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Thermo-acoustic performance of full engine encapsulations – A numerical, experimental and psychoacoustic study

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ABSTRACT

This paper presents the development and investigation of a thermo-acoustic encapsulation for a diesel engine by means of a combined approach of thermo-acoustic recordings, numerical simulations and psychoacoustic evaluation. The encapsulation is positioned in close proximity to the engine and completely surrounds the entire engine block. Experimental tests are performed with the help of an acoustic engine test bench, where the surface of the engine is observed by infrared cameras and the sound is monitored by a microphone-array. Thermal and acoustic measurements of the engine without an encapsulation are recorded and used as reference data for simulations to evaluate and improve the functionality of different design concepts of the encapsulation in comparison to the same engine without encapsulation. The received experimental results are also used to select proper materials as well as to design the heat insulating and sound absorbing encapsulation. Based on the experimental investigations, some weak points of the first prototype are identified. These experimental findings, as well as numerical simulations of the sound radiation, are used as a basis for further design improvements to the encapsulation. The new design that is developed shows a significant improvement in the insulation of the car engine, both thermally and acoustically. In the last step, the perception of the engine sounds are evaluated by measuring changes in the perceived loudness and sound preference of the engine with and without encapsulation by human participants. This allows for a more objective evaluation of the acoustic behavior of the developed engine encapsulation.

1. Motivation

In recent years, comfort has become an important factor in customers evaluation of cars and their purchasing process excessive. Noise emission from the engine can be perceived as a negative aspect with respect to the car quality. However, the combustion process is a major excitation of structural vibrations, which is the largest source of emitted vehicle noise. An engine encapsulation is a passive measure to improve the NVH (noise, vibration, harshness) behavior, which can significantly reduce the sound radiation from the engine, if it is designed in an appropriate manner. Furthermore, the efficiency of the engine can also be increased by a thermal encapsulation because it increases the heat stored in the motor oil [1]. The higher oil temperature causes a reduction in the fuel consumption and can also reduce the air pollution due improved cold start behavior [2]. Consequently, a proper engine encapsulation will also contribute to the cars environmental friendliness, which has become a new paradigm in evaluating the quality of products. In addition, thermal encapsulations can increase the customer value due to the shortening of the heating period of the vehicle.

Insulations have, depending on their design, different influences on the cooling system. In some cases it may be necessary to re-dimension the cooling system to secure thermal safety in all operating points. The focus of the current study was on the main dimensions of the vehicle radiator and the coolant pump. When designing an encapsulation, it is also important to select materials which are thermally stable for all uncooled components within the capsule. In [3] an adaptive system is proposed that fulfills both the thermal safety requirements of the encapsulated engine and the wish to retain as much heat as possible. This system with active closing elements ensures an efficient flow of air through the radiator for optimal engine cooling during driving, but also

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blocks the dissipation of warm air when the vehicle is parked. It can be stated that the cooling circle of the engine, which was used for the investigations in this paper, was able to handle the additional heat without any problems. The same conclusion can be drawn out of the review article about cold-start efficiency [4]. Therein, encapsulations are presented as one opportunity to improve the cold-start behavior, problems regarding to the cooling system were not observed. Further, [5] discuss engine encapsulations to reduce the exhaust emissions by increasing the heat storage and they also don't report any problems with the original cooling system of their investigated engine.

A historical overview of the different stages of development of engine encapsulations is given in [6]. In [3] the differences between engine mounted encapsulations, body mounted encapsulations and also mixed forms are investigated. The current paper investigates an engine mounted encapsulation that is positioned in close proximity to the engine and surrounds the whole engine block. There are some approaches of full engine encapsulations in the literature [5], however psychoacoustic aspects are not considered. Further, the paper at hand also presents results of numerical 3D simulations of the structural vibrations and sound radiation of the combustion engine. In contrast, previous studies often don't include any simulations or are only executed as a 1D simulation.

An important future problem in engine design is the fact that the vehicle noise emission limit will be reduced by the legislative authority in steps over the next few years [7,8]. Simultaneously, the limits for exhaust emission will also be tightened [9]. Engine encapsulations offer the possibility making major contribution reaching these goals. The trend towards more efficient and environmentally friendly mobility has led to downsizing of engines in recent years. A particular application of combustion engines is as a range extender for electric vehicles, where an undetectable, quiet engine would be preferable, as the operating mode is not controlled directly by the driver.

A good starting point for the acoustic evaluation of an engine encapsulation is the A-weighted sound pressure level. However, a psychoacoustic investigation is also desirable in order to evaluate the quality of the acoustic insulation by the encapsulation with respect to the human auditory perception. The present study focusses on loudness as the sensation most closely related to the physical level of the sound. Ultimately, the perception, and not just a physical parameter like the sound pressure level, decides on the perceived quality of the engine sound and acceptance of a particular engine encapsulation.

2. Development process of the encapsulation prototypes

The first step of the process is to analyze the current configuration of the engine without encapsulation through both measurements and simulations. The results of these investigations are then recorded as reference values to be used in an evaluation of the different engine encapsulations. In Section 3 the thermal properties of the encapsulation are first considered and then in Section 4 the acoustic properties are investigated in detail. These sections also both include a description of the workflow applied to the respective simulations.

The experimental set-up used can be seen in Fig. 1. The left part of the figure shows the combo-microphone array, which consists of 30 microphones that are used for measuring the spatial distribution of the sound pressure. Single microphones are also used for measurements of the near as well as the far field. The engine test bench, which sits inside an anechoic room, can be seen on the right side of Fig. 1. Acoustic measurements are gathered while the engine is running where it is also possible to simultaneously record several operating details of the engine (e.g. the cylinder pressure, the oil temperature, the flow rate and the temperature of the in- and outgoing cooling water).

The material for the encapsulation prototypes will be determined based on the analysis of the current engine state. A very important property of the material is the temperature resistance. Hence, an infrared camera is used to determine the temperature that the encapsulation material must be able to tolerate without any problems. Fig. 2 shows a particular absorbing sandwich material with a damping loss factor of about 0.13, which is used for the complete engine encapsulation. This material system basically consists of a very soft and highly absorbing foam layer that surrounds the vibrating structure with a much stiffer fiber material on its outside. The foam layer has a thickness of 16 mm and the fiber layer has a thickness of 9 mm. Both the foam and the fiber materials are very light and temperature resistant up to 160 °C.

Fig. 2. High absorbing sandwich material of the thermo-acoustic encapsulation.

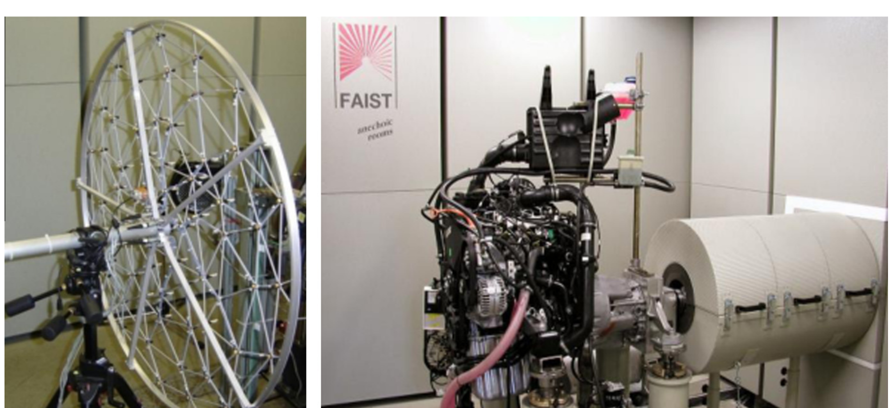

Fig. 1. Combo-microphone array (left) and engine test bench in an anechoic room (right).