Modeling of diesel structure-borne noise in an unsteady operating mode

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Abstract. The article considers some aspects of the modeling of the working process and structure-borne noise of a diesel engine in a transient mode. The main factors that cause differences in the diesel working process from similar stationary modes are described. A method for calculating the structure-borne noise from the diesel working process at the transient mode is presented. A study of the noise of a 6-cylinder (S=10.7 cm, D= 12.4 cm) diesel engine during acceleration was performed. The results of calculations showed that the noise of the 6-cylinder diesel engine is 2...3 dB higher in the entire range of engine speeds compared to similar speeds in steady-state for diesel full-load characteristics.

1. Introduction
In urban traffic conditions, most of the time the internal combustion engine operates in unsteady modes (USM). The experience of vehicles exploitation shows that these modes not only reduce efficiency, increase emissions of toxic components of exhaust gases, but also increase the engine noise level. When evaluating the external noise of the car according to GOST, noise measurements are made during acceleration of the car.
Therefore, development of methods and software tools for studies of the internal combustion engine noise at transient operation modes is an important and actual task.

2. The impact of the transient operation mode on the working process of a diesel engine
Among the sources of the engine structure-borne noise, the working process is crucial for diesels [1, 2] due to the high rate of pressure increase in the cylinder. Therefore, one of the tasks of the study was to determine the factors that cause changes in the working process of a diesel engine in acceleration mode compared to stationary modes.

It was found that the main influencing factors are: decline of the processes of mixing and combustion, an increase in the ignition delay period, the possibility of fuel sub-injection and other violations of the fuel supply process, thermal inertia of engine parts.

A sharp decrease of air-fuel ratio is most typical for supercharged engines. As the engine boost increases, this problem gets worse. This is explained by the fact that with a sharp increase in the load, the rate of pressure growth significantly lags behind the rate of increase in fuel supply due to the inertia of the supercharger. Also, increase of fuel in the working mixture may be affected by imperfections in the engine control system, its inability to respond to the acceleration mode.

Deterioration of the mixture formation at the USM leads to local re-enrichment of air-fuel mixture...
in the combustion chamber. This is caused by violation of the dynamics of gas exchange. The air velocity in the intake channels decreases, which affects the intensity of the vortex movement of the charge in the cylinder. This factor is especially important for diesels with volumetric mixing, in which it is extremely important to ensure the necessary charge turbulence.

The working process of a diesel engine is largely determined by its fuel system [3-5]. The deterioration of fuel evaporation due to low temperatures of the charge air and the surfaces forming the combustion chamber also negatively affects the mixture formation. Deterioration of the mixture formation leads to an increase in the ignition delay period. If the control system does not change the injection advance angle, this leads to a transfer of the main combustion phase to the expansion process and burnout at the outlet, which negatively affects the combustion efficiency.

A particular impact on the deterioration of diesel performance in USM is the possibility of a violation of the quality of fuel supply, for example, the possibility of fuel sub-injection in the absence of those in the steady state operation mode. One of the parameters of the fuel system operation is the residual pressure or residual volume in the high-pressure fuel line (HPL). The last parameter appears if there is a residual vacuum in the HPL. Residual pressures (or vacuum) determine the initial pressures or initial free volumes in the HPL before the next injection cycle. When the diesel engine is running, the residual vacuum of the previous cycle is equal to the initial pressure of the subsequent one. At USM, when there is a change in the speed or displacement of the fuel pump rail, there is a corresponding change in the residual and initial pressures. The initial pressure determines the speed of sound propagation and the compressibility of the fuel. Consequently, there is a difference in the initial pressure at SM and at USM and, accordingly, a difference in the working process of a diesel engine. This is due to changes in the fuel supply, changes in the start and end of the injection, and its duration. The appearance of fuel sub-injection in diesel USM cycles is associated with the appearance of the initial pressure on the USM significantly higher or lower than for SM, with the same speed and fuel pump rail position [6, 7].

One of the important factors in the difference between transient and stationary modes is the influence of thermal inertia of engine parts [8]. This is especially evident on diesel acceleration mode. Thermal inertia increases the ignition delay period and increases the harshness of operation of the diesel engine, which leads to an increase in structure-borne noise.

When using existing software tools for calculating the diesel working process (the Diesel-RK software, programs developed in MADI, the AVL FIRE software), it is necessary to supplement the initial data set for the stationary mode with amendments that take into account the transition mode. To solve this problem, special software tools can be used, for example, the MATLAB Simulink.

3. Method for calculating the diesel structure-borne noise in unsteady mode

After studying the influence of the acceleration mode on the working process of a diesel engine, a method for calculating its structure-borne noise from the working process was formed. It is based on the model of an engine as a structure-borne noise source developed at the Department of Heat Engineering and Automotive Engines of MADI [1] and is shown in Figure 1. Noise calculation is carried out in the software "Acoustics of internal combustion engines", developed in MADI.

At the first stage, a set of data on the engine and its three-dimensional model is formed. Next, the working process is calculated taking into account the unsteady operating mode, which results in an array of indicator diagrams for different engine speeds.

At the next stage, using the obtained indicator diagrams, the structure-borne noise from the working process is calculated and an array of sound power spectra is formed. Finally a curve for the dependence of the total sound power level on the crankshaft speed and time is obtained.

4. Results of calculating the structure-borne noise of a diesel engine in acceleration mode

Using the developed method, the structure-borne noise of the 6-cylinders diesel engine (D=10,7 cm, S=12,4 cm) in the acceleration mode was calculated.

The main parameters of the research object are shown in Table 1.
Figure 1. Method for calculating the structure-borne noise of a diesel engine in acceleration mode.

| №  | Name of parameter                  | Value  |
|----|-----------------------------------|--------|
| 1  | Engine type                       | diesel |
| 2  | Layout                            | in-line|
| 3  | Type of cooling system            | liquid |
| 4  | Number of cylinders               | 6      |
| 5  | Bore $D$, mm                      | 107    |
| 6  | Stroke $S$, mm                    | 124    |
| 7  | Compression ratio $\varepsilon$    | 17.3   |
| 8  | Nominal speed $n_{nom}$, min$^{-1}$| 2260   |

At the first stage, the working cycle was calculated for steady-state and non-steady-state operating modes. As a result, a set of indicator diagrams was obtained, a comparative analysis of which showed differences in the rate of pressure increase near the TDC (Figs. 2 and 3).
Figure 2. Comparison of indicator diagrams in steady-state and acceleration modes at \(n=1000\) \(\text{min}^{-1}\).

Figure 3. Comparison of indicator diagrams in steady-state and acceleration modes at \(n=2300\) \(\text{min}^{-1}\).
At the next stage, the spectra and total sound power levels of the diesel engine working process were calculated for all the studied operating modes.

To verify the calculations, an experimental determination of the noise level of diesel engine was performed. It showed good convergence of the results.

Some calculation results are shown in Figure 4 and Figure 5.

Figure 4. Changing the overall sound power level of diesel engine in different operating modes.

Figure 5. Sound power spectra of diesel from the working process at \( n = 2300 \text{ min}^{-1} \).
Analysis of the sound power spectra showed that in the acceleration mode, the sound power level in the low frequency range of the spectrum is higher than in the stationary mode, over the entire engine speed range.

As a result, the overall sound power level of the diesel engine in the acceleration mode for all crankshaft speeds is 2...3 dB higher than in similar stationary modes.

5. Conclusion
1. The analysis of the features of modeling the working process and structure-borne noise in the unsteady mode for a diesel engine is made. A method for calculating the structure-borne noise of the engine in the acceleration mode is formed.
2. Simulation of the operating cycle of 6-cylinder diesel with D=10.7 cm, S=12.4 cm in the software "Diesel-RK" in steady-state mode according to the full-load characteristic is performed.
3. The structure-borne noise of the 6-cylinder diesel was calculated in the software "Acoustics of internal combustion engine" in steady-state mode based on the full-load characteristic. The difference in the obtained total sound power level for engine speed $n=1000 \text{ min}^{-1}$ and $n=1500 \text{ min}^{-1}$ compared to the experimental values was less than 1 dB.
4. The calculation of the working process and structural noise of the studied diesel engine in the acceleration mode from the minimum to the maximum speed is performed.
5. The results of studying the structure-borne noise of diesel engine in different operating modes are compared. In the acceleration mode, the overall sound power levels of the studied diesel engine are 2...3 dB higher than in steady-state modes in terms of full-load characteristics over the entire range of diesel speeds. Thus, when developing measures to reduce the structure-borne noise of the designed diesel engine, it is necessary to take into account its operation in an unsteady mode.

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