

## Modern Approaches for Modeling of Structure-Borne Noise of the Internal Combustion Engine

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**Abstract**—The article considers the structure of acoustic radiation of an internal combustion engine and modern technologies for noise research. Models of the internal combustion engine as a source of noise and methods for modeling the design and calculating the structure-borne noise of the engine at different stages of its design are described. The method of the engine structure-borne noise calculating for unsteady operation mode is presented. Differences in the working process of the engine for the transient operation mode are shown. Some results of calculations of diesel engine structure-borne noise for different operation modes using MADI methods and using the AVL EXCITE software are presented.

**Keywords**—Engine noise, Structure-borne noise, Noise modeling, AVL EXCITE, Noise source.

### 1 Introduction

The internal combustion engine is the main source of vehicle noise. Therefore, to reduce the noise of traffic flows in the city, it is necessary to improve the acoustic characteristics of the engine. The task becomes more and more important with the increase in the car park of the megapolis. Different methods and tools should be used to calculate noise at different design stages. It is also important to calculate the noise not only for steady-state operation modes, but also for transient ones, since the external noise of the car is evaluated according to the standards during acceleration. In addition, in urban conditions, the car also moves most of the time in transient modes.

### 2 Simulation of internal combustion engine noise

By its nature, all acoustic radiation from an engine is divided into sources of aerodynamic and structure-borne noise [1]. Aerodynamic noise occurs as a result of fluctuations in gas flows and, despite the overall high level, can be relatively easily silenced by selecting a silencer of a certain volume and design. Structure-borne noise is caused

by vibrations of the external surfaces of the engine due to the impact of impulses from the working process on its body parts and collisions of engine parts in movable joints.

The main work in the field of studying engine noise, which is currently being carried out at the Department of "Heat engineering and automotive engines" in MADI, is aimed at modeling the sources of structure-borne noise of the internal combustion engine [2, 3] and finding ways to reduce it level, for example, by using alternative fuels [4-8].

The following mathematical model is used to calculate the sound power from a noise source:

$$P_W(kf_0) = z_S(kf_0) \cdot \rho c \cdot S_{ICE} \cdot \bar{v}_{e(S)}^2(kf_0) \quad (1)$$

where:  $z_S(kf_0)$  – relative coefficient of resistance to radiation normalized by the area of the outer surfaces of the engine;  $\rho$  - air density;  $c$  – sound speed in the air;  $S_{ICE}$  – wave resistance of the air;  $S_{ICE}$  – engine outer surfaces area;  $\bar{v}_{e(S)}^2(kf_0)$  – average squared effective vibration velocity on the outer surface.

Further calculations depend on the research tasks and the corresponding software tools.

To estimate the noise at the stage of engine layout, the vibration rate of the outer surfaces can be calculated using the following model:

$$\bar{v}_{e(S)}^2(kf_0) = \frac{1}{2\pi \cdot M_{ICE} \cdot T^2} \sum_{k=a}^N G^2(kf_0) \cdot \frac{1}{z_v(kf_0) \cdot \eta(kf_0) \cdot (kf_0)} \quad (2)$$

where:  $k$  – ordinal number of harmonic;  $G(kf_0)$  – spectral density of the load factor at the frequency of the  $k$ th harmonic ( $N \cdot s$ );  $T = \frac{30\tau}{n}$  - working cycles sequence period (s);  $\tau$  – engine cycle factor;  $f_0 = \frac{60}{n}$  – crankshaft rotation frequency (Hz);  $n$  – number of crankshaft revolutions per minute (rpm);  $A$  – number of the lower harmonic of the load factor (provided that  $f_0$  is the first);  $N$  – number of the highest harmonic of the load factor (provided that  $f_0$  is the first).

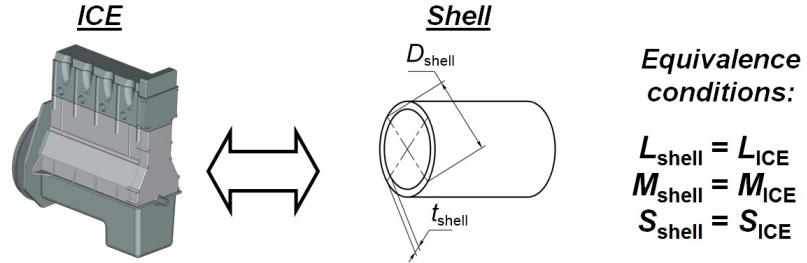
The oscillatory characteristics of the engine design with sufficient accuracy for the engine layout stage are described using the equivalent cylindrical shell model (Fig. 1).

The mass and surface area of the engine can be obtained using simplified 2D models or using three-dimensional modeling of engine body parts.

Modeling of the main excitation factors (working process and piston shifts) is performed at this stage using the techniques developed in MADI.

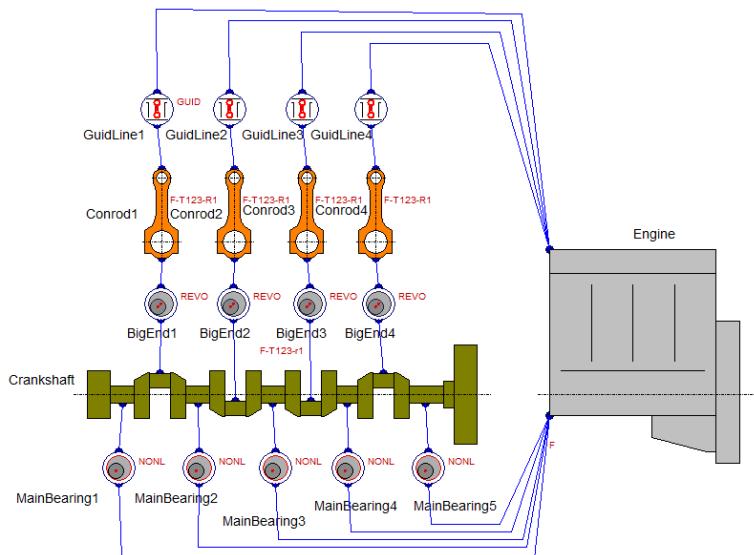
When performing noise calculations at the stage of finishing the design of an existing engine or at the later stages of design (detailed study of the design and workflow), it is necessary to use modern object-oriented tools.

One of these tools is the software of the AVL List GmbH, which is currently being actively implemented at the Department of "Heat engineering and automotive engines".

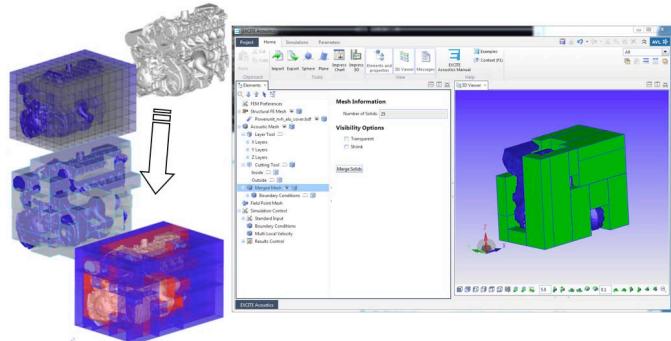


**Fig. 1.** The model of the equivalent cylindrical shell for the engine noise calculation

This software includes modules for calculating the working process (AVL BOOST, AVL FIRE), vibrations and engine noise (AVL EXCITE). Its use involves a significant amount of initial data about the parameters of the working process and engine design (Fig. 2, 3) and finite element models of its construction (Fig. 4).



**Fig. 2.** The diesel engine structural model in the module AVL EXCITE Power Unit

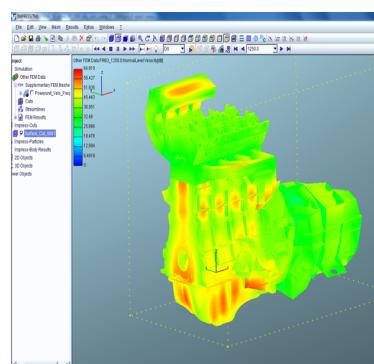


**Fig. 3.** Preparing the diesel engine calculation model in the module AVL EXCITE Acoustics

In this case, the calculation results contain detailed information about the vibrations of the external surfaces of the engine (Fig. 5), the spectral characteristics of its acoustic radiation, sound pressure overall level and the structure of its sound field in space.



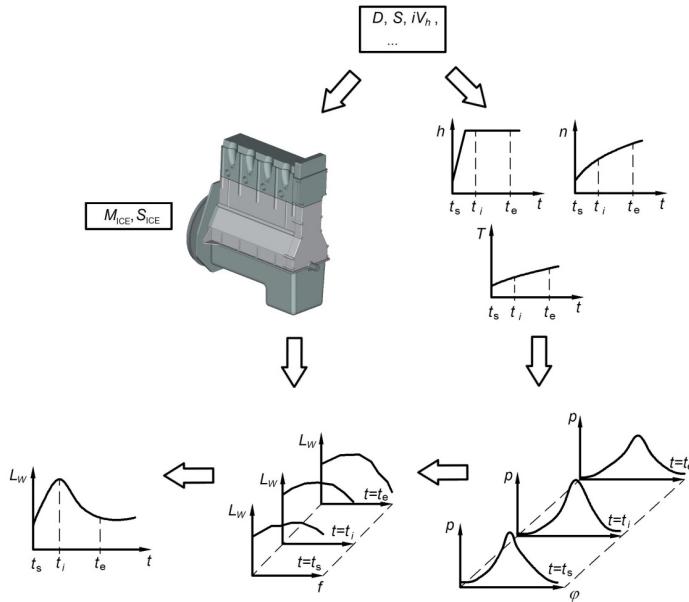
**Fig. 4.** An example of a finite element model of engine



**Fig. 5.** Example of the results of calculating the speed of vibrations of the external surface of the engine in module AVL EXCITE

### 3 Simulation of Engine Noise in Unsteady Operation Mode

To simulate engine structure-borne noise in unsteady operation mode, the technique presented at Fig. 6 is used. The method includes the following steps [3].



**Fig. 6.** The sequence of the engine structure-borne noise calculation for the transient mode

1. The determination of conceptual parameters of the engine. As input data, the engine type (diesel or spark ignition), cylinder diameter  $D$ , piston stroke  $S$ , compression ratio  $\epsilon$ , etc. are accepted here.
2. Modeling of the internal combustion engine design. It is performed depending on the engine design step using analytical dependencies or three-dimensional models. As a result, the necessary mass-geometric parameters are determined (mass  $M_{ICE}$ , external surface area  $S_{ICE}$  and engine length  $L_{ICE}$ , construction material parameters), which are also transmitted to the program for engine noise calculation.
3. Calculation of the working cycle taking into account the transient process. The transient process itself appears to be quasi-stationary. The difference between the engine cycle calculation in this case from the traditional stationary mode is to take into account changes in individual factors: the fuel supply, the thermal state of the engine parts that form the combustion chamber. As input data, the time dependences on the pump rack moving  $h$ , engine speed  $n$ , and temperature  $T$  are set.

However, for modern supercharged diesels and common-rail fuel systems, methods for calculating the injection characteristics and thermal state in an unsteady operation mode have yet to be developed, and it requires experimental data on the diesel transition process. The Department is carrying out research in this direction [9-14].

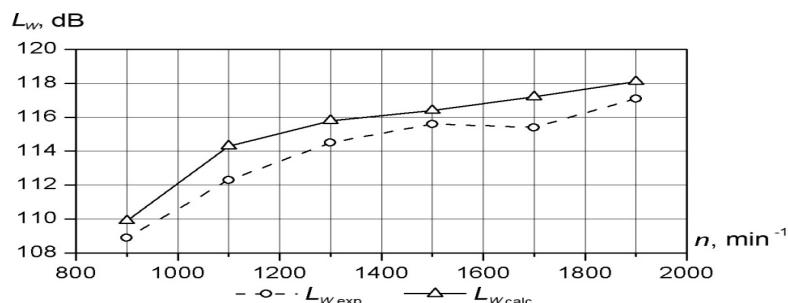
Therefore for a given time interval from  $n_s$  ( $t_s$ ) to  $n_e$  ( $t_e$ ), for each selected engine speed (time point) of the quasi-stationary unsteady operation mode, the working cycle and an indicator diagram are calculated. Then received data is transferred to the program for noise calculation.

4. Calculation of spectra and total sound power levels of the main engine structure-borne noise sources. At this step, the existing model of structure-borne noise from the working process and piston shifts for stationary mode is used.

First, the spectra and the total sound power level are calculated for each engine speed that makes up the transient process. Then, using the dependence of the speed change on time and the set of spectra and noise overall levels obtained for each operation mode, a graph of changes in the acoustic characteristics of the engine depending on the time or speed of the internal combustion engine in an unsteady mode is formed.

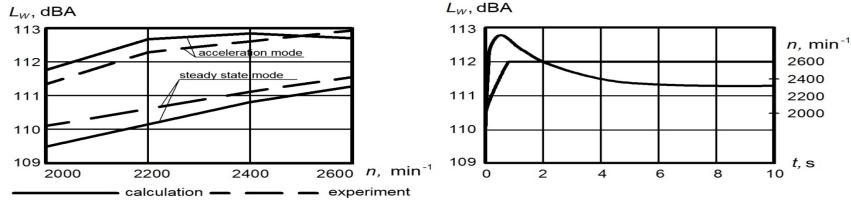
#### 4 Results of the Engine Structure-Borne Noise Research

The Department has accumulated a large volume of experimental and research results on engine noise using the equivalent cylindrical shell model [2-4]. For example, for the 8-cylinder diesel engine ( $D=12$  cm,  $S=13$  cm), a calculated and experimental noise research was performed for the speed characteristic, which showed acceptable accuracy of the results obtained (Fig. 7). Comparison of the obtained experimental and calculated total sound power levels showed that the difference between them is 0.8...2 dB, which is sufficient for such studies.



**Fig. 7.** Experimental and calculated total sound power levels of 8-cylinder diesel engine ( $D=12$  cm,  $S=13$  cm)

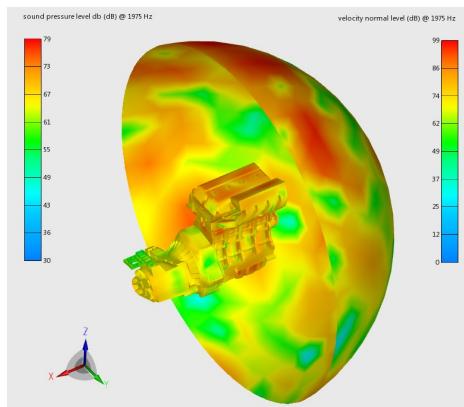
Fig. 8 shows the results of noise calculation in the acceleration mode for the 8-cylinder diesel engine ( $D=12$  cm,  $S=12$  cm). Experimentally determined engine parameters [3] describing the transient process were used as initial data.



**Fig. 8.** Results of noise calculation in the acceleration mode for the 8-cylinder diesel engine ( $D=12$  cm,  $S=12$  cm)

Using a set of initial data, the calculation of the working cycle of the diesel engine for a number of operation modes for speed characteristic was performed. After that, the noise level of the 8-cylinder diesel engine was evaluated in the acceleration mode, and the spectra and overall sound power levels were determined. Analysis of the calculation results showed that the noise level during acceleration is 1,5...2,5 dBA higher compared to the same speeds in the steady-state mode.

An example of the results of engine noise calculation in the form of a sound field and the distribution of the vibration speed of external surfaces obtained using the AVL EXCITE is shown in Fig. 9.



**Fig. 9.** Example of engine noise calculation results in the AVL EXCITE

## 5 Conclusion

1. A review of the models used to evaluate engine noise at different stages of its design is performed.
2. MADI developed methods for modeling the structure-borne noise of the engine and allow for sufficient accuracy of the calculation at the stage of external design.
3. At the stage of detailed study of the engine design, it is necessary to use modern software tools based, for example, on the methods of finite and boundary elements to calculate its vibration characteristics and sound field. As a similar tool, the AVL

software was used. For the calculations previously obtained information about the working process and a 3D models of the engine body parts are required. The calculations of external surfaces vibrations and the sound field of the engine for a number of operation modes were performed.

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