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Customer: TEKES/SMART

VIBRATION RESPONSE OF AN ELECTRIC GENERATOR

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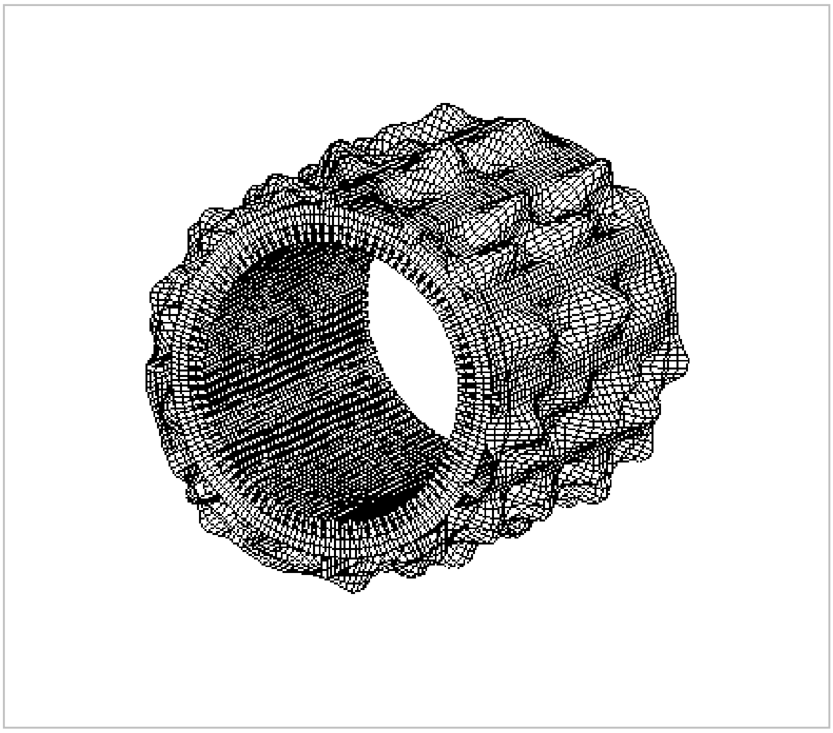

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VIBRATION RESPONSE OF AN ELECTRIC GENERATOR

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Summary

The vibration response of an electric generator was calculated starting from the electromagnetic forces and also its noise emission was assessed. The whole chain electromagnetic forces - stator core - stator frame - air has been considered and it has shown, how vibration and noise emission of an electric generator can be reduced with the help of mechanical modelling and calculation.

For practical use the response calculation was too slow. This is due to the huge number of simultaneous excitations and how Ideas, the calculation program, manipulates them. However, this problem can be overcome doing the mode superpositioning with a better, commercial or self-made, program.

The coupling of the stator and the stator frame is crucial for the correctness of the results. The frame has a lot of local natural modes in the interesting frequency range. On the other hand, the material parameters of the stator packet are somewhat uncertain. The sensitivity of the coupling was not studied in this project, but it is possible that a small change in the material parameters cause the stator packet and the frame to couple differently. This phenomenon should be studied further.

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1 Introduction

This report is part of TEKES supported SMART technology programme. It focuses on the mechatronic systems. One of its research projects is MASI (Modelling and Simulation of Multitechnological Mechatronic Systems), which is divided into five subprojects. The subproject called MAGEN considers the noise produced by a synchronous electric generator powered by a diesel engine.

The usual sound sources of an electrical machine are the fan, the bearings and the sound radiation from the surface. The last one is the most important source of noise for electrical machines with six or more poles. This noise is usually found in the frequency range 0.5 - 3 kHz.

In an electric generator the magnetic field produces the circumferential forces required for the energy transfer. In addition, the field creates radial forces. These forces interact with the stator and excite it. The stator is in contact with the frame, which also is excited. The vibration of the frame accelerates the surrounding air, which is heard as noise. To avoid excessive noise the designer of the generators needs methods to calculate the vibration and noise emission levels.

In this paper it is shown how to calculate the vibration response and the noise emission of an electric generator starting from the electromagnetic forces.

2 Electric generator

The main components of an electric generator are the stator, the rotor and the frame (Figure 2 and Figure 3). The energy is transmitted from the rotor over the air gap to the stator by the electromagnetic field. Electrical currents flowing in windings in the stator slots and on the rotor poles produce the magnetic field.

A stator core is manufactured by piling up 0.5 mm thick insulated steel sheet stampings. Thin steel sheet is used to prevent eddy current losses. The stampings are assembled perpendicular to the shaft. They have cuttings that form slot holes for copper windings. There are also air channels in the stator core for cooling. They are formed by leaving about 1 cm gaps between the stampings at every few cm. Radial flat steel bars keep the air channels open. Longitudinal beams are welded on the outside to hold the core packet together. (The stator in Figure 3 is of different type, which does not include air ducts or longitudinal beams. Figure 6 clarifies the construction.) The stator core is completed be immersing it into hot liquid resin.

The rotor poles are made of somewhat thicker steel sheets, typically 2 mm thick. The poles are fixed on a solid steel shaft. The copper rotor winding is made on the pole sides.

The stator frame is a coaxial cylindrical shell made of steel. It is connected to the stator core with longitudinal beams, which are welded to the stator core and the shell. This kind of frame forms air ducts for cooling the stator and keeps the stator packet together.

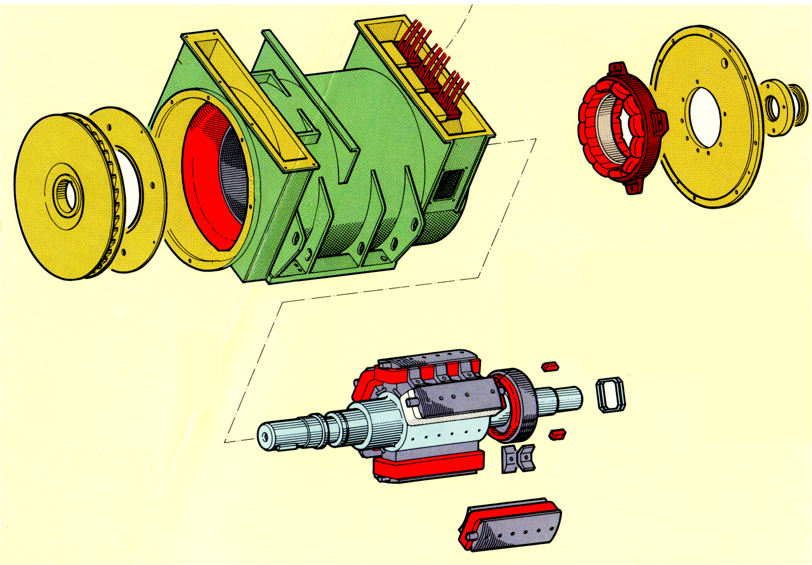

Figure 2. Components of a electric generator

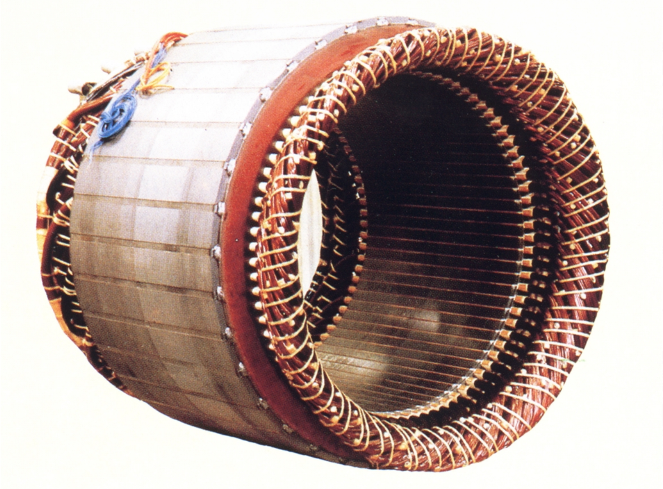

Figure 3. A stator, the core and the copper windings

3 Magnetic forces

The magnetic field produces the circumferential forces required for the energy transfer. However, it also produces radial forces. The radial forces mainly cancel themselves out, but due to small asymmetries in the construction they may excite vibrations. The magnetic field is usually calculated in 2D. This is a relatively good approximation, since the air-gap is very small compared to the other dimensions of the generator. Another simplification that is usually made is to neglect the interaction between the magnetic field and the mechanical deformation. At higher frequencies where noise is mainly emitted the interaction is considered small. Because of this assumption, the magnetic forces can be treated like any external forces in mechanical calculations.

The magnetic field and forces are calculated by stepping in time. Conventionally the calculated magnetic forces are presented as a Fourier series with two parameters, polar angle and time (Figure 4). Commercial mechanical analysis programs do not understand this form. They want the force data at a specific point on structure as a function of frequency or time.

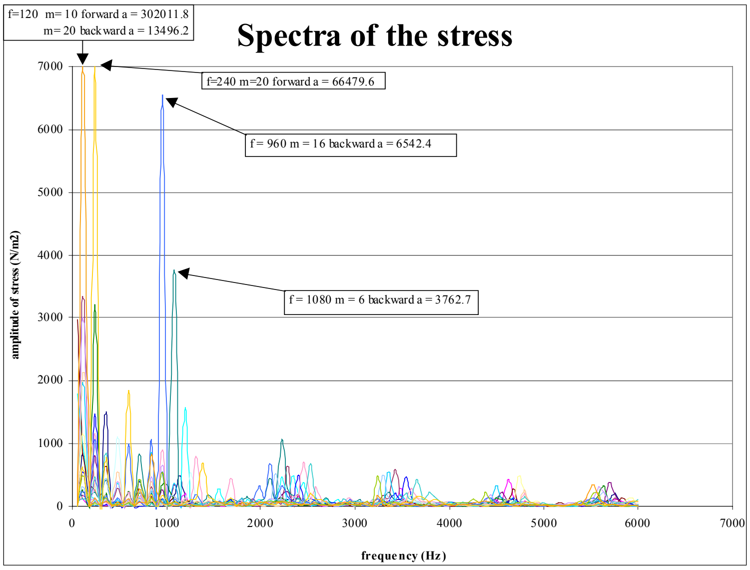

Figure 4. A double Fourier series presentation of magnetic forces

In harmonic response calculations a rotating force wave can be expressed as forces with phase differences. In Figure 5 the magnetic forces are shown at a time step. It shows how the magnetic forces concentrate at the tips of the stator teeth. The finite element mesh for the magnetic field calculations needs to be dense near the air-gap, much denser than the mechanical element mesh of the stator.

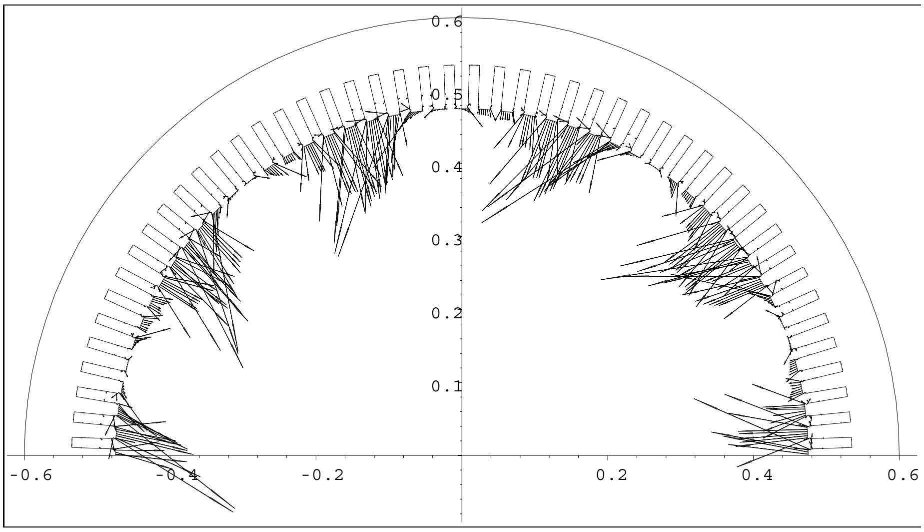

Figure 5. Magnetic forces at a time step

In this project the following was considered the best way to transfer the calculated magnetic force data to the mechanical model.

- At every time step
  - The radial and tangential forces for every tooth are summed separately.
  - Also the twisting moment of the forces is calculated around the root of the tooth for every tooth.
- The complex Fourier transformation is done on the data.

The result is the complex harmonic components for every tooth in radial and tangential direction as well as for the twisting moment. For response calculations this data is expanded to the nodes of the finite element model (see Chapter 6).

4 Material model of the stator

It is impossible to model the stampings and their interaction exactly, therefore some kind of idealised model must be used. The most straightforward method is to model the stator geometry correctly and use an equivalent material model. Because of the structure of the stator core the material model is orthogonal so, that the cross-section is isotropic, but in the axial direction material properties are different.

The stator is not composed of only the steel stampings, but also of copper windings (Figure 3). The windings are even more difficult to model than the stator core. However, they form a considerable part of the mass of the stator. If the generator is a part of a larger device, leaving out the mass of the windings may cause errors. That is why it was taken into account in the density of the stator core.

Measured data is needed for determining the material parameters for the described equivalent material model. This has been done in report BVAL35-001082 for a stator core of the same type.

Structural damping is another difficult material parameter with the stator, which should be determined by measurements. Since better data was not available, 2 % proportional damping was used in the response calculation.

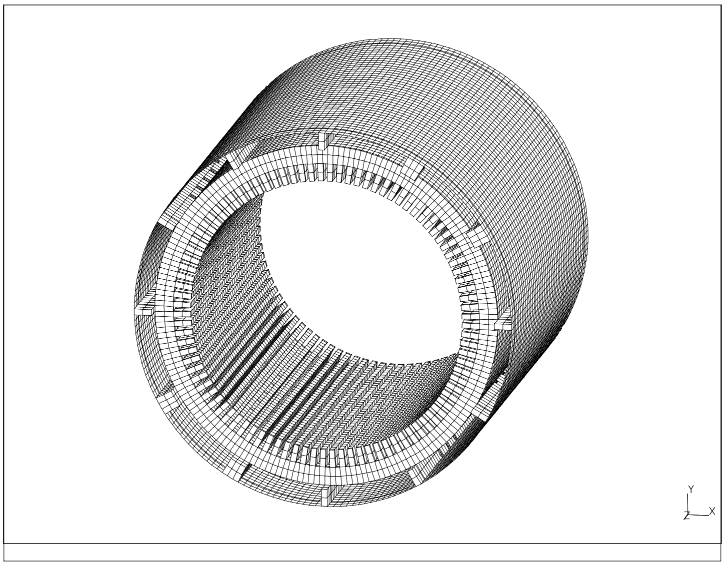

Figure 6. The finite element model of the stator

5 Finite element model

The magnetic forces are practically always calculated in 2D. However, 2D model cannot be used in the mechanical calculations. This is because the mechanical boundary conditions effect much more to the natural modes and frequencies of the stator. Another important reason is the complex 3D behaviour of the stator frame, which can not be taken into account with a 2D model.

In this project the stator core was modelled geometrically correctly with solid elements. The longitudinal beams were also modelled with solid elements and the frame was modelled with shell elements. The size of the elements was chosen so, that natural modes near 1000 Hz could be correctly determined. The finite element model is shown in Figure 6.

The material model determined in report BVAL35-001082 was used with the stator core. The other parts are made of steel.

There are problems with this kind of element model, when natural modes at high frequencies are calculated. The thin cylindrical shell of the stator frame will have more and more local natural modes (Figure 7) the higher the calculation frequency is. Also the teeth of the stator will have local natural modes. Since there are many teeth and they all have the same natural frequencies, it would be difficult to go above the first tooth frequency. However, it is not necessarily a realistic phenomenon, since the windings are modelled only as mass. If the calculation frequency range includes the tooth frequencies, the modelling of the windings should be considered.

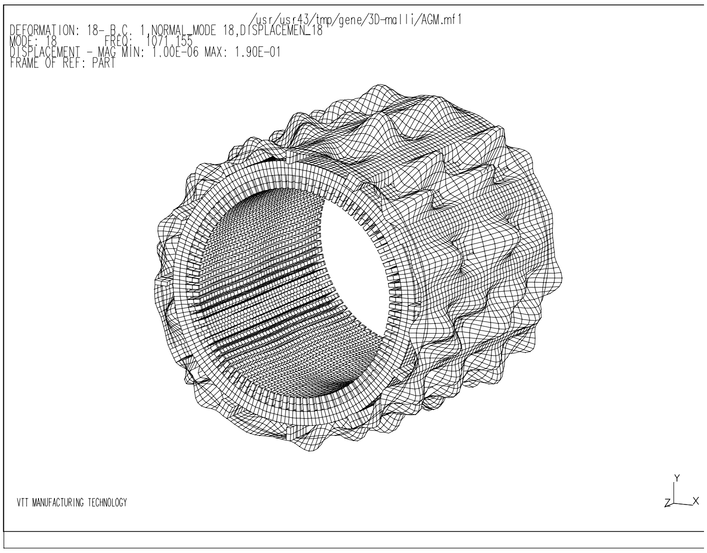

Figure 7. A local natural mode of the stator frame

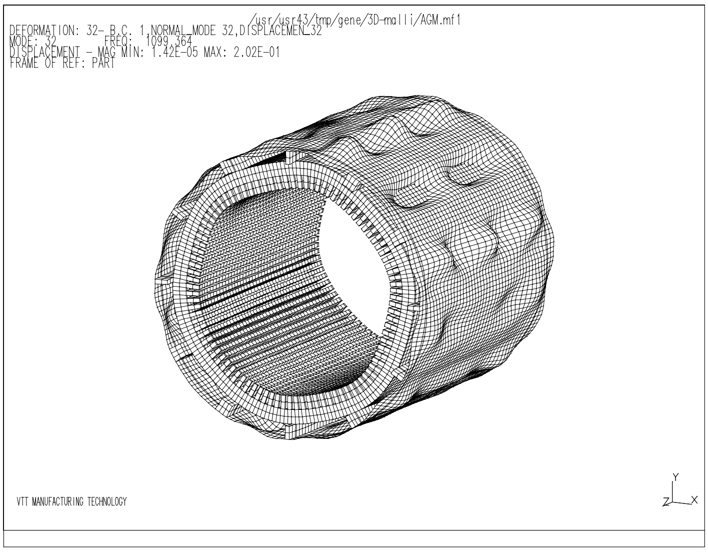

Figure 8. A tube like natural mode of the stator

6 Mechanical response

The mode superposition method is usually used in response calculations. That is the response is calculated as a linear combination of the calculated natural modes. Usually also the damping is given as a modal parameter. In this case 2 % equivalent viscous damping ratio was given to every natural mode.

The magnetic forces are calculated in 2D, because the force distribution in the axial direction is assumed constant. Thus the 2D forces are applied at all node layers along the length of the stator. In the 3D model there are thousands of nodes at the tooth tips and the magnetic forces act on every one. It is far too time consuming to feed in that much data manually. In the project a Matlab program was created, which transforms the magnetic tooth force data into an Ideas program file.

The program reads the complex harmonic components calculated from the magnetic forces as described in chapter 3. For every tooth the forces at the head and the root of the tooth are calculated so that sum of the forces and the twisting moment are correct. These forces are then distributed to the nodes at the head and the root of the tooth.

Altogether the magnetic forces resulted 33000 excitations. This huge number of simultaneous excitations caused problems with Ideas. It read the excitations very slowly and could not calculate the response for all excitations at the same time. By dividing the excitations into four sets and calculating them separately the response calculation finally succeeded, but the four results had to be combined afterwards. Also the response calculation was very slow. Ideas obviously calculates the equivalent forces at every calculation frequency even for constant excitation. With another way organised program the response calculation would have been much faster.

There are a lot of natural modes, because of the local modes of the stator frame (Figure 7). However, due to the constant force distribution in the longitudinal direction only the lowest tube like modes of the stator (Figure 8) are excited strongly and dominate the response. The response of the frame depends on its coupling with the stator. The response on the frame shell can be manifold compared to the core.

The calculated response of the stator and the stator frame is shown in Figure 9. The response is shown on the maximum amplitude point of the frame. It is on the top in the middle (see Figure 8). The results compare quite well with the measurements.

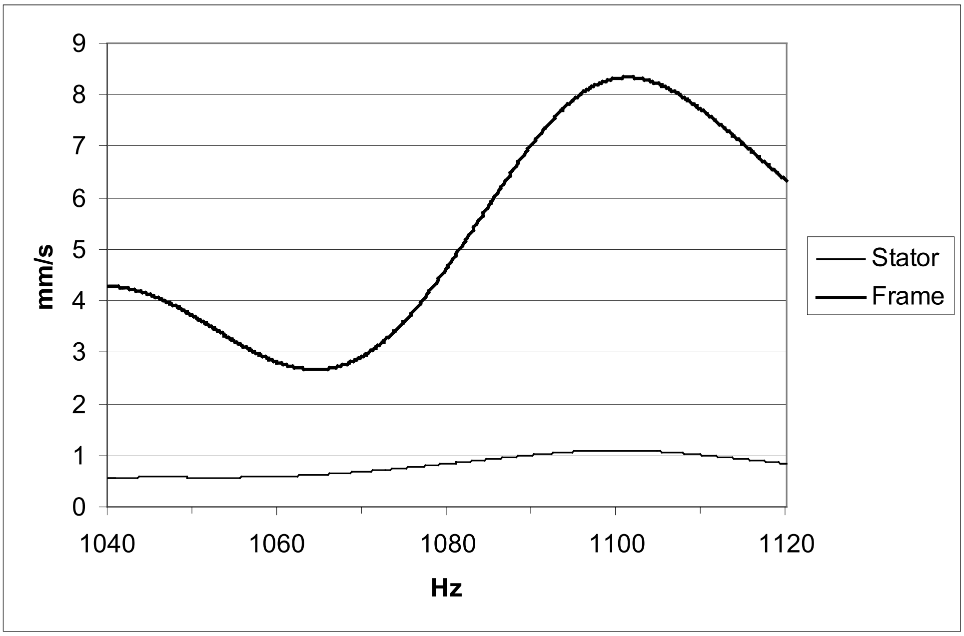

Figure 9. The calculated velocity amplitude of the stator and the stator frame on the maximum response point of the frame

7 Sound radiation

The usual sound sources of an electrical machine are the fan, the bearings and the sound radiation from the surface. Only the last one is excited by the electromagnetic excitation. It is also the most important source of noise for electrical machines with six or more poles.

Nowadays two powerful numerical methods are available for calculating the radiated sound, the finite element method (FEM) and the boundary element method (BEM). BEM is more suitable for pure sound radiation calculations. However, it is not necessary to calculate the sound pressure to assess the radiated sound power of the stator frame.

When the radiated sound power of a substructure is assessed by measurements, the following formula is used.

$$P = \rho c \sigma A \langle v^2 \rangle \tag{1}$$

ρ is the density of air, c is the speed of sound in air, σ is the radiation index, A is the surface area and $\langle v^2 \rangle$ is the mean square velocity averaged over surface and time. By calculating the response at some representative points and applying this formula the radiated sound power of the stator frame can be estimated.

The radiation index σ is an important factor in the formula. Approximate ways to calculate it can be found in literature. It is frequency dependent and takes into account the coincidence. Basically it is a resonant situation where the wave on the structure and the sound wave in the air have same length and speed. However, it is possible to compare similarly dimensioned constructions even without the radiation index, since their indices should be about the same.

In Figure 10 the radiating sound power of the calculated stator is shown. The sound power was calculated with the above formula. Because of the slowness of the response calculation only eight response points was used and the radiation index was not used. Thus the result may not be quite representative, but it shows that the radiated sound power can be assess without calculating the sound pressure in the farfield.

Figure 10. The calculated radiating sound power of an electric generator.

8 Conclusions

The vibration response of an electric generator was calculated starting from the electromagnetic forces and also its noise emission was assessed. The whole chain electromagnetic forces - stator core - stator frame - air has been considered and it has shown, how vibration and noise emission of an electric generator can be reduced with the help of mechanical modelling and calculation.

For practical use the response calculation was too slow. This is due to the huge number of simultaneous excitations and how Ideas, the calculation program, manipulates them. However, this problem can be overcome doing the mode superpositioning with a better, commercial or self-made, program.

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