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AURALIZATION IN A MOVING BASE DRIVING SIMULATOR AS PART OF A DIGITAL TWIN

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ABSTRACT

The Swedish National Road and Transport Research Institute (VTI) has been performing driving simulator based research since developing the first computer based advanced driving simulator during late 1970's and early 1980's. Parallel to that VTI has been developing different versions of Road Surface Tester (RST) vehicles with laser based surface measurement systems in combination with very precis positioning systems. Today the driving simulaton is on it's fourth iteration, and with a new road surface testing Mobile Research Platform (MRP) comprising high resolution laser scanning, LIDAR and other camera based systems just procured the notion to combine the measurements from the real world road area with the virtual driving simulator world has resulted in an ongoing effort to create a digital twin in the simulator environment of the real world measured by the new MRP. A part of that includes measuring the roughness of the pavement with simultaneous recording of sound, both exterior and interior, and thus determine transfer functions between road surface and interior sound environment. By implementing the transfer functions in the simulator sound model, any virtual road surface can then be implemented and experienced by the drivers. Data collection is ongoing and preliminary virtual implementations are presented here.

Keywords: driving simulator, digital twin, interior sound.

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1. INTRODUCTION

During the second half of 2024, VTI (The Swedish National Road and Transport Research Institute) received its new road surface measurement vehicle. Dubbed the "Mobile Research Platform" it comprises scanning laser interferometers, accelerometers, inclinometers, dGPS, cameras, LIDAR as well as a versatile data collection system allowing additional channels of data collection modules such as microphones for rolling noise measurements or air quality sensors. Such a complex system is likely to exhibit some initial complications before all systems are running as smoothly and robustly as needed and hence some of the first measurements were performed in the end of March and beginning of April, 2025. With this new data collection system, many aspects of both the road surface but also the surrounding road area is mapped in a detailed 3D model. This inspired the notion that the collected data could be implemented in the driving simulators at VTI as "digital twin" of the real world. A project was started in the beginning of 2025 to investigate the possibilities of implementing real world data into the driving simulators.

During development of the fourth iteration of the VTI driving simulator ecosystem, the decision was made to create a sound generator from scratch based on simple physical modeling, inspired by the vehicle dynamics model. While there exists highly advanced physical models for the tire-road interaction (see e.g. [1]), they are generally too computationally heavy to use in a real-time environment such as a driving simulator. The simple physical model sound generator is described in section 2, and this paper presents the initial efforts to enhance the physical modeling sound generator as part of this digital twin.

2. THE CURRENT SIMULATOR INTERIOR SOUND GENERATOR

Previous systems used looped samples of interior sound recordings, which meant that any update to the sound required a lot of time and money. The new system would be based on measurements, but would recreate interior sound through real-time synthesis so that parameters could be changed when necessary. A model was created based on the assumption that all interior tire/road noise was an effect of the road surface profile (see Fig. 1).

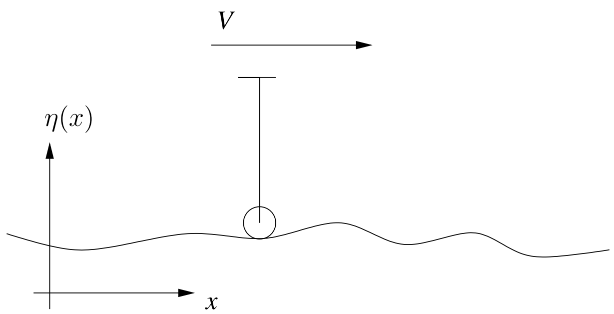

Figure 1. Simple geometry of a wheel rolling on an uneven surface profile $\eta(x)$ at speed V.

Of course a wheel does not fit into all the smallest cavities of the road surface, but as a model of how the longitudinal velocity is translated into energy input into the tire, suspension and subsequently into the cabin as sound it is reasonably valid. Fig. 2 presents the three calculation steps, where in the first step $\eta(x)$ represents the vertical displacement as function of traveled distance x. The vehicle speed V (in [m/s]) means a transformation from vertical displacement as function of distance to vertical displacement as function of time: $y(t) = \eta(V,t)$. In the second step a time derivation of $y(t)$ leads to a vertical velocity as function of time, $u(t)$. The final step transforms the vertical velocity to sound pressure inside the cabin $p(t)$ through a transfer function H.

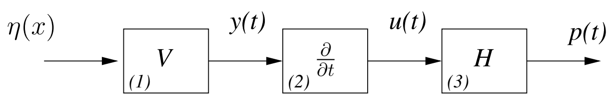

Figure 2. Calculation steps from road surface profile $\eta(x)$ to sound pressure $p(t)$.

The transfer function thus includes both airborne and structure borne transmission, as well as all the tire properties such as cavity resonances and tread pattern. A road surface profile was measured and interior sound was recorded in a car driving on the same road. It was assumed it was possible to describe the road surface using a stochastic signal and a simple first order low pass filter in order to obtain a simple enough input signal to determine the transfer function. Fig. 3 shows the one-third octave band surface roughness spectrum of the measured road, and a first order low pass filter was adapted to fit so that the cutoff corresponded to the -3 dB point of the spectrum which through the vehicle velocity in turn corresponded to a cutoff frequency. By applying the inverse of that simple first order filter to the interior sound recording, matching through the speed of the vehicle during recording, Burgs method [2] was then used to calculate a 16384 point impulse response representing the transfer function H.

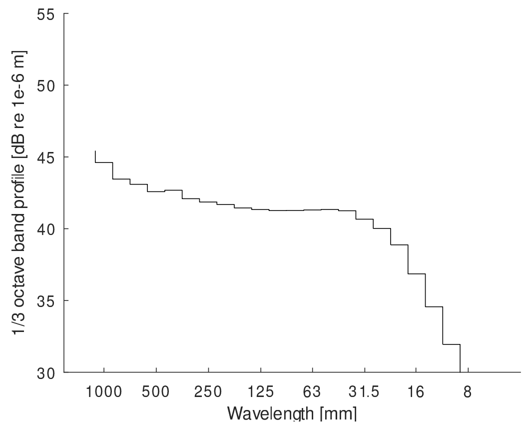

Figure 3. 1/3 octave band road surface profile.

The actual sound generation in the simulator is handled by Csound, an open source software for creating sound and music [3]. White noise is generated in real time, which is then fed through a first order low pass filter to mimic the road surface properties. The cutoff frequency of the low pass filter is continuously updated as a function of the simulated vehicle speed, so the the faster the vehicle speed, the more high-frequency content is included. As a higher vehicle speed also means an increased vertical speed due to the road surface profile, the level of the input white noise is also varied with varying speed. The resulting signal is then convolved with the calculated impulse response.

3. NEW DATA FROM THE MOBILE RESEARCH PLATFORM

Figure 4. The VTI Mobile Research Platform (top, ©Satu/VTI) with the microphone for exterior sound recording mounted close to the left rear wheel (bottom, ©Ramboll).

The new VTI Mobile Research Platform (Fig. 4) records the road surface profile, vertical chassis acceleration in different positions and external sound close to the left rear wheel. In the preliminary measurements performed recently an internal microphone was added on a separate channel to record interior sound.

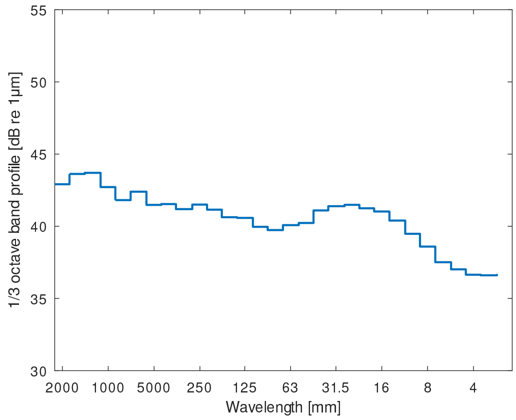

Figure 5. 1/3 octave band road surface profile spectrum of a road section measured using the VTI MRP.

The road surface profile is recorded with one vertical data point each 0.9 mm in the longitudinal direction resulting in a spatial sampling resolution of 1111 m^{-1}. Fig. 5 shows an average road surface profile level spectrum in 1/3 octave wavelength bands for a road section measured in Linköping, Sweden. The corresponding exterior and interior sound spectra are presented in Fig. 6. The sound recordings were divided up corresponding to four subsections of the road and were recorded at slightly different average driving speeds. The interior sound spectra all exhibit a relatively prominent peak in the 5 kHz band, with no variation between road sections. This points to an internal sound source unrelated to the tire-road noise. A corresponding peak is not present in the exterior sound spectra, but the expected peak around 1 kHz i clearly present as is also common in standard ISO 11819-2 (CPX) spectra. A CPX spectrum from the same road section as measured by the MRP is included in Fig. 6 for reference. In addition to road surface profile and exterior and interior sound the vertical acceleration of the vehicle chassis was also recorded. The accelerometers are positioned at the same positions as the profile lasers are positioned as the main use of the accelerometer signals are to compensate for the vertical motion of the vehicle suspension in the road profile measurement signal. The vertical acceleration can however also be an indicator of structure borne sound transmission.

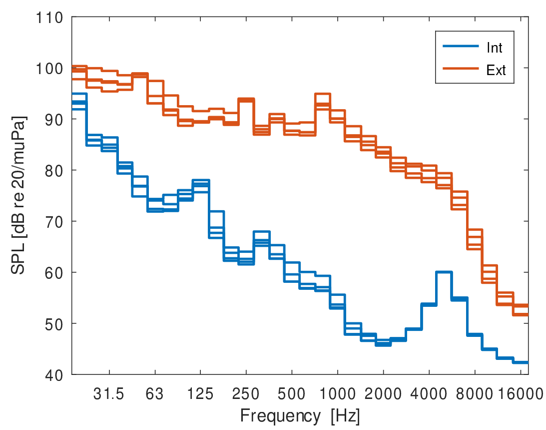

Figure 6. 1/3 octave band sound spectra for sound recorded along different subsections of the road measured using the VTI MRP.

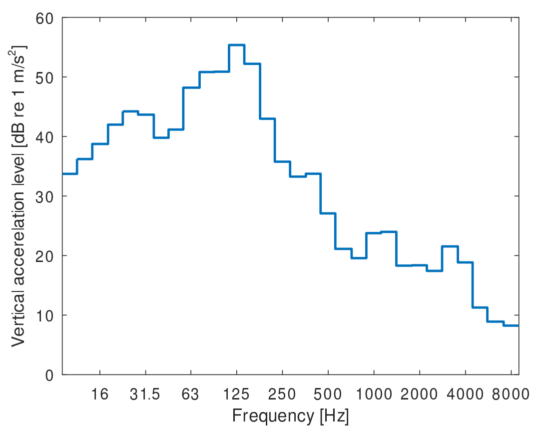

Figure 7. 1/3 octave band spectrum for vertical acceleration level VTI MRP chassis.

A challenge is that the vertical acceleration values are synchronized with the road surface profile data points at one value per 0.9 mm. The sound is recorded with a constant sampling frequency of 50 kHz, so in order to relate the vertical acceleration to the sound, the 0.9 mm spatial resolution is translated into a time resolution via the MRP vehicle speed. Fig. 7 shows the vertical acceleration level spectrum for the MRP driving speed of 50 km/h used during these measurements. The interior sound spectra show a relatively prominent peak at the 125 Hz band, which seems to correlate with the peak at the same frequency in the acceleration spectrum. This indicates a large contribution from structure borne sound around that frequency range.

4. CONCLUSIONS AND FURTHER WORK

The Mobile Research Platform at VTI provides an opportunity to divide the previous single transfer function between road surface profile and interior tire-road sound into a few parts. Exterior sound recording provides a basis for determining the airborne part of the sound transmission, and vertical accelerations provides a basis for indicating the structure borne part of the sound transmission. Ideally accelerometers should be attached to the wheel suspension where the transmission path is better captured. Also, it might be difficult to separate airborne and structure borne transmission unless a vertical acceleration can be applied to the wheels without simultaneous sound emission. The very first preliminary measurements have just been performed at the time of writing. The continuation of the project will perform multiple measurements in order to identify parts of the profile-to-sound transfer function that than be implemented in the simulator using Csound.

5. ACKNOWLEDGMENTS

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