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Virtual Engine and Ventilation Noise Generation for an Underground Loader Cabin

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Abstract

We have developed a Virtual Reality model for an Underground Loader for mines. One important part of the model is the Audio Rendering Subsystem for real-time noise generation. It replicates the sounds which are audible in the loader cabin. Audio Rendering Subsystem is built around the Audible Model Platform, which consists of engine noise and ventilation noise parts. Engine noise is re-constructed from the engine orders and engine broadband noise. The ventilation noise is generated based on the calculated air flow patterns within the cabin. The cabin noise is generated by the model has been compared to binaural recordings in the real operating conditions and have found to be representative. Future development steps include taking account the separately-driven cooling fans and the effects of the torque converter to the audible noise.

Introduction and motivation

Effective audio is a key to building a convincing Virtual Reality (VR) experience [1,2]. In Virtual Environments (VE), sound events and acoustics [3,4] are simulated to sufficient accuracy to create an immersive experience while not placing excessive demands on system resources. The most important requirement is real-time and concurrent operation of the audio simulator and visualization to preserve the illusion of immersion. Visualization events must be tightly synchronized with the auralized [3,5] environment. Sounds can be created in the VEs in various ways. A common practice is to play back recorded noise signals. At the other end of the spectrum, audible models are being developed to generate sound and noise based on parameters such as tonal component levels, frequencies, relative phases, broadband noise frequency content, and modulation [6]. Such models offer the potential to create virtual audio experiences and are therefore a focus area of current research.

The modeling target

We developed a VR model for a Sandvik LH410 (formerly Toro 7) Underground Loader for mines, officially Loading and Hauling Device, LHD, also seen in Figure 1 [7]. The model consists of VR software, Dynamics Solver unit, Motion Platform, and Audio Rendering Subsystem. With the model it is possible to virtually drive the LHD in a mine and do the tasks related to the real work cycle.

Figure 1: Sandvik LH410 (formerlyToro 7) Loading and Hauling Device, LHD. Photograph courtesy of Sandvik [8]**.**

Noise sources in LHD and their characterization

There are several noise sources inside the LHD cabin. The most important noise sources are shown in Figure 2. The most prominent noise is the engine noise. Related to the engine noise are noises from the hydraulics and the transmission. The transmission is connected to the engine via a continuously-variable moment converter, which makes the engine-transmission ratio variable. Ventilation noise can also be significant especially at the maximum position, and it is manually controlled. The engine cooling noise is controlled independently, and its effect is determined by and independent control system driven by the engine temperature and other engine parameters. Additionally, there is also noise from the work cycle.

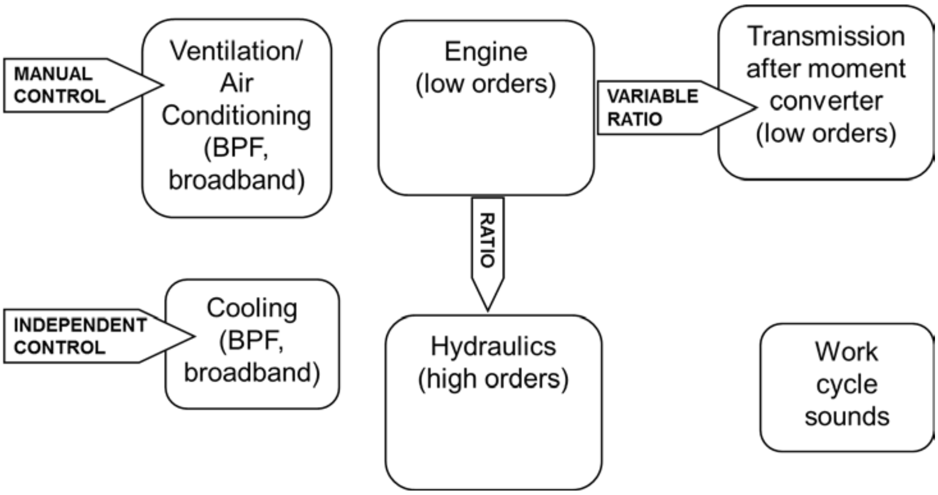

Figure 2: LHD noise sources.

All these noise sources and their relevant parameters were captured. The acquired data contained the artificial head binaural audio recordings in the cabin (Figure 3), recordings outside the cabin for the reference, tacho pulses related to the engine rpm, tacho pulses after a moment converter, RPM of the engine cooling fan and engine load information. All data acquisition was done in the time dome to make it possible to process the data and extract also dynamic parameters as well as possible.

Figure 3: Binaural recording setup inside the LHD cabin.

From measurements to parameters

Measurements made in the LHD cabin were processed for the noise model. The process of extracting the order magnitudes and relative phases in function of RPM and load was automated. First, the recorded audio data was analyzed using spectrogram which gives a general idea of different noise components. A spectrogram of the audio recording is shown in Figure 4. The cabin noise consists of different noise components, including engine, hydraulics, cooling and ventilation. Noise from engine, hydraulics and cooling is periodic.

For the model, the dominant periodic components of each source were selected. Engine noise contains 6 dominant components with frequencies varying between 20 Hz and 300 Hz. Hydraulics has 3 dominant components at 300 Hz - 600 Hz. For cooling, 2 components are selected with constant frequencies around 200 Hz and 500 Hz. The cabin noise has also a broadband component having energy at low frequencies below 250 Hz. Ventilation also produces broadband noise.

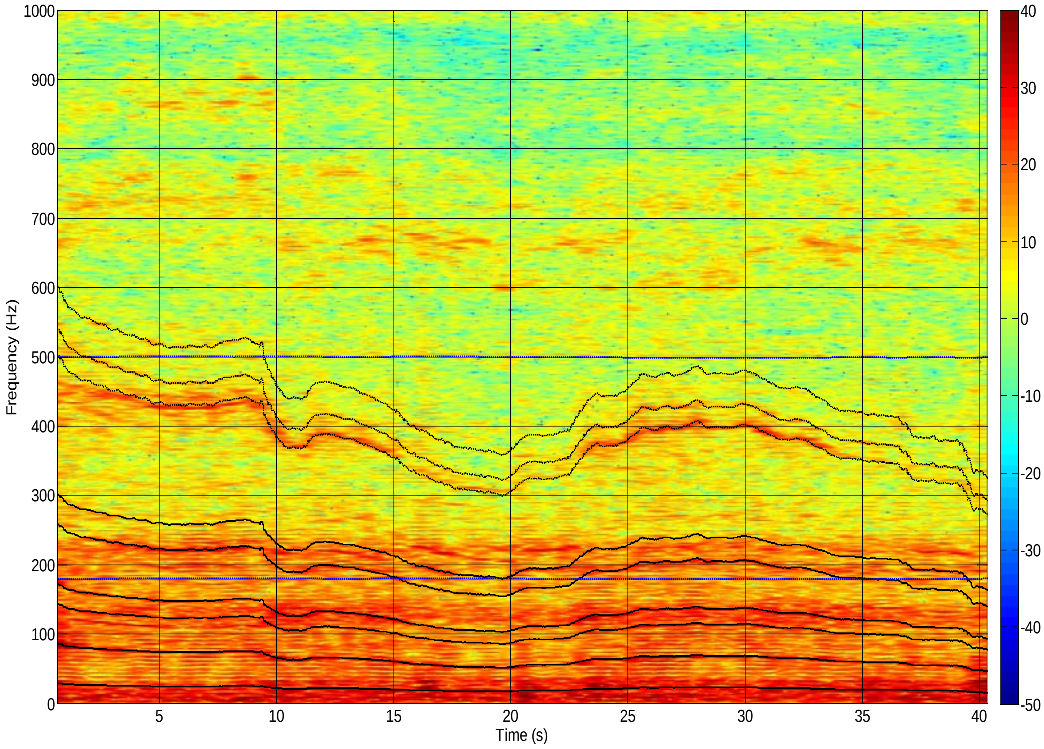

Figure 4: Spectrogram of the audio recording.

The frequencies of the engine noise components depend on the engine RPM, which can be obtained from the measured tacho pulses. An advanced filtering method is required to extract the components from the data. An RPM-locked bandpass filtering based on Vold-Kalman algorithm was used for extracting the amplitudes and phase angles of the engine noise components, as suggested by Brandt et.al. [9]. The hydraulics noise components were processed in the same way, with the exception that the frequencies are related to the RPM of the moment converter. In the recording, the cooling noise has a constant rotation speed. Therefore, constant amplitudes and phase angles can be used for modeling the cooling noise. The broadband noise component was approximated with pink noise.

Finally, the amplitude and phase angle values were stored in lookup tables. For the engine and hydraulics noise, the values depend on RPM and load. The amplitude and phase angle values were used in the model to produce periodic noise having the desired properties.

Audio Rendering and Audible Model Platform

In the VEs, the sound events and acoustics must be simulated with a sufficient accuracy. The most important requirement is the real-time operation to preserve the illusion of immersion. The sound events are generated in the sound creation block, and they are put in the proper places in the VE model in the sound localization block. The 5.1 loudspeaker system has been the main source of the sound, and the panned sound within these loudspeakers may be transformed into a suitable form for headphones as well. The audio subsystem gets its input from the virtual reality software.

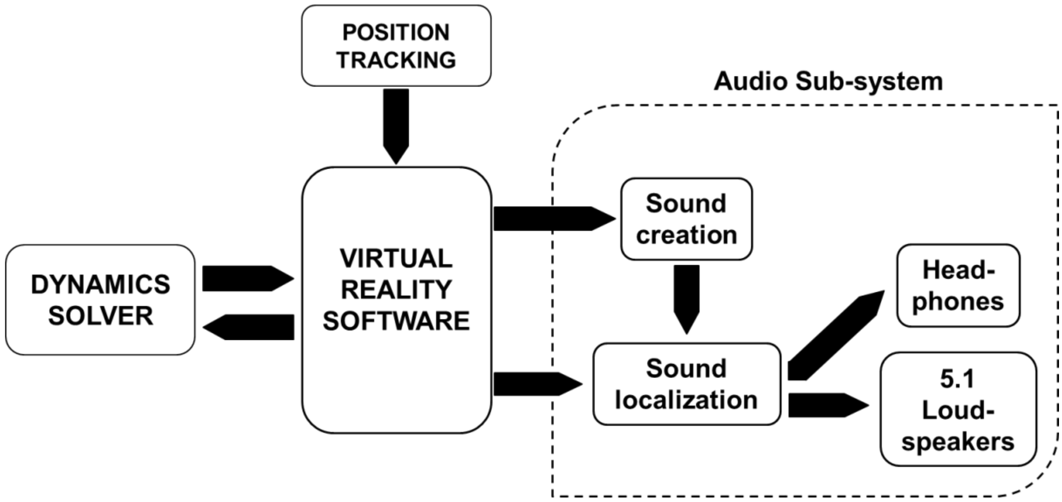

Figure 5: A modular sound generation system for virtual reality.

The Audio Rendering Subsystem is a separate unit whose operation is synchronized to main VR system via User Datagram Protocol (UDP) [10] network protocol, as illustrated in Figure 5. It replicates the sounds which are audible in the LHD cabin. Such sounds include engine, hydraulics, cooling, and ventilation noises. A real-time model is built within the Audio Rendering Subsystem by using Audible Model Platform (AMP). Simulator producing audio exist [11], but our approach is unique in two ways: it is mainly targeted for the moving machinery, and it may be connected to a larger VR system in real time.

AMP is a parameter-based, real-time sound and noise generation platform. The AMP is not directly based on the structural or mechanical physics of noise generating equipment. The noise model may include parameters such as angular velocity (RPM), load, listening position and other relevant factors. The AMP is currently used for cabin noise modeling, as well as for fixed engine applications and outdoor noise applications, most recently for noise modeling of wind turbines.

AMP noise profile parameters include engine and other rotating mechanical system acoustical order structure, levels and phases, as well as, similar parameters for auxiliary mechanical systems, such as cooling, turbo and hydraulics. Furthermore, broadband noise is parameterized whenever applicable, and otherwise modeled based on a steady-state empirical model. Due to the parameter-based design, changes in parameters also cause real-time changes in the rendered audio.

The noise profile parameters can be extracted from the measurements or numerical models. AMP also visualizes engine orders and generated noise, and the visualization parameters can be sent back to the VE. Each order contribution is visualized in real time, as well as the overall noise spectrum. Individual narrowband or broadband components can be turned on and off to evaluate their noise contribution.

The acoustical environment that is reproduced by the acoustic sub-system is realistic enough that the immersion sensation can be achieved for the user. A detailed diagram of the audio sub-system is shown in Figure 6. The engine and air conditioning (ventilation) noise model creates the related sounds for given engine RPM values. The important properties include the time, speed- and load-related engine order structures, broadband components, and air conditioning noise properties.

The model is based on the parameters of the real engine and air conditioning noise, and the actual sound events are re-created based on the parameters. The process to get the data for the engine model includes obtaining recorded or simulated noise, extracting the engine noise and possibly air conditioning noise parameters, and converting these parameters into a suitable format to drive the engine model. This approach provides flexibility and smooth operation. On the other hand, it also requires substantial calculation power and a good knowledge of existing or virtual engine sounds and their properties.

In the model the main sources of noise are engine orders, hydraulics orders, engine broadband noise and ventilation noise. All of these are affected by various parameters coming from external VE source, such as dynamics solver. The noise level and sound quality parameters are also calculated and are available in the model or as outputs to VR software. The engine cooling noise, noises from the work cycle and noise after the moment converter were not re-created. Work cycle noise was pre-recorded and played back with the main VR system.

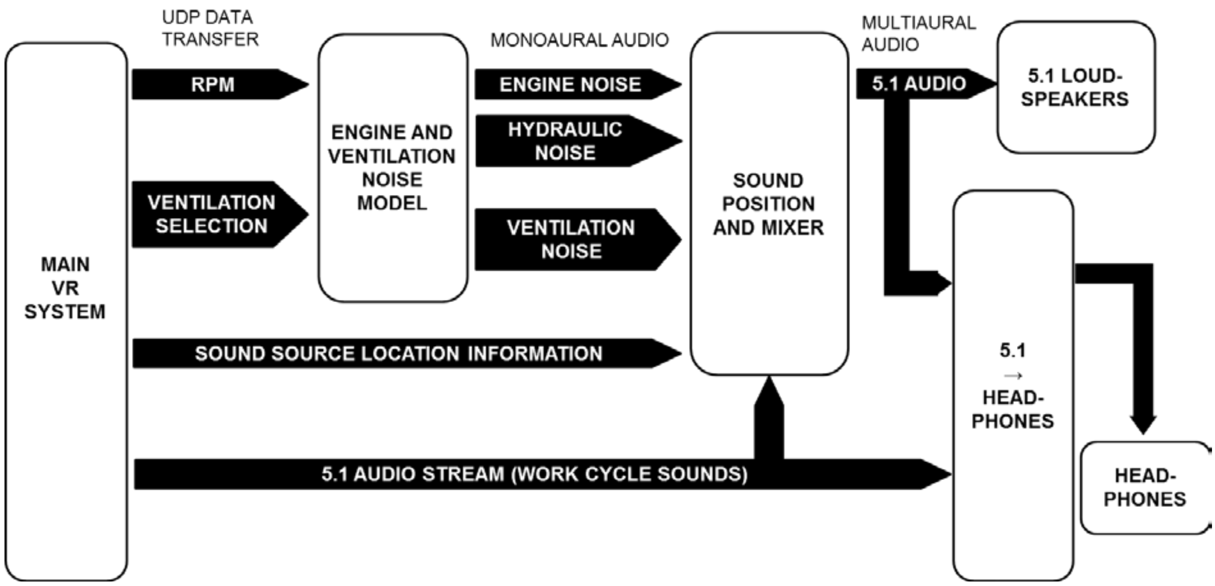

Figure 6: Audible Model Platform (AMP) for the LHD cabin noise model. The sources of noise are engine orders, hydraulics orders, engine broadband noise and ventilation noise.

Implementation of LHD cabin noise model

The loader cabin noise model was implemented in Simulink using AMP. The model is shown in Figure 7. It contains the different noise sources, including engine, hydraulics, cooling and ventilation. The engine RPM and load may be set manually, using a joystick or via UDP from a virtual reality environment.

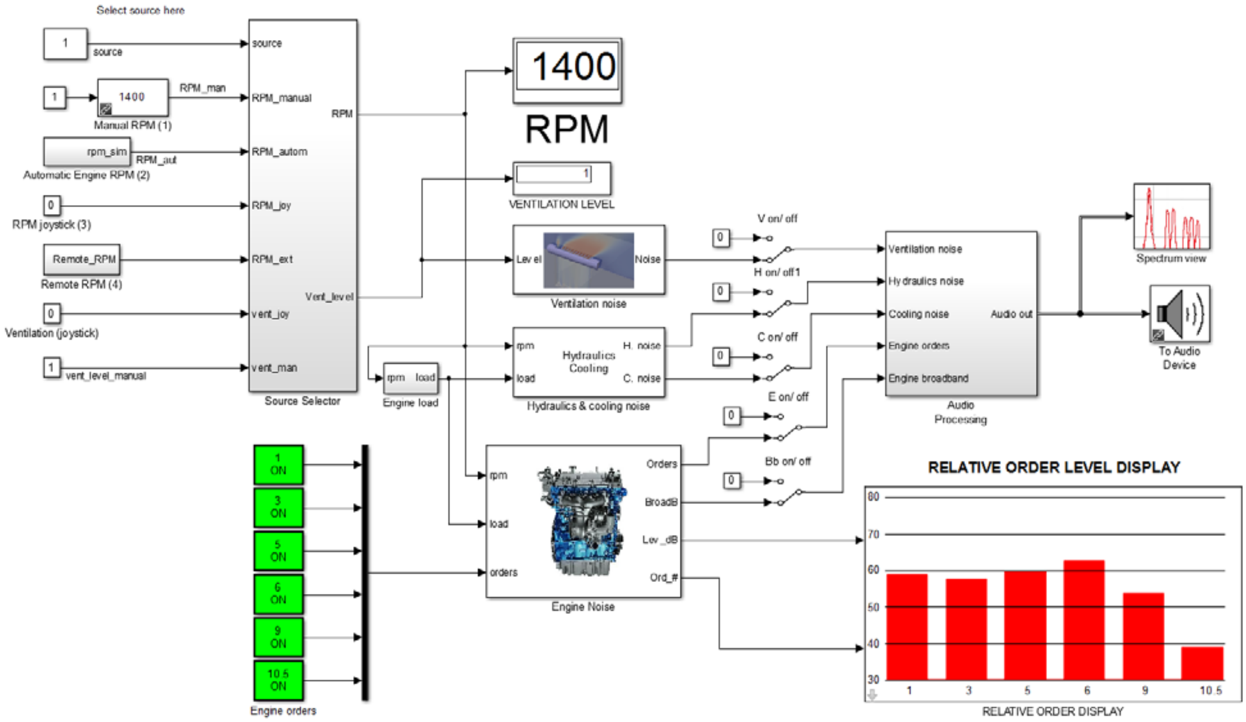

Figure 7: AMP-based simulation model realization for LHD cabin noise.

In the model, each noise source can be switched on or off. This enables listening to a subset of sources or even one of them. Furthermore, the engine sound can be modified by switching off some of the engine orders. Similar modification can be done for hydraulics and cooling noise, as it also consists of harmonic components. The flow speed of ventilation has three levels including minimum, half-speed and maximum. Ventilation level setting has also an effect on the overall noise.

Engine and hydraulics noise rendering

The periodic noise sources are modeled as a series of sine wave generators, each generator for a respective engine order. For each source, the amplitudes and phase angles are read from corresponding lookup tables. Broadband noise is generated by low-pass filtering of white noise. Due to the dynamic nature of the model, when the engine speed and other parameters vary continuously, the quality of the reproduced sound was an important factor also during the transients in these driving parameters. Glitches and other artifacts are easily generated if the quality and tracking of the software signal generators are not good.

Ventilation noise rendering

The ventilation noise was re-generated according to the Computational Fluid Dynamics (CFD) calculated air flow at the ventilation outlets. The LHD cabin was divided into a grid of small computation or control volumes over which the Navier-Stokes equations were solved numerically, resulting in 3D data for the flow field. With this data the flow speed and pressure loss at the ventilation orifice are calculated. Using the calculated values, an approximation of the acoustic power of the ventilation noise, L_w, can be obtained [12].

The ventilation noise was reproduced and simultaneously visualized in the VR model. The flow patterns and noise contribution were calculated for each setting position of the ventilation level selection.

Ventilation noise is generated by filtering white noise with a bandpass filter. Since the ventilation noise spectrum depends on the flow speed setting (minimum, half-speed or maximum), a different bandpass filter is used with each setting. The filters are obtained by fitting the magnitude response of the filter to the approximated L_w curve. In Figure 8, the original L_w curves and the fitted bandpass filters are shown.

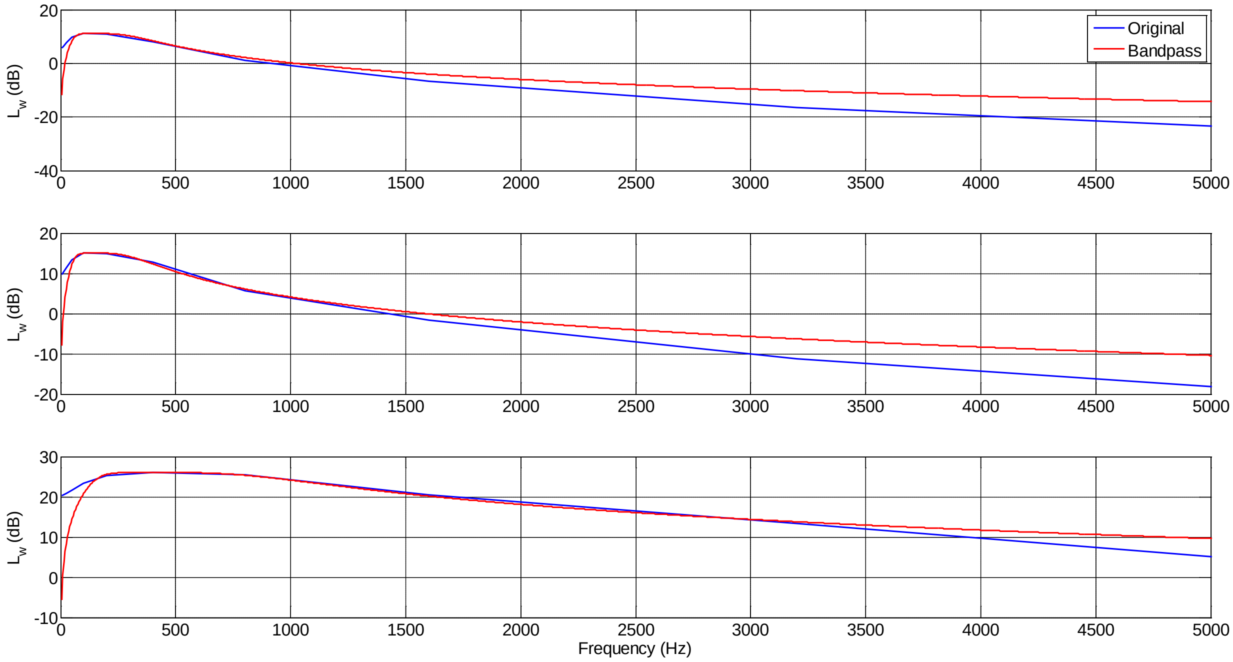

Figure 8: Ventilation noise spectra for minimum flow speed (up), half speed (center) and maximum flow speed (low).

The LHD cabin noise generated by the model was compared to binaural recordings in the real operating conditions and was found to be representative enough to replicate the experience of the LHD cabin within the Virtual Environment.

Conclusions and future work

In general, the audible model was able to reproduce the audio for the Virtual Environment realistically, and was also able to operate in real time. Furthermore, there were no audible artifacts.

There are several improvement possibilities for the model. Many sound sources including cooling are related to the LHD control system and they are on only during the periods needed, which makes their modeling challenging. Furthermore, the torque from the engine is transmitted via torque converter, as is often case with the moving machinery. This makes the relationship of the RPM and transmission line sliding, thus making it challenging to generate the proper audible orders from the noise sources after torque converter.

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