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Advances in the holistic numerical simulation workflow to analyze the sound of combustion engines based on human auditory perception

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Abstract

In this paper a holistic simulation workflow is presented, which aims to calculate the resulting sound radiation of combustion engines with only the cylinder gas pressure curve as input data. The crank drive motion is analyzed with the help of an elastic multi-body model which also takes into account the elasto-hydrodynamic interactions in the fluid films. The multi-body model is coupled with a finite element model of the crankcase and its mounted parts, which allows the surface velocity to be calculated. This model is also coupled with a finite element based acoustic model of the ambient air volume in which the pressure distribution at any point in the acoustic fluid can be calculated. Finally, in the last step of the workflow the acoustic results are evaluated with respect to human auditory perception through a complex psychoacoustic model. Therefore, a listening test has to be carried out in advance in order to generate the psychoacoustic model. It should also be noted that the psychoacoustic model could be reused in future applications if it is a sufficiently similar configuration with respect to that used for generating the psychoacoustic model. Recently, the overall simulation workflow has been improved by taking into account the influence of the motor oil on the resulting perception of the auralized simulation results in a computationally efficient way. Furthermore, a technique inspired by the MP4-technology is implemented in the auralization component of the existing holistic workflow to further increase the overall efficiency of the process.

Keywords: Psychoacoustics, Numerical Analysis, Auralization, Combustion Engines

1 Introduction

During the last years, the individual assessment of the vehicle's quality increasingly depends on the acoustic performance and the noise comfort. Both are still dominated by the noise of the combustion engine. This paper presents a holistic virtual engineering approach to evaluate engine sounds numerically. Thereby, the approach includes two major advantages. First, the acoustic behaviour of an engine is evaluated with respect to the human auditory perception, as the perceived sound quality is more representative than a classical measure like the sound pressure level. Second, a holistic simulation workflow is used. For this reason, only a virtual prototype is required for investigating the acoustic behaviour early in the product development process. This means, in comparison to the common way of psychoacoustic modelling that the hearing tests are executed with auralized results of numerical simulations instead of recorded ones of a running prototype. Fig. 1 shows the workflow to generate the psychoacoustic model based on auralized simulation results. This is only necessary once and only if a new application is investigated that is not similar to a previous one. Otherwise, the corresponding psychoacoustic model that was already generated can be reused.

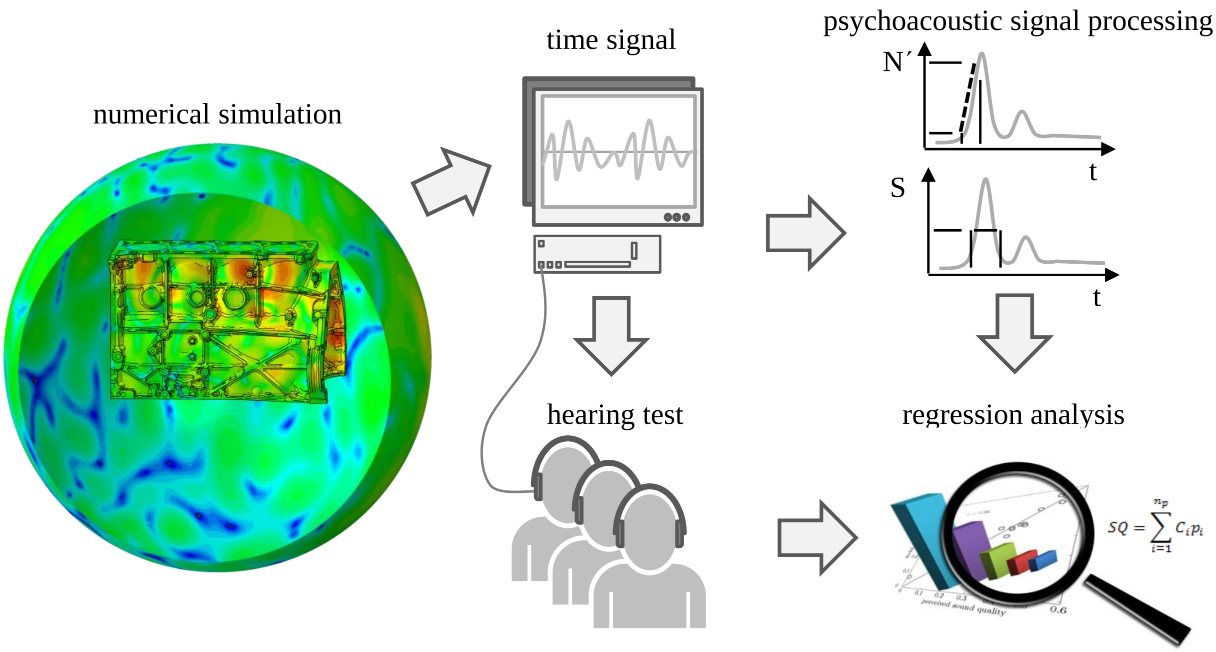

Figure 1: Workflow for generating the complex psychoacoustic model

For generating the psychoacoustic model, regression and correlation analysis are used to find the best combination of parameters to describe the perceived sound quality that is evaluated by hearing tests. Mostly, psychoacoustic basic parameters like loudness, tonality, roughness, sharpness and their derivatives are used to build a function to predict the perceived sound quality. Technically, everything can be used that is calculable out of the time signal of the sound samples. Naturally, parameters with a physical or psychological meaning are preferred. Due to the robustness of the prediction model many researchers try to keep it simple. For example, Höchstetter et. al [1] uses a linear regression models with maximum three independent parameters. To prove the validity of the generated models the result of a second hearing test with new sounds is used. The presented approach was validated for sounds of a diesel engine in [2] and for different encapsulations of this engine in [3] as two different application examples which also require different psychoacoustic prediction models. In both cases correlation coefficients higher than 0.95 were reached for the independent sounds.

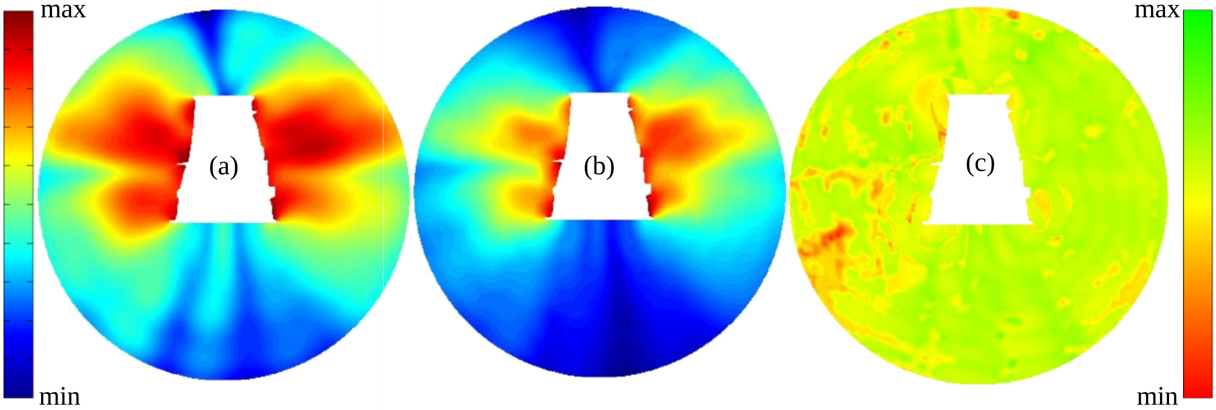

Figure 2: Comparison of the distribution of (a) the sound pressure level in dB(A), (b) the Zwicker loudness in sone and (c) the sound quality of the same engine configuration

Nowadays, it is still common to evaluate the acoustic behavior via sound pressure and power levels in dB(A). Generally, it can be stated that a psychoacoustic analysis of automotive sounds is a good first step [4]. It is shown in [5] that a design variation with additional mass had only an effect due to the measured sound pressure level but was not hearable. Fig. 2 shows the comparison of the distribution of (a) the sound pressure level in dB(A), (b) the Zwicker loudness [6] in sone and (c) the sound quality of the same engine configuration in the middle plane of the surrounding air volume. It becomes clear that the loudness as basic psychoacoustic parameter gives still a similar information as the A-weighted sound pressure level, but, obviously, the perceived sound quality depends on more parameters. Finally, the evaluation of the perceived sound quality seems to be the best parameter to predict the human auditory perception, as in [2]. Further, it is also important to consider the directionality in the analysis of acoustic parameters [7].

2 Holistic numerical simulation workflow

In this section the numerical part is discussed in more detail, due to the fact that the following advances in the holistic workflow are related to this part of the overall methodology. At first, a multi-body simulation (MBS) of the crank drive dynamics is carried out to obtain the excitation of the cylinder crankcase, which is mainly caused by the internal cylinder pressure, the forces in the crankshaft main bearings and the secondary motion of the piston. The calculation of the piston lateral motion and the piston tilting requires the consideration of the hydrodynamic fluid film reactions and the solid contact between piston and cylinder. Generally, a MBS result is needed for one operating cycle of the engine, which means for two full rotations of the crankshaft to take into account all steps of the operating cycle (intake, compression, ignition, and exhaust). The only necessary input of this elastic multi-body simulation is the gas pressure curve of the combustion process (see Fig. 3a). The finite element method (FEM) is used in the following vibration analysis of the engine. It is executed exclusively in the frequency domain in order to reduce the computational costs. The bearing reactions are considered as forces and the excitations of the cylinder walls are considered as pressures (see Fig. 3a, b) to facilitate the application of the loads to the FE-mesh [8].

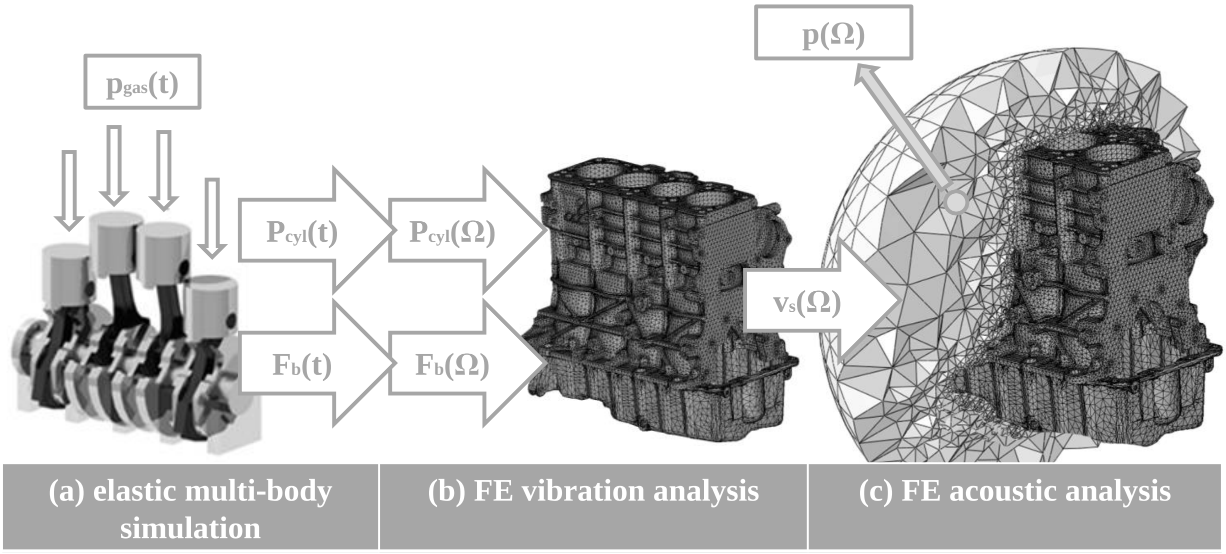

Figure 3: Numerical simulation workflow

In the next step, the surface velocities from the vibration analysis (see Fig. 3b) are used as excitation of the surrounding air volume in the following acoustic analysis (see Fig. 3c). Generally, tetrahedrons with quadratic shape functions are used to discretize the whole engine and the air volume. More detailed information about the numerical part of the overall workflow can be found in [8].

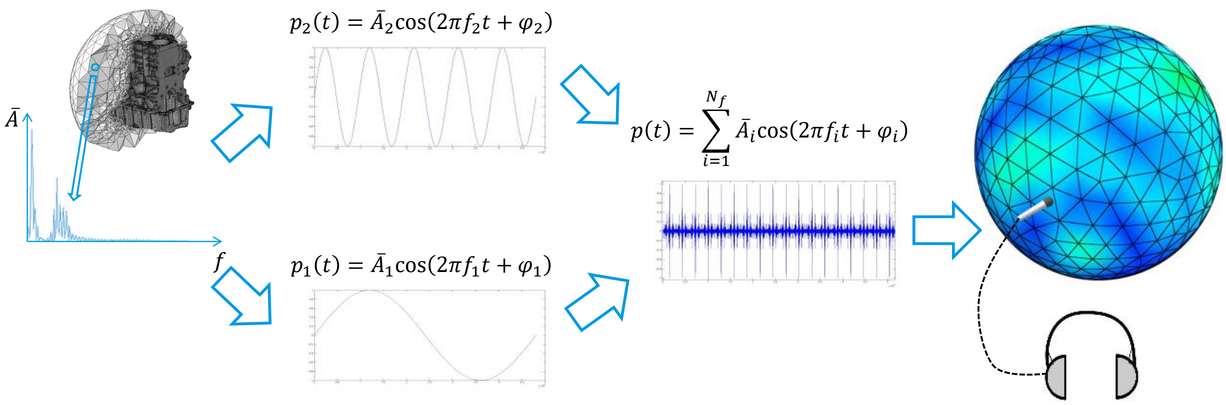

Figure 4: Auralization process

After finishing the numerical calculations the results are auralized. The time signals are input for the hearing test and the signal processing to calculate the psychoacoustic basic parameters, their derivatives and further related parameters. Fig. 4 shows the workflow of the auralization process and how it is implemented [2]. The acoustic simulation performed in the frequency domain results in a complex sound pressure distribution in the whole air volume. The superposition of a cosine function per calculated frequency f_i with the corresponding amplitude $\bar{A}_i$ and the angular phase shift φ_i leads to the time signal of the sound pressure $p(t)$ at each point of the air volume (see Fig. 4). In the present study only multiples of the half engine orders are considered, as engine sounds are dominated by these orders. It has to be taken into account that the finite elements have to be small enough to represent the wavelength of the highest frequency of interest sufficiently accurate.

3 Advances in the holistic simulation workflow

Fig. 5 shows one result of the virtual engineering approach compared to a measured sound pressure level. The measurement was executed in an anechoic room while the engine was running with a constant rotational speed of 2500 rpm and a momentum load of 47 Nm. The sound pressure was measured by a microphone array. The measuring plane was oriented parallel to the oil pan bottom. In the simulation, the same plane was analyzed and the same engine run specifications were taken into account for the elastic MBS. The calculated sound pressure agrees very well with the measurements. The distribution is very similar and the dynamic range of 20 dB of the resulting amplitudes is identical. The calculated amplitudes are higher than the measured ones. Moreover, the eigenfrequencies in the simulation results are shifted to higher frequencies. It should be noticed that the numerical analysis was carried out as the presented workflow in [8]. Consequently, both effects are expected and can be explained due to the influence of the oil pan filling as it is explained in the following paragraph.

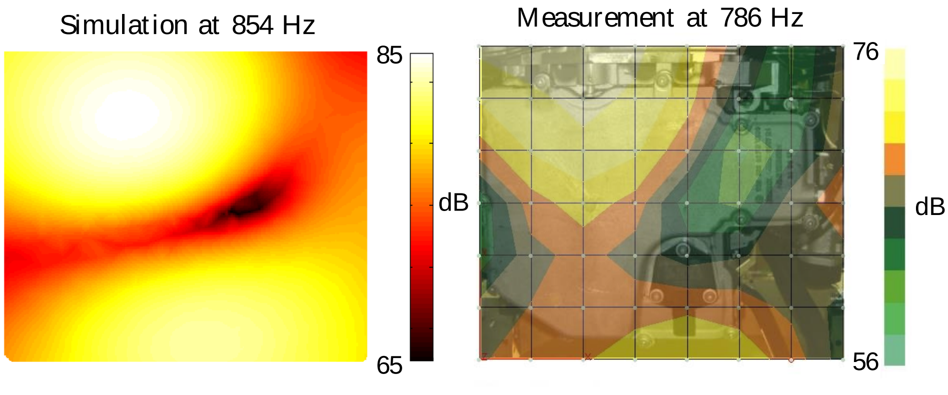

Figure 5: Comparison of the calculated and measured sound radiation of an oil pan

In Fig. 6 the influence of fluid in the oil pan is shown. The vibration response of the oil pan bottom is measured with the help of a 3d-laser-scanning vibrometer under free free boundary conditions for different filling levels. The excitation is realized by an electrodynamic shaker using white noise. The filling of the oil pan increases the mass, but does not lead to a significant change in the stiffness properties. The eigenfrequencies shift slightly to lower frequencies and the amplitudes are also reduced due to the fluid in the oil pan. Additionally, the eigenmodes are visualized in Fig. 6 to show that the basic vibration behavior and in turn the resulting radiation characteristic are not changed significantly by the different filling levels.

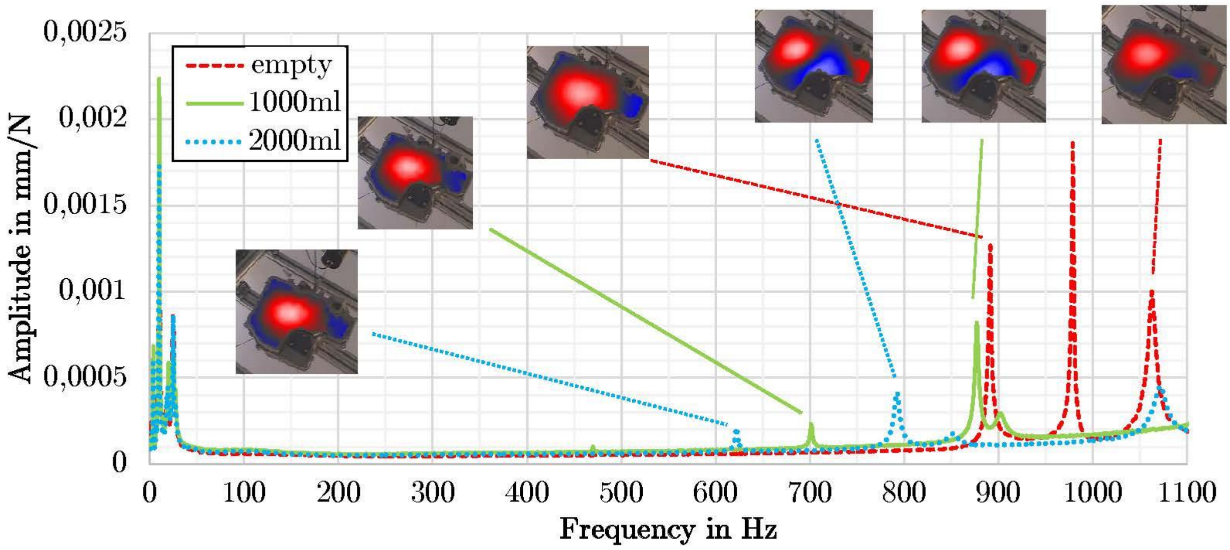

Figure 6: Vibration response of the oil pan for different fluid filling levels: empty (dashed red line), 1000 ml filling (solid green line) and 2000 ml filling (dotted blue line)

In the approach that is used in [2] and [8] this influence of the motor oil is not taken in into account. Different approaches to consider this influence are under progress. The problem is that this additional fluid-structure interaction causes a huge increase in the complexity and, consequently, in the required computational effort. For this reason, at first a simple approach is investigated, in which only the additional mass of the motor oil is taken into account. This requires only marginally additional computational effort and seems to be an appropriate assumption. Unfortunately, the results are not satisfying. The decrease of the eigenfrequencies caused by the mass elements is to large [9]. This can also be seen in Fig. 7 and 8. Furthermore, some mode shapes differ from those observed in the experiments (see the 2nd and 3rd row in Fig. 8). Besides, it can be seen on the left hand side of Fig. 7 and 8 that the experimental and numerical results of the oil pan without filling agree very well. In general, the experimental investigation has shown that some mode shapes are changing due to a different filling level, but most of them are unchanged (see Fig. 6-8). A higher filling level mostly decreases only the eigenfrequencies and the amplitudes of the resonance peaks. The fact that some modes are changing their shape leads to the conclusion that the motor oil has also a certain influence on the stiffness of the system. For this reason, the modelling of the oil has been improved with the help of volume elements, which show better results compared to the experimental results (see Fig. 7 and 8). To keep it simple, common continuum elements as for the aluminium part of the oil pan are used for the oil. The mass is naturally chosen as in the experiments, but the Young's modulus is tuned with the help of the experimental results with a filling level of 1000 ml, especially with the help of the first eigenfrequency (see red ellipse in Fig. 7). This results in a Young's modulus of 300 N/mm². Furthermore, it was observed that a Poisson ratio of 0.01 leads to proper results instead of a ratio close to 0.5. Originally, a Poisson ratio of 0.5 was assumed due to the fact that oil is almost incompressible, but in combination with the unrealistic modelling as a solid body this ratio was unsuitable. For other filling levels than 1000 ml the Young's modulus was scaled linear with the same ratio as the fluid level changes whereas the Poisson ratio always remains unchanged.

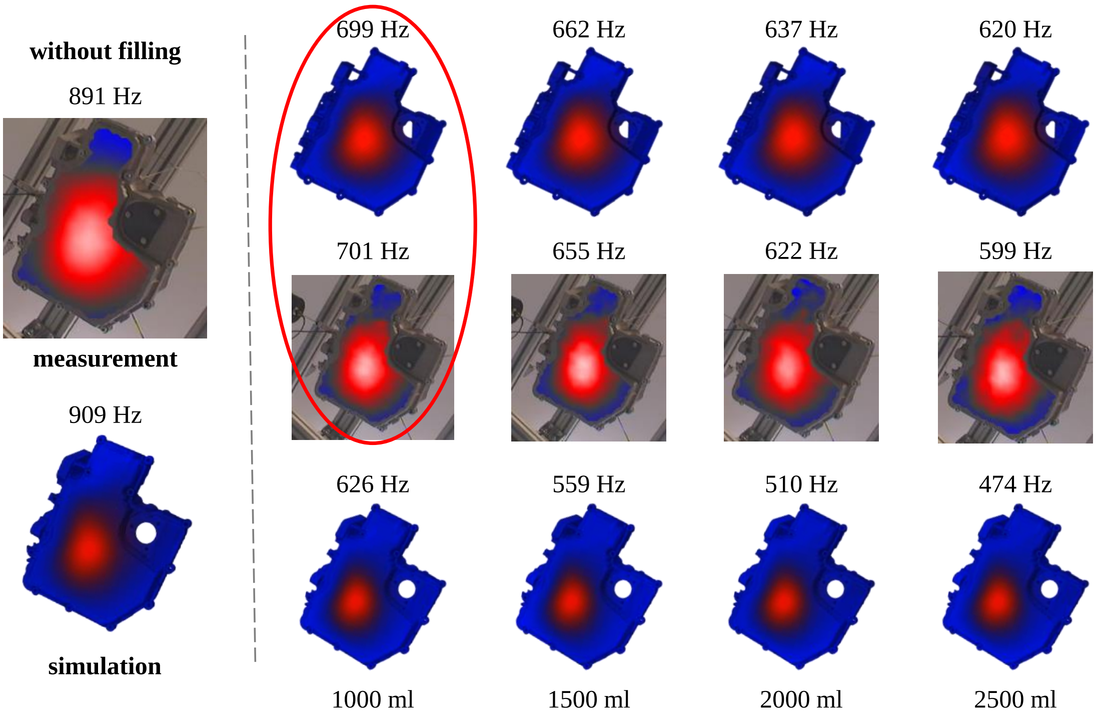

Figure 7: Eigenfrequencies and mode shapes of the 1st mode for different filling levels in the case of adapted volume elements (1st row), measurements (2nd row), mass elements (3rd row)

The presented approach to take the oil into account with volume elements is still simple and doesn't increase the computational effort significantly, but it has some drawbacks. The adaption of the properties of the volume elements was made only for one mode of one filling level. Consequently, the agreement of the numerical and experimental results in the other modes and filling levels is worse. In addition, the reference has to be determined experimentally, which is in conflict with the holistic virtual engineering workflow that needs no real prototypes at all. Moreover, it should be noticed that the very small Young's modulus of the oil could cause some problems with respect to the condition of the matrices. Currently, investigations are made that compare the results of both presented approaches with a full co-simulation of the fluid dynamics via CFD and the vibrations of the structure via FEM. Further, the so called smooth particle hydrodynamics (SPH) method is studied in comparison as another opportunity to include the motor oil in the overall simulation workflow.

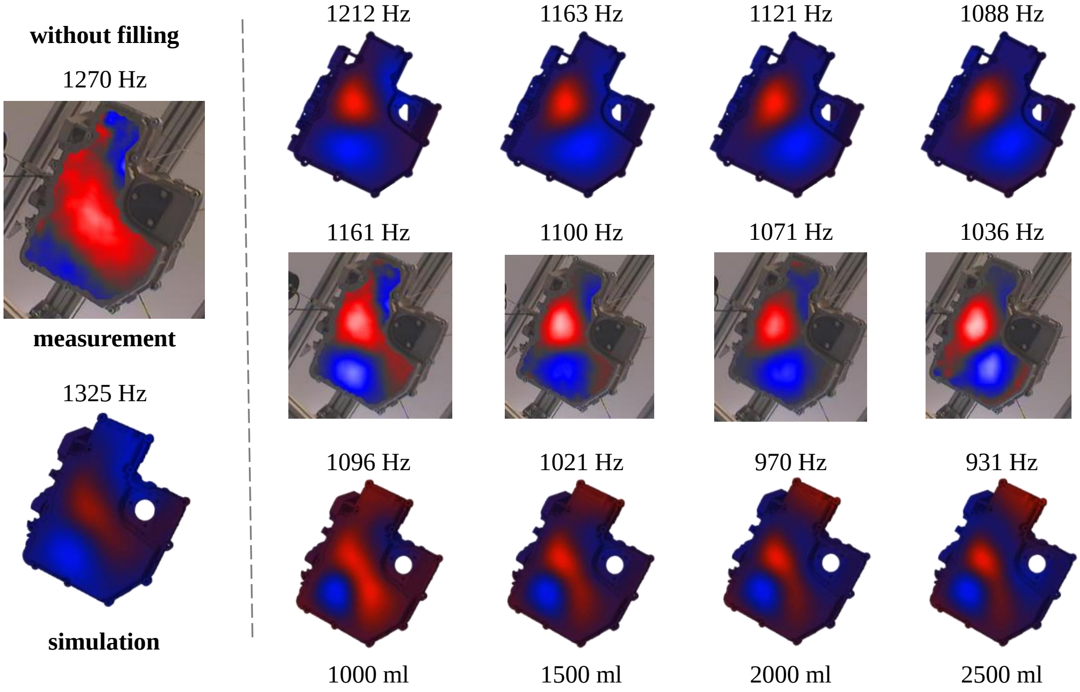

Figure 8: Eigenfrequencies and mode shapes of the 3rd mode for different filling levels in the case of adapted volume elements (1st row), measurements (2nd row), mass elements (3rd row)

Another idea to increase the efficiency of the holistic workflow is to reduce the number of frequencies which have to be calculated numerically in the acoustic analysis. However, neglection of the high frequency domain of the human hearing range is inappropriate, as important phenomena such as ticking occur at high frequencies with relatively small amplitudes. For this reason, an additional component is implemented into the holistic workflow, which is inspired by a special feature from the MPEG-4 High Efficiency Advanced Audio Coding (HE-AAC) scheme. HE-AAC is a further development of MP3-technology which has been extended by a few special techniques. In particular, the basic principle of the so called Spectral Band Replication (SBR) [10] is interesting. That means translated to the presented workflow, that the results in the higher frequencies can be generated out of the lower frequency results, instead of having to solve the complete FE problem to obtain these high frequency results. To implement this approach the following specifications are used. An arbitrary frequency of 5 kHz is defined as the maximum calculated frequency. Then all of the higher frequency components up to the highest frequency of interest (15 kHz) are constructed by using the characteristic of the dominant engine orders with decreasing amplitudes with increasing frequency. For each generated frequency only the most dominant engine order of its integer divisors is used. The amplitude attenuation with increasing frequency can be created with an arbitrary function which should never be lower than a defined minimum level. Here a linear attenuation function is tested, which results in hardly any distinguishable difference between the sound signal that consist only of calculated frequency components and the one with generated components. This method to increase the efficiency of the overall process can only work due to the fact that the human ear cannot differ very well between distinct sounds in the higher frequency range. For example, the audible difference between single sinusoidal tones and narrow-band noise becomes smaller and smaller with increasing frequency [6]. In addition, the spectra of most sounds show characteristic envelope curves and for the most cases the envelope curves of the low- and high-frequency domain of a sound have a strong correlation. Periodic continued harmonic components are one example of it. Finally, it can be stated that the removal of the requirement to calculate the higher frequencies is an enormous improvement of the holistic workflow. Aside from the computational effort saved by calculating a lower number of frequencies, it is also possible to use a coarser FE mesh, as the required element edge length depends on the highest calculated frequency. Consequently, the computation of each individual frequency is also sped up significantly.

4 Conclusions

In this paper a holistic virtual engineering approach is presented that evaluates the acoustics of engine sounds with respect to human auditory perception. Recently, the overall simulation workflow has been improved by taking into account the influence of the motor oil on the resulting perception of the auralized simulation results in a computationally efficient way. Nevertheless, alternative methods to consider the influence of the motor oil on the acoustic behaviour will be investigated in the future. In addition, a technique inspired from MP4-technology is implemented in the auralization component of the existing holistic workflow to further increase the overall efficiency of the process significantly. Therefore, the limitations of human ears in sensing differences in the high frequency domain are used.

Acknowledgments

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References

[1] Höchstetter, M., J. M. Sautter, J. L. Verhey, U. Gabbert, "*Role of the duration of sharpness in the perceived quality of impulsive vehicle sounds",* Acta Acustica united with Acustica, *Vol. 102, 2016.*

[2] F. Duvigneau, S. Liefold, M. Höchstetter, J. L. Verhey, U. Gabbert, "Analysis of simulated engine sounds using a psychoacoustic model", *Journal of Sound and Vibration, Volume 366, 2016, pp. 544-555. DOI: 10.1016/j.jsv.2015.11.034.*

[3] S. Liefold, F. Duvigneau, M. Höchstetter, "Sound quality of engine encapsulations", *ATZ worldwide, June 2015, Volume 117, Issue 6, pp 20-23. DOI: 10.1007/s38311-015-0020-2*

[4] F. Duvigneau, M. Höchstetter, U. Gabbert, "Objektivierung der auditiven Wahrnehmung von Fahrzeuggeräuschen", *Lärmbekämpfung, Bd. 11 (2016) Nr.3 – Mai, pp. 99-104.*

[5] F. Duvigneau, T. Luft, J. Hots, J. L. Verhey, H. Rottengruber, U. Gabbert, "Thermo-acoustic performance of full engine encapsulations - A numerical, experimental and psychoacoustic study", *Applied Acoustics, Volume 102, 15 January 2016, Pages 79-87. DOI: 10.1016/j.apacoust.2015.09.012*

[6] E. Zwicker, H. Fastl, "Psychoacoustics - facts and models", Springer Verlag, Berlin, 2007.

[7] F. Duvigneau, S. Liefold, M. Höchstetter, R. Orszulik, "Evaluation of the Directional Characteristics of the Sound Quality", *accepted in ATZ worldwide*, September 2016

[8] F. Duvigneau, S. Nitzschke, E. Woschke, U. Gabbert, "A holistic approach for the vibration and acoustic analysis of combustion engines including hydrodynamic interactions", *Archive of Applied Mechanics, DOI: 10.1007/s00419-016-1153-5*

[9] S. Koch, F. Duvigneau, U. Gabbert, E. Woschke, "Untersuchung des Einflusses von Öl auf das Schwingungsverhalten von Ölwannen", *12. Magdeburger Maschinenbautage: Smart, Effizient, Mobil*, Magdeburg, 2015, ISBN 978-3-944722-26-9

[10] Patent WO9857436: *Source Coding Enhancement using Spectral-Band Replication.* Published at 17. Dezember 1998, Inventor: Liljeryd, Lars Gustaf.