reliability analysis. In the fifth step the uncertainties are quantized using probabilities. In the last step the decision maker has enough information to make his design decision.

To clarify the concept of the uncertainty analysis a short example is shown in Figure 8.4. The example is a real industrial case which was made in a work shop. The work shop consisted of a group of designers and experts. The case was from very beginning of a design process were the question was on more or less conceptual alternatives. In the work shop it was not possible to go into qualitative level. The conclusion in this example was to recommend a more detail reliability analysis and moreover to list criteria for a subsequent decision step.

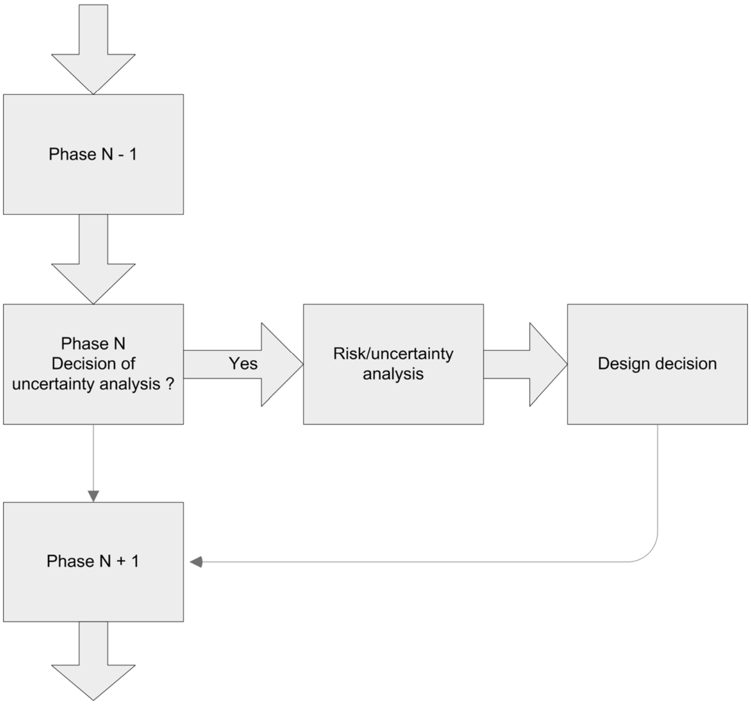
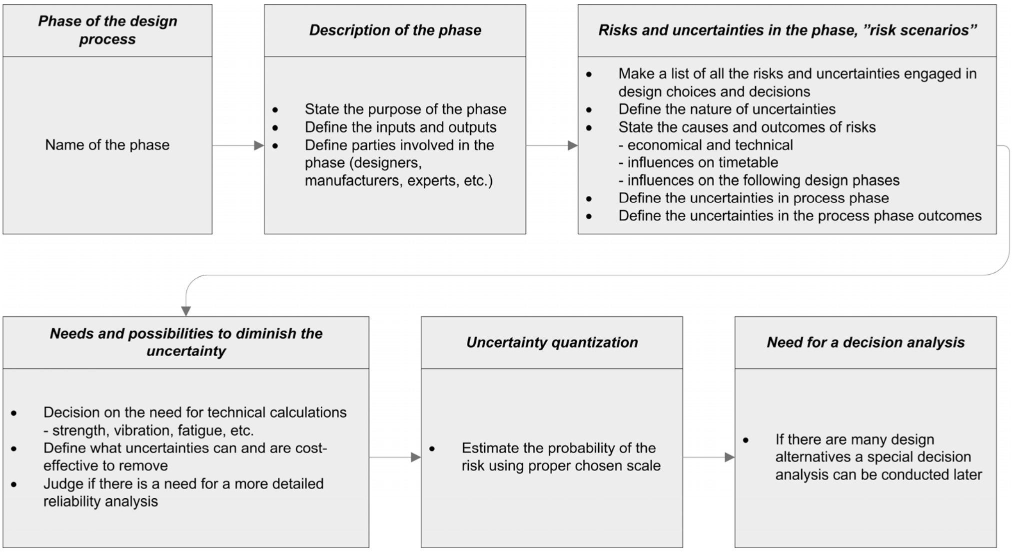


Figure 8.2. Uncertainty analysis in the design process.



Description of the phase

- State the purpose of the phase
- Define the inputs and outputs
- Define parties involved in the phase (designers, manufacturers, experts, etc.)

Risks and uncertainties in the phase, ”risk scenarios”

- Make a list of all the risks and uncertainties engaged in design choices and decisions
- Define the nature of uncertainties
- State the causes and outcomes of risks
  - economical and technical
  - influences on timetable
  - influences on the following design phases
- Define the uncertainties in process phase
- Define the uncertainties in the process phase outcomes

Needs and possibilities to diminish the uncertainty

- Decision on the need for technical calculations
  - strength, vibration, fatigue, etc.
- Define what uncertainties can and are cost-effective to remove
- Judge if there is a need for a more detailed reliability analysis

Uncertainty quantization

- Estimate the probability of the risk using proper chosen scale

Need for a decision analysis

- If there are many design alternatives a special decision analysis can be conducted later

Figure 8.3. Uncertainty and risk study in the design process.

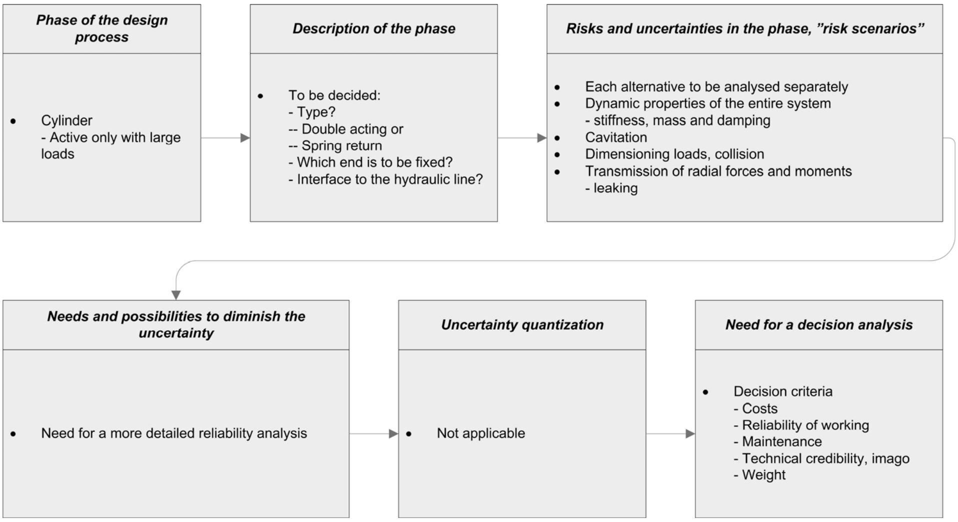


Figure 8.4. Example of and uncertainty and risk study in the design process.

8.4 Probabilistic and risk based analysis procedures for component degradation analysis applications

Report [Ahlroos et al. 2004a] presents a survey of probabilistic component degradation methods where is a survey of the relevant degradation mechanisms affecting components in various industrial environments, see Chapter 1, and a more detailed presentation of various relevant forms of corrosion, see Chapter 5.

Report [Ahlroos et al. 2004b] presents a survey of applicability of probabilistic component degradation analysis methods where a survey of the most relevant and advanced probabilistic component degradation analysis methods and tools, see Chapters 2.1 to 2.5, and a description of their applicability and development needs, see Chapters 2.6.2 and 2.6.3. More than ten degradation analysis codes are covered, they are also evaluated and compared against each other. Most presented analysis codes apply structural reliability methods, e.g. probabilistic fracture mechanics (PFM). The applicability of the analysis codes to modeling of various forms of fatigue and corrosion is discussed in more detail.

Compared to reports [Ahlroos et al. 2004a, Ahlroos et al. 2004b], in report [Cronvall 2004] the discussion of probabilistic analysis procedures and their applications is considerably widened and elaborated, including an analysis example. In addition, risk analyses and approaches are discussed in the publication as well. Some of the most relevant issues of the publication are summarized in the following.

PFM is a modeling approach that combines both deterministic and probabilistic features. Many components, which could be otherwise rejected, can be saved by removing such arbitrary and unrealistic worst case assumptions as simultaneous occurrence of improbable events, and allowing the model to account probabilistically for actual variation in critical parameters which are based in test results or experience. PFM is employed to remove such unrealistic conservatism in component reliability analyses. The application of PFM includes the randomization of one or several input parameters, e.g. material strength or the dimensions of initial flaws. An accurate enough randomization of a parameter can be performed only if there is statistically enough measured data of enough good quality. Thus probabilistic analyses require considerably more input data than deterministic analyses. When applying PFM also probabilistic sensitivity analyses and confidence intervals should be considered.

The main results from the probabilistic analyses are component failure probabilities. The failure modes in question are specified by determination of the response and limit state functions, which are based on degradation models and related critical values for examined model parameters. The failure probabilities should be compared to maximum allowed failure probabilities, if such are available.

Risk analysis is a technique for identifying, characterizing, quantifying and evaluating hazards. The main goals of risk management are to minimize the occurrence of accidents by reducing the likelihood of their occurrence, reduce the impacts of uncontrollable accidents and transfer risk (e.g. via insurance coverage). The estimation of likelihood or frequency of hazard occurrence depends greatly on the reliability of the system components, the system as whole and human-system interactions. The engineering definition of risk is now accepted as being the product of the probability and the consequence of the event. In risk assessments concerning components this probability is often the failure probability. Several risk analysis procedures are available.

The analysis tool selected for probabilistic analyses is NESSUS by Southwest Research Institute (SwRI). It was deemed as the most versatile and advanced of the commercially available general reliability analysis codes. Another advantage concerning NESSUS is that it can be linked with various other advanced analysis programs. In the probabilistic analyses, NESSUS was used in combination with mechanical simulation program ADAMS and finite element method (FEM) based structural analysis code ABAQUS.

As a practical application a component in a straddle carrier manufactured by port technology company Kalmar was analyzed. As a result of a risk based consideration, a load bearing steel plate near the wheels was chosen for the analyses. The analyzed degradation mechanism was fatigue caused by the cyclic loads which in turn are induced from driving the carrier. Load cycles of several types, amplitudes and frequencies were identified and analyzed.

The realization of analyses is described in the following. First the loads induced from driving of the carrier were simulated with ADAMS using a complete three dimensional model of the vehicle. Based on ADAMS analysis results, suitable probabilistic distributions were developed for the load parameters, which were further used in the stress analyses. The probabilistic analyses with NESSUS were performed next. In those the stress distributions experienced by the considered component are needed as well, and to calculate them NESSUS independently used ABAQUS at the same time for the task. NESSUS provides numerous probabilistic analysis procedures, several of which were used in the analyses. Thus it was possible to compare these analysis procedures against each other. The final results from the analyses were failure probability of the component as a function of the number of load cycles, and sensitivity of the analysis results to various relevant analysis model parameters.

The combined use of these advanced analysis codes is an effective way to obtain accurate evaluations of the structural lifetimes and failure probabilities of various components. Almost any geometry, material behavior and loading can be analyzed, and still the analyses can be performed cost effectively, e.g. with a reasonable amount of work and within a reasonable time. With the use these analysis codes it is also possible to decrease the need to make expensive full scale component/machine/vehicle prototypes.

8.5 Fatigue

Report [Ahlroos et al. 2004a] represents a survey of probabilistic component degradation methods. Chapter 4 includes short introduction to reliability analysis of the fatigue, fatigue design criteria principles, loading and life estimation approaches. Also some neural network applications are presented.

Computational methods for load history analysis are reported in the report [Ahlroos et al. 2004b]. Fatigue results form cyclic fluctuation of stress. It is the main cause for breakdowns in structures. It is easy to see the importance of the reliable fatigue estimation when 50 to 90 present of mechanical failures in structures are caused by fatigue. The report represents shortly several fatigue life estimation methods, cycle counting methods, signal reconstruction and load cycle density estimation methods.

Olli Alkkiomäki has presented a spline method for transform the rain flow histogram into continuous density estimation. He has first tested several density estimation methods in his master's thesis [Alkkiomäki 2004]. Density estimation methods can be used to model the histogram of load cycle amplitudes and means. By transforming the histogram into continuous density estimation, it is possible to extrapolate the accumulation of load cycles. Several methods are first compared using simulated histograms, and the most appropriate method is selected for real data. Confidence intervals are calculated for the density estimation using the bootstrap method. Service loading over a longer period of time is predicted from the density estimation. The variance for the service loading is calculated from the confidence intervals.

The spline method proved to give the best results of the compare density estimation methods. The service life of a component or a structure can be estimated by using continuous density estimation methods. Confidence intervals provide a method for estimating the variance of service life [Alkkiomäki 2004].

Alkkiomäki has studied more the spline density estimation in the article [Alkkiomäki et al. 2005a] where he describes a method for estimating the fatigue life from a short period of measured variable amplitude load history. The proposed method is considered to be most suitable for the fatigue assessment of structures and components subject to random service loadings, such as ground vehicles or off-road machinery. The method can also be used to model non-random load histories. Spline density estimation is fully automatic and represents a good compromise between low computational cost and good accuracy. The bootstrap method was successfully used to calculate the confidence intervals for the spline density estimation.

Strain gauge measurements from the prototype and production models provide relevant information about the loadings of a structure or a component during its service life. However, the measured variable amplitude loading history represents only a fraction of the whole service life. Methods for extrapolating the service loading for a longer period of time exist in literature, but the variance of the service loading distribution is often neglected. By estimating the variance of the work cycles, it is possible to predict the service loading and for a larger population of work cycles than there is measured data. This would allow, for example, determining the loadings for a larger population of users from as small group of users and determining the most damaging user form the population [Alkkiomäki et al. 2005b].

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9. Summary

The usage of simulation methods belong to modern product development. The advantages which are gained through simulation are manifold: expensive and time-consuming prototypes and the number of the tests decrease, the properties of the products improve, the time which is used for making of products shortens and the quality standard of products rises. Computer based modelling and simulation assists in developing an idea into a product. This improves the competitive ability of the company and shortens the path of new innovations from the idea to the market.

The simulation-based product development can be challenging for organisations. This is due to the many new techniques required. Information and new ideas must be created, examined, processed, tested, and transferred to organisations. Combining modelling and simulation to product development seamlessly requires a new way of thinking of the whole product process.

This research studies six different theoretical product development models. These six models were the basis for a reference model that was used as a communication tool in interviews with product development management. The generic model was composed after interviewing the design project leaders of five different companies. The product development theories found in the literature were quite similar, but they differ from the process used in companies. The process used in companies includes less tools (e.g. for innovating) and is usually more focused on gathering technological information and administrating ongoing development projects than theoretical models.

The newly developed process model for smart machines emphasises more detailed description of design activities than the generic model used. In the new model the business cases are studied and thereafter only the most promising projects are funded. The second stage after the business case is researching and developing new relevant technologies, methods and tools to be used in the future products.

In the design concept phase the simulation activities are performed using rough models and the main task is to generate and evaluate feasible concepts so that technical requirements are met. Product properties are studied on a conceptual level and possible system elements are connected. Traditionally, in the concept design phase many alternative designs were sought, usually without regards for their value and quality. In simulation-based design process the alternative concepts are quantified and therefore the best concept is selected for further development. In the design product phase, real-time and human-machine interface simulations are introduced to product development. 3D-models are detailed and dynamic and strength simulations are performed. This phase helps to perfect the design, increasing the possibility that certain parts will not be rejected in further testing. The test and verify phase involves the construction and evaluation of virtual and physical prototypes. Prototypes are tested to determine whether or not the product will work as designed and whether or not the product satisfies the customer's key needs.

One focus in the project was on managing large and complex overall system models using independent sub-models. Methods and practices were developed and tested to increase modelling efficiency and quality. Most of the actual modelling and simulation work was done on the industrial vehicle case model. During the project a simulation model base managing system was built for the case model and the usability of the system was tested in several simulation cases.

The model base was used for the development of vibration isolator component models. It was the basis for the building of the real-time simulation model and also for preliminary verification of that model. A kinematical human model was added into the industrial vehicle case model cabin. Simulation results were used as input data for reliability calculations. In all these cases either individual parts or the overall industrial vehicle case model could be used for the simulations.

The project demonstrated the superiority of the sub-model based modelling method on large and complex modelling and simulation projects. Although the used modelling and simulation tool did not fulfil all the requirements for distributed and object oriented modelling, most of the basic ideas were able to be tested. The project also showed the lack of general modelling and data formats as well as interoperability of different kinds of simulation environments. When using commercial software the available connections to other software tools and environments are often limited and predefined by the vendor. Additionally, the usability of the simulation results was sometimes limited due to the lack of standardised general data formats.

Real-time simulation and virtual technologies present interesting possibilities in many areas. Presently, virtual technologies are used to reasonable degree but real-time simulation is mainly used for research and training purposes. The main problem in exploiting real-time simulation is the lack of commercial tools suitable for systematic forming of models suitable for real-time simulation. The present training simulator technology is mostly based on kinematics and visualisation, while the dynamics modelling of the systems has been modest.

One goal of the project was to develop methods and tools suitable for the use of real-time simulators and virtual technologies in the product development process, condition monitoring, operator training and determination of a customer's needs regarding new procedures and products. A computer code was developed, suitable for real-time simulation of practical size systems. The code includes several separate function libraries that provide functions for the modelling of multi-body systems which utilise several different modelling methods. A sample of different numerical solution methods is included in a solver library. The visualisation of the virtual world is based on the use of 3D-format graphics. A controls interface enables the use of several commercial I/O-boards with reasonable amount of work and offers a systematic way to connect different types of I/O-devices. The modification of devices can be done via XML-based input file. An XML-based input file is also utilised with dynamics models. Bodies, joints and forces, as well as some basic force components, such as tyres and motors can be described in an input file. In addition, the graphical properties (of the virtual world) are formed using XML-based components. The connection between I/O-devices and force and joint primitives is described in the same file.

The rapid change in people's work and ways of interaction with their environment has highlighted the criteria of good design, e.g. the functionality and safety of the products and environments and also the usability and ease of use. Awareness and comprehension of various factors influencing a human are essential because of their strong influence on product design.

The operating environment facilitates interaction of a task between human and machine. Thus it is a necessity to comprehend and investigate not only the efficiency, performance, and comfort of an operating environment, but it also becomes necessary to identify weaknesses, lacks, errors or contradictions between human, machine and job. Safety, human factors, indoor conditions and physical and communicative interfaces are potential target issues in human machine system level simulation, evaluation and development. Thus, future machine design should be based on technology centred design as well as on human centred design.

Tools to analyse the user friendliness of the different plans and to discover where more attention should be paid are critical. Two different human models were selected and developed for this purpose: the kinematic human model OSKU and the kinetic human model HEMMO. OSKU is a kinematic simulation tool for easy work task design and analysis. In kinematic simulation of human posture, such aspects as visual range can be analysed without taking dynamic forces into account. Motions are described by choosing pre-recorded motion clips from a list. OSKU calculates automatically postures and motion paths which comply with the given boundary conditions. This tool is suited to conceptual design of the operator's work place and operational work tasks. HEMMO helps to virtually test effects of machine design and parameters on a human operator, and to ease the analysis of the dynamic interaction between the machine and the human operator. The development of HEMMO has been focused on improving the reliability and the usability of the human model, to improve the automated parameter tuning for different sized human models, to find ways to include the stochastic human behaviour into the virtual simulations and to test different ways to describe muscular action. To tune and verify the human model, laboratory measurements were performed on a motion platform.

Increasing demand for more accurate and reliable computer simulation requires reliable models. In order to create reliable mathematical models for numerical shock and vibration simulation the dynamic properties of the used parts and components have to be well known. However, well-defined models for mechanical components with strong non-linear dynamic properties and high level damping are not often available.

In the presented work a practical process of determining dynamic properties of components for simulation work was developed. Research cases studied shock and vibration isolators, vehicle tyres, joint and material properties. Laboratory and field test results were used to characterise the dynamic properties and to verify the developed simulation models. Computer codes producing tyre models for simulation purposes were compared. As a framework for the component model development the use of modular design approach was discussed.

Although many questions were answered and new results were obtained there is still room for improvement. However, the developed approach, a process for determining the dynamic properties of components, was found to be flexible and suitable for real life design and product development work. As a result of the conducted research work there is now available a networked component model development process. These facilities may be used for various electronic equipment, machine and building applications. Simplified component modelling processes may be developed for individual manufacturers' practical needs. Finally, the obtained vision for further development is quite clear: the conducted work seems to have been on the right track and this was supported by the heightened international interest in the results. In future, the developed type of capabilities might provide a high technology advantage for efficient simulation and product development work needed in the competitive international markets.

The multi-body system simulation approach was applied to fault diagnosis of the reel. The reeling sequence follows calendaring at the end of the papermaking process. The simulation model consisted of mechanical, electrical and hydraulic subsystems that were coupled together. Three abnormal operation conditions of the reel were simulated using off-line simulation: excessive friction on the rails, leakage in the servo valve and noise in the force sensor signal. In simulations conducted with the real-time simulation model, excessive friction cases were considered.

Condition monitoring and diagnosis were seen as important tasks in controlling machine reliability and operability. Sensors which measured such conditions as strain, pressure from the hydraulics, and control currents were used to provide essential data for the development of an automatic fault recognition and classification system. Unsupervised Kohonen self-organizing maps (SOM) were used. The SOM employed managed to classify all the test configurations in the appropriate categories. However, the training must be done with care, or problems in the classification may appear. For example, changing the map size confuses different classes.

In the case of the reel, a failure risk analysis flow chart with analysis methods was developed. Short measurement is not as reliable as longer one and the variance of the measurement should not be ignored. The distribution of the fitted data can be narrower after long term data collection. In most cases, the service load spectra for a component or structure are probabilistic rather than deterministic. Therefore, statistical analysis is often required to obtain the stress distribution. In addition, the fatigue strength of the component or structure has a statistic distribution due to the many sources of variability.

Hence the loading information during the reeling was seen as essential from the operation reliability point of view. A cumulative stress factor method was developed to further process the maximum and mean load class counts stored into the measured rain flow matrices. The measurement results and simulated responses can be evaluated in parallel to each other, giving more depth to the monitoring and analysis activities.

To control safety and reliability in product design, applications of probability-based design methods and methods to control various uncertainties are needed. With these methods, the failure mechanisms and faults affecting reliability can be taken into account in the early stages of product design. Degradation results from a variety of degradation mechanisms, physical or chemical processes such as wear, fatigue, cracking, embrittlement, erosion, corrosion and oxidation. These degradation mechanisms act on components due to environmental loads, such temperature changes, pressure, radiation, reactive chemicals and synergistic effects. Various degradation mechanisms may also act simultaneously, like for example fatigue and creep. Due to the stochastic nature of many of the properties or phenomena, probabilistic modelling methods are deemed suitable for the degradation analyses. In general, the nature of degradation models of structural components can be deterministic, probabilistic or a combination of these two types. An important example of a combined approach is probabilistic fracture mechanics (PFM), in which one or more of the physical model parameters are considered to be random. The features of a manufactured product are always uncertain to some extent, due to manufacturing tolerances, material property variations, in-service degradation, and so on. The design process for new products should include tools for the control of various uncertainties.

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Title

Simulation-based design process of smart machines

Abstract

This publication is intended to serve as a key to the results of the research project ‘Simulation-based design process of smart machines’. The basic idea of the project was that the simultaneous design of different technical processes is inevitable in order to develop modern, optimized products. The project had three principal themes: simulation-based design, control of machine reliability and operability and the interaction between these two.

The project included development of simulation-based design process and especially applying computer simulation tools and methods on it, and actual modeling and simulation related practices in managing complex sub-models as well as an overall system simulation model base. Methods and tools were developed for the use of real-time simulators and virtual technologies in the product development process, condition monitoring, operator training and determination of a customer's needs regarding new procedures and products. Practical process of determining dynamic properties of components for simulation work was developed. This study aims to enhanced simulation model also with adequate methods and tools focused on interactive human machine system.

A new concept for model and simulation based machine operability and reliability was studied. This publication represents also methods for reliability analysis, real time simulation applications as well as load monitoring application and solutions for estimating remaining lifetime. Methods to control safety and reliability in product design, applications of probability-based design methods and methods to control various uncertainties were studied.

Keywords
smart machines, machine design, simulation, modelling, sub-systems, real-time simulation, man-machine systems, erconomics, dynamic properties, shock and vibration isolators, condition monitoring, risk analysis, reliability

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