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NUMERICAL STUDY OF A THERMO-ACOUSTICALLY ENCAPSULATION

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Abstract. In recent years comfort has become an important factor when evaluating the performance of modern automobiles. One important aspect that has negative ramifications on the perception of quality is the generated noise. Therefore, an important goal in current research activities is to minimize the acoustic noise that is radiated by a combustion engine. To achieve this goal, the paper at hand investigates the performance of a thermo-acoustic encapsulation. Using this passive approach it is hoped to improve not only the acoustic but also the thermic behavior. From a tribological point of view the heat storage of the motor oil is of utmost importance. By encapsulating the motor the oil temperature can be increased. Since the oil temperature is directly related to the fuel efficiency the consumption can be decreased and therefore the pollution is reduced as well. We avoid, moreover, a so called cold start-up of the engine resulting in a reduced abrasion. Consequently, a thermo-acoustic encapsulation has several positive effects increasing the environmental friendliness.
In a first step acoustic and thermic phenomena are considered separately. The finite element method (FEM) is deployed to simulate a stripped engine block. Detailed analyses are conducted with and without thermo-acoustic encapsulation. The numerical results clearly indicate the potential of such an encapsulation. Both, a significant sound pressure reduction and an improved thermic insulation can be proofed. In a last step several parameter of the encapsulation are varied illustrating the vast potential for an optimized design.

1 SIMULATION OF THE NOISE RADIATION

In this chapter the encapsulation of the engine structure as well as the simulation of the noise radiation are presented. The examined structure consists of the cylinder crankcase with the associated oil pan (including oil pan cover). By using the finite e1ement method (FEM) these components are discretized separately and then linked together. First, the structural vibrations are calculated and then the resulting sound radiation in the fare field is analyzed. The surrounding air volume is modeled as a sphere with a coarser discretization to the periphery. Due to the computational cost, the acoustic simulation is carried out exclusively in the frequency domain. While the Sommerfeld radiation condition is fulfilled automatically by using the Boundary Element Method [1] (BEM), it can be fulfilled within the FEM using absorbing boundary conditions [2], infinite finite elements [3] or the Perfectly Match Layer method [4]. In the present study absorbing boundary conditions are applied. In a preliminary study a plate like structure has been investigated in order to evaluate the numerical approaches with help of the analytical solution based on the Rayleigh integral. It was shown, that the three different modeling approaches of the boundary conditions in the fare field do not differ significantly. But, the application of absorbing boundary conditions require the least computation time. The acoustic simulation can be performed uncoupled, which means that the influence of the fluid on the vibrating structure is neglected. The engine structure is quite stiff in comparison to the air and is, consequently, not nameable influenced by the surrounding air pressure under fare field conditions. The structure-fluid-coupling is implemented using special interface elements. These are embodied as shell elements with the contour of the surface structure and transform the surface velocity of the structure to corresponding pressure values. For both, the structure and the fluid, quadratic tetrahedral finite elements are used. The structure is made of aluminum and is cross-linked with an average edge length of 4 mm. At the interface the structure mesh and the fluid mesh show coincident nodes. At the periphery the average edge length of the fluid elements is 10 mm. In total, the model without encapsulation includes 516759 structural and 532359 fluid elements resulting in 882816 structural and 697734 fluid nodes, respectively. The acoustic and thermal analysis of the system is also carried out separately in an uncoupled manner. The fluid elements as well as the thermal elements have only a single degree of freedom.

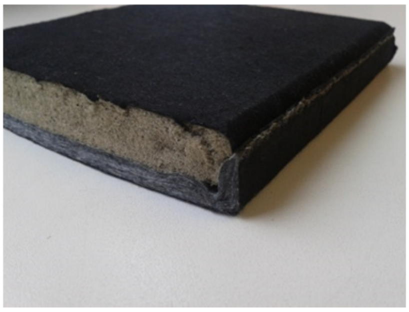

Figure 1: High absorbing sandwich material of the thermo-acoustically encapsulation

For the coupling of the structure with the surrounding fluid interface elements are introduced, which are part of the fluid model. On the nodes of the interface elements the previously calculated displacements and velocities of the structural surface are applied using special boundary conditions. The structural vibrations are excited with help of bearing reactions, which are introduced into the bearing blocks of the cylinder crankcase. The bearing reactions are obtained from an elastic multi-body simulation of the crank drive dynamic. This requires an experimentally determined cylinder gas pressure curve only as input data. Using the method shown in [5] cylinder deformation effects resulting from the combustion process and arising forces can also be considered.

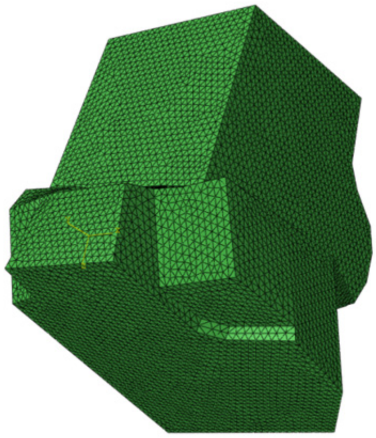

Figure 2: Finite element model of the thermo-acoustically encapsulation

For the encapsulation of the engine a special absorbing sandwich material is used as shown in Fig. 1. Such a material system basically consists of a very soft and highly absorbing foam layer directed to the vibrating structure and additionally a much stiffer fiber material on the outside. Both materials are very light and temperature resistant. Again a 3D model is used for the encapsulation structure, which is meshed with quadratic tetrahedral elements. A first test realization of the encapsulation on an engine test bench is shown in Fig. 4. The motor contour has only been modeled very roughly since for the first approach only plate like material pieces could be provided by the customer. Fig. 2 shows the designed FE model of the encapsulation.

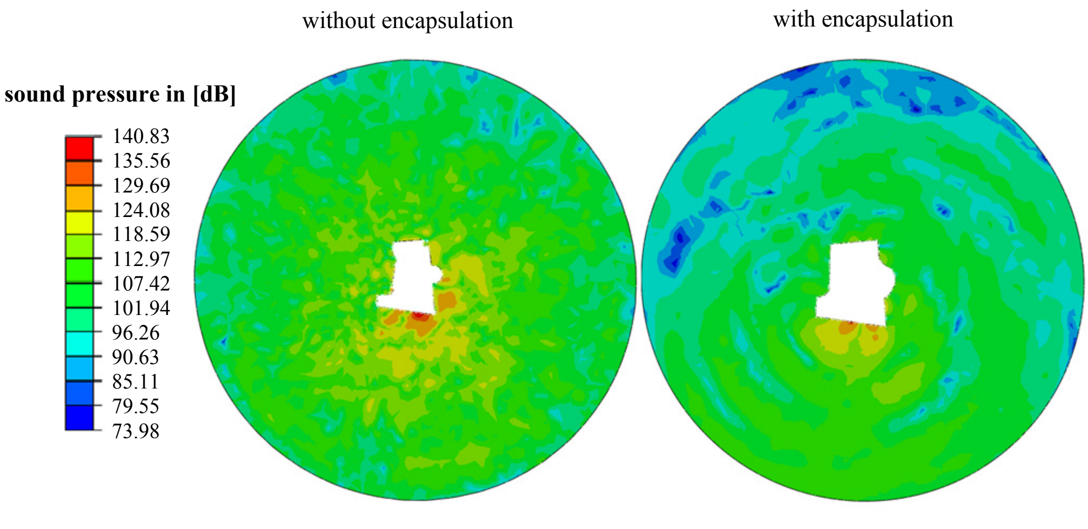

Figure 3: Radiated sound pressure of an engine with and without a thermo-acoustically encapsulation

The structural FE model has been extended by an additional number of 554536 elements and 842008 nodes by the encapsulation. Each node exhibit three degrees of freedom. The feedback of the encapsulation is neglected with respect to computational costs, because the encapsulation is much softer than the structure. Therefore the previous calculated structural vibrations are used in analogy to the previous discussed fluid model. Structural displacements and velocities are applied to the internal contour nodes of the encapsulation as boundary conditions. The structural vibrations of the encapsulated surface is used to excite the surrounding fluid. Hence a re-meshing of the fluid is required. In Fig. 3 the sound pressure distribution with and without the encapsulation is visualized in a cut through the center plane of the spherical air volume. Fig. 3 shows a considerable sound pressure reduction for the case where the encapsulation is surrounding the engine. Furthermore, it can be observed that with the encapsulation the dominant radiator is still the oil pan.

2 HEAT-STORAGE POTENTIAL OF THE ENCAPSULATION

In this chapter, the second aim of the thermo-acoustic encapsulation is investigated in detail. The encapsulation should be additionally also store the heat of the engines oil. The stored heat improves the cold starting behavior of the engine, meaning that the optimal operating points of the engine, which reduce wear and tear and therefore also exhaust emissions, are quickly reached. Of course, engine overheating and overloading of the cooling circuit have to be excluded. For the thermal consideration, an FE-simulation is conducted as well. The finite element mesh is directly taken from the acoustic simulations. Only the engine oil inside the oil pan is added. It is also modeled with quadratic tetrahedrons. Fig. 7 shows a comparison of the cooling of the engine oil between simulation and experimental results. It is assumed that the oil temperature is nearly the same in the whole oil volume. Nevertheless, it was tried to take a temperature from a point out of the simulation which is close as possible to the measuring point. Thermal radiation effects are neglected in this first approach. Only the transient heat conduction is calculated. As initial condition a starting temperature between 110 ° C and 100 ° C is defined for the entire model like in the experiment with and without encapsulation, respectively. The ambient temperature is defined with 23 ° C according to the experiment. The environment is considered in the model by a surface film condition as a thermal sink on the outer surface of the structure or encapsulation. A flow speed of zero is assumed; so only pure convection has been considered. For the thermal simulation temperature dependent material parameters are used. Fig. 7 shows that the calculated cooling curve of the oil of the bare engine coincides very well with the measured curve. In contrast, the effect of the encapsulation is highly overestimated in the simulation. From these facts several conclusions can be drawn. Firstly, the simulation is well suited to match the phenomenon well. Furthermore, the main heat loss seems to be caused by the oil pan (at least at a standstill). Otherwise the good agreement between experiment and simulation in the case of the configuration without encapsulation would not be plausible, since in the simulation model all ancillaries and other components are missing and the test station and simulation model are only identical in the area of the oil pan. The discrepancy in the simulation with the encapsulation is due to the non-identical geometry. But also the modeling as an ideal, closed two-layered encapsulation seems to be inappropriate. The influence of different leakage effects and impacts on locations, where the prefabricated insulating panels are connected, is not shown. Regarding all discussed aspects an improvement of the model is necessary in the further work.

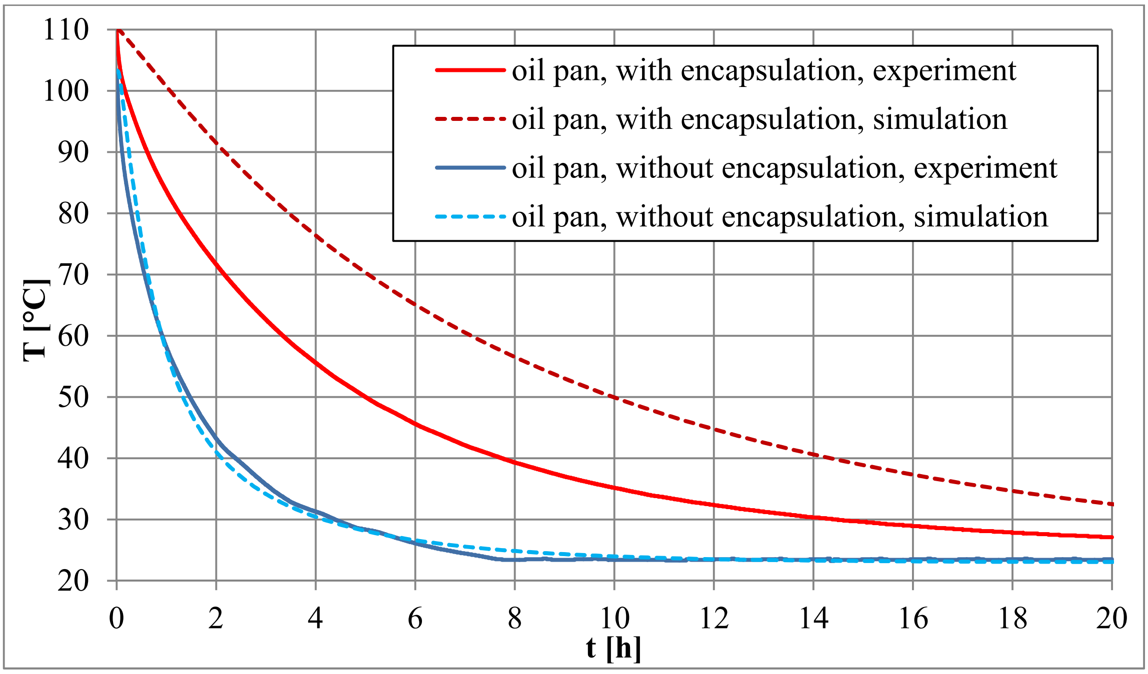

Figure 4: Experimental und numerical cooling curves of the oil temperature

3 NUMERICAL STUDIES OF DIFFERENT ENCAPSULATION INTERFACES

In the present section the interface between the engine and thermo-acoustic encapsulation is investigated. One objective is to examine the influence of the contact area between the encapsulation and the motor. On these contact surfaces the structure-borne vibrations of the engine are directly transferred to the encapsulation. The air-coupled transmission path can therefore be neglected. It is assumed, that with an increased contact area also the transmission of the structure-borne noise is improved and thus the effectiveness of the encapsulation is deteriorated. To this end, three different configurations are compared. The numerical results are obtained using the model presented in Section 1. These three configurations are presented in Fig. 5. The spherical air volume surrounding the engine is decreased compared to the model introduced in Section 1, cf. Fig. 3. The complexity of the numerical simulations is accordingly reduced.

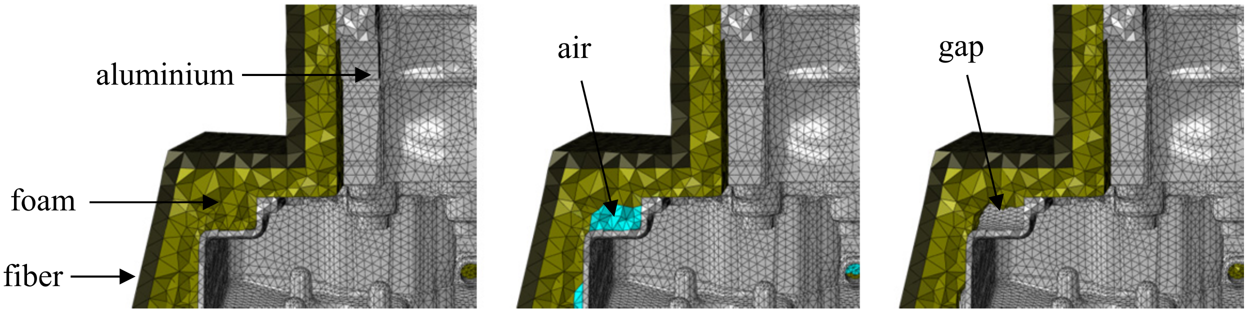

Figure 5: Three different interface models between the encapsulation and the stripped engine block

The left picture in Fig. 5 shows the limit case. Here, the entire motor surface is in contact with the thermo-acoustic encapsulation. All the space between the engine and the original encapsulation is filled with foam material. In the middle picture of Fig. 5 an encapsulation is shown, which consists of two layers each having a constant thickness (fiber layer and foam layer of the encapsulation). The remaining gaps are filled with air. This modeling is intended to reflect the situation on the real test bed. It is assumed that the structure-borne noise path is the dominant transmitter of the motor vibrations to the encapsulation. It is therefore checked with the third configuration on the right-hand side of Fig. 5, if it is appropriate to neglect the influence of the air between the encapsulation and the motor.

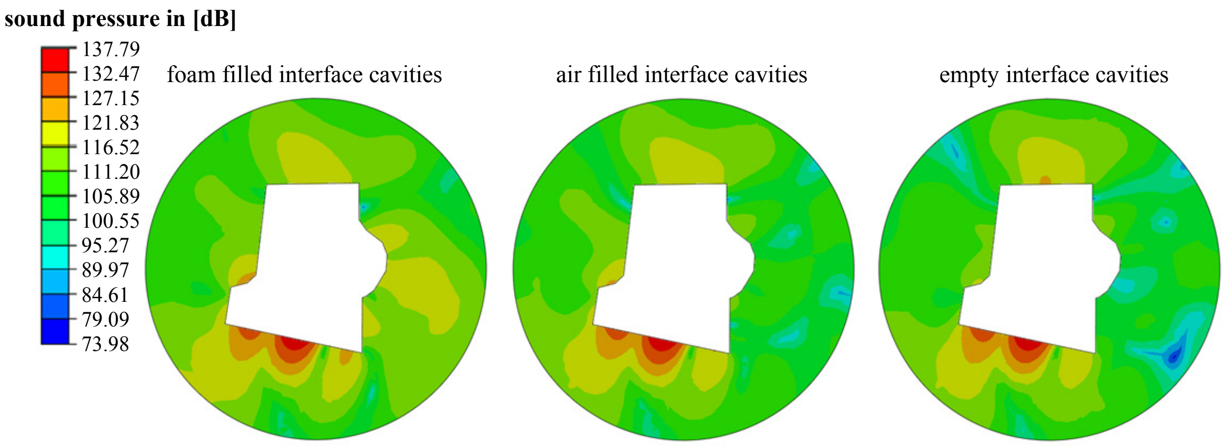

Figure 6: Sound pressure distribution of an encapsulated engine with different interface configurations

The sound pressure distributions of the three variants illustrated in Fig. 5 are displayed in Fig. 6. They confirm the assumption that the air between the encapsulation and the engine block can be neglected. Additionally it is found that the contact area between the encapsulation material and motor surface should be kept as small as possible to reduce the structure-borne noise transmission. Although a significant influence in the results due to model changes can be seen, it is also obvious that the global nature of the sound radiation is hardly changed. The critical areas, where the maximum sound pressure is to be found, are almost indifferent towards the proposed modeling approaches. These however occur in the vicinity of the oil pan. There a particularly large contact area with the encapsulation is observed. The results of the various models are consequently barely distinguishable in these areas. Most of the interface cavities are on the sides “walls” of the engine block. The lateral sound radiation shows accordingly the biggest dependence on the different modeling techniques. Ideally, all structure-borne noise paths should be eliminated. In this particular case the efficiency of the encapsulation would be maximized. For real-life applications this is however not possible since the encapsulations needs to be mounted on the engine block.

4 CONCLUSIONS

For the thermo-acoustic encapsulation a complete FE-simulation has been build up. In this way the effectiveness of acoustic and thermal improvements by the encapsulation can be estimated. The high potential of thermo-acoustic encapsulations with respect to thermal improvements has been proven numerically as well as experimentally. The potential of acoustical improvements has been proven numerically, too. Structure-borne noise paths between the motor and the encapsulation should be avoided. The mutual influence of the thermal and acoustic effects in a coupled simulation needs to be investigated in more detail in the future. In addition it has been figured out, that the joints between the single plates of the encapsulation have to be taken into account. Simultaneously also an inclusion of leakage effects in an improved simulation model will result in a better representation of the real behavior. Of course, the material parameters have also a sensitive influence on the results as well. Based on an experimentally validated simulation model methods of topology and shape optimization will be applied to receive an improved thermo-acoustic encapsulation of the engine.

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