REDUCTION OF STRUCTURAL NOISE OF VEHICLE ENGINE-ESSENTIAL FACTOR IN DECREASE THE ACOUSTIC POLLUTION OF ENVIRONMENT

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1. INTRODUCTION

External noise of automobiles and buses (hereinafter referred to as Motor Vehicle -MV) along with the toxic properties of ICE exhaust gases characterize their environmental parameters.

Due to this fact as far back as 1968. UN ECE Regulations were introduced, which restricted the level of external noise (in dBA) of the different categories of automobiles and buses. Standards for noise levels in automobiles and buses were being tightened all the time. For example, maximum permissible noise levels in light vehicles so far have declined from 82 to 74dBA, and heavy trucks like KAMAZ decreased from 92 to 80dBA (The UN ECE Regulation № 51-02). In the Soviet Union, standards for external noise of MV, including motorcycles, have begun to act with 1975. and the standards were different, more liberal and only 2000. have been equated with the international ones.

Of course, the former higher noise levels did not always require to carry out special measures to reduce external noise of Soviet MV's. However, after the introduction of ECE Regulation № 51-02 since 2000. development departments of automobile and engine plants in Russia started to give greater attention to the solution of this problem.

In accordance with the methodology of the UN ECE Regulation № 51, MV test aimed to determine the external noise is carried out for a ride 20m long, with the intensive acceleration and at high engine speeds. For example, a light automobile of VAZ-class with manual transmission accelerates on the specified trajectory with 2 and 3 shifts. Acceleration with 2 gear shifts begins with 50km/h (approximately n=4500rpm), and ends with n=5200 rpm.

Ranking of sources of external noise according to the internationally accepted method of testing shows as a rule that the majority of MV's manufactured in Russia, express the most influential source on the overall level of external noise of vehicle as a structural engine noise (system and exterior surfaces vibration).

Figure 1 shows the example of 2 spectra of external noise in case of acceleration of a heavy truck with 5-speed and 8-speed transmission. The initial speed of diesel engine crankshaft

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during acceleration of the vehicle with 8 gears is much lower, and virtually does not increase, while the 5-speed gearbox causes a sharp acceleration the vehicle. This circumstance explains that high-frequency part of the spectrum of external noise at frequencies above 800 Hz, with the 8-speed transmission is reduced by 5-8 dB(A), which leads to a decrease in the overall level of external noise of the vehicle of 4 decibels.

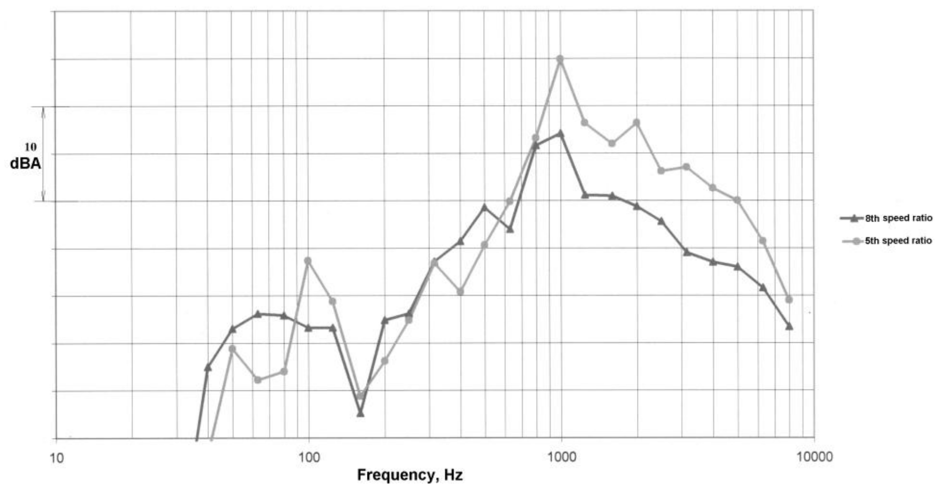

Figure 1: *The dependence of external noise spectra from the acceleration of 5-speed and 8-speed transmission*

By comparing the spectra of noise during acceleration of the vehicle with 5-speed transmission and freewheeling with the engine shut off, it followed that in the frequency range from 630 to 5000Hz noise decreased from an average of 78 to 69 dB (A), and the overall level of external noise, the car has decreased by 10 dBA. rpm.

2. ACCEPTABLE LEVELS OF STRUCTURAL NOISE OF AUTOMOBILE ENGINES IN THE USSR AND THE RUSSIAN FEDERATION

In NAMI there used to be developed OST 37.001.266-83 (Industry Standard), "The noise of automobile engines. Permissible levels and measurement methods ", which came into effect from 1985. It was based on the techniques of noise measurement of stationary machines. In this case, normalized to a distance of 1m, maximum structural noise at the point with the highest noise level) in dBA with the engine on the max.rpm .This document guided until 2010. motor factories of the Russian Federation in the preparation of technical specifications (TU) for ICE relative to its level of structural noise. In OST 37.001.266-83, the boundary levels of structural noise on the serial engine of Soviet manufacturers were adopted 103dBA, and for prospective engines 101dBA. Now, such noise levels of ICE should be considered as too high. These noise levels of ICE were caused primarily by the tougher flow of the working process in automotive diesel engines of Soviet manufacture, lack of turbocharging, increased frequency of the crankshaft of diesel engines vibration without turbocharging, insufficient rigidity of the crankcase details of individual ICE including through the use of aluminium alloys. In those years, the main objective was to reduce engine mass and reduction of fuel consumption of ICE, which did not help reduce the structural noise of ICE. In addition, as noted above, the rules to limit external noise of vehicles until 2000. were much more liberal then UN / ECE № 51.

The situation has now changed dramatically, the engine builders are required primarily to fulfil the modern environmental requirements for MVs: standards for emissions of automobile engines (requirement E-3: E-4) and standards for exterior noise of MVs (the UNECE Regulation № 51-02), but without reducing the structural noise of MVs, the problem of reducing engine external noise in the majority of MVs produced in Russia can not be solved.

Hence, the relevance of introduction of a new document for standardizing the noise of automobile engine produced in Russia was evident.

In addition, in recent years, new regulations on noise assessment, taking into account the metrological modern technology adopted in the measurement of noise of stationary machines. Based on these circumstances, in 2010. in NAMI, for the first time in Russia, was designed GOST (State Standard) R 53838 to limit the structural noise of ICE (1).

3. NOISE CHARACTERISTICS OF AUTOMOTIVE ENGINES

When rationing engine structural noise according to GOST 53838, the following will be taken into account:

- 2.1 Adjusted, for frequency response of A sound level meter, sound pressure level LrA, dBA;
- 2.2 Sound pressure levels in octave or third octave bands Lp, dB;
- 2.3 Sound power level in octave bands Lw with mean frequencies ranging from 125 to 8000 Hz, dB;
- 2.4 Adjusted, for frequency response of a sound level meter (hereinafter - corrected to A), sound power level L_{WA}, dBA;

Noise characteristics of clause 2.1 shall be determined in the certification and verification of engines (acceptance testing), and their values may be claimed by the manufacturer (supplier) in accordance with GOST 30691.

Noise characteristics of clause 2.2-2.4 define for research purposes in the acoustic design of engines and comparison of their structures by acoustic emission, for comparison with the noise standards of other ICEs, etc. In the acceptance testing of the new engine, all the noise characteristics listed in 2, should be determined and for control tests - only the sound pressure level - LrA. (2.1)

Noise characteristics are determined for single engine and release (types, models, brands), or serial deliveries and are included in the supporting documents in the application form in accordance with GOST 30691 and (or) in the operational documents (passport, label, manuals and others by choice of manufacturer or supplier). Manufacturer (supplier) guarantees the values of noise characteristics specified in the engine documents or in a contract for the supply.

Noise characteristics for the serial delivery engines are based on statistical analysis of measurements sampling machine according to GOST 27408 (2). In accordance with GOST 53838 LrA sound pressure levels for engines, production of which will begin before 01/01/2012, as well as engines upgraded during this period, the measurement at different rpm of crankshaft rotation ***n*** and the engine at full load, should not exceed the values shown in Table. 1.

Permissible sound pressure levels LrA at the measuring distance of d=1m from the engine, production of which began before and after 01/01/2012 was listed in Table 1.

Table 1: *Permitted values of sound pressure* L_{rA}

Engine type	Rated crankshaft speed min^{-1}	Standard value dBA		Type of transport vehicle
		Before 01.01.2012.	After 01.01.2012.	
V-8 Diesel	2100	98	96	M3, N3
V-6 Diesel	1900	97	06	M3, N3
V-8 Petrol	3200	94	94	M3, N3
L-6 Diesel	2500	97	95	M2, N2
L-4 Diesel	over 2500	98	96	M1, N1
L-4 Diesel	locked 2500	96	94	M2, N2
L-4 Petrol	over 4000	99	97	M1, N1
L-4 Petrol	locked 4000	96	94	M1, N1

Remark:

For plants manufacturing engines for vehicles of its own, the rules on the permissible sound level values are not established. Level of external and internal noise of these vehicles (Motor Vehicles - MVs) shall comply with ECE Regulation № 51-02, and GOST R 51616 (inside noise Motor Vehicles).

This provision also applies to cars and buses (MVs), manufactured by other companies, which apply the above-mentioned engines.

As can be seen from Table 1, permitted values of sound pressure levels -LrA should not exceed 99, or 97dBA (as of 2112.).

As follows from the notes on the Table 1 for plants manufacturing engines for vehicles of its own production, the noise of vehicles is normalized in accordance with the requirements of ECE Regulation № 51-02 (GOST R41.51) and GOST 51616 (internal noise). The same goes for the other manufacturers where the above-mentioned engines are applied. The definition of conditions is due to the acoustic characteristics of the test room. Volume of the room without sound insulation coverings should not be less than 200 m^3. The coefficient of the acoustic conditions of the premises K_{2A} (dB) should be determined, its value should not exceed 2dBA. Methods of determination of K_{2A} are annexed to the GOST 53838 [1].

In the recent years, in the global engineering, it is common that engine manufacturers announce their own noise characteristic data [3].

In this regard, in the appendix to GOST 53838 there is a method of determining the declared noise of the engine. Engine manufacturer guarantees that in conditions of mass production, the sound pressure level Lra will not exceed the values quoted in Table 1 for more than 1dBA.

4. WAYS TO REDUCE THE STRUCTURAL NOISE OF VEHICLE ENGINE

There are two fundamentally different ways of reducing engine structural noise.

- 1. Reduction of the structural noise of the engine itself (*active* methods of noise reduction);

- 2. *Passive* methods of reducing structural noise due to application of vibro-acoustic material installed around the vehicle's powertrain (the screens and materials on the walls of the engine compartment of a bus, full insulation of the engine).

The first method is more complex, especially its not easy to implement under the current design of ICE, it requires specialized knowledge, necessary experimental equipment and instruments, required software, and most importantly- changing the design of ICE, and hence the acquisition of new equipment for the manufacture of quieter engine. Nevertheless, in the whole global automotive engine development in recent years suggests that the first method is preferred. In addition to reducing the external noise of automobiles and buses, the application of the first method reduces the cost of MV, while the application of the second way of reducing structural noise increases the cost of MV. For example, a full insulation of powertrain compartment of heavy vehicles increases the cost of MV for about 1000 $ U.S.

The second method is used in the current design of ICE and there is no guarantee that screens and elements of the capsule in the service conditions, after the maintenance and repair of MV will be set back, or will be reinstalled in such a way that the necessary sealing of the power unit is violated (there are gaps, openings, etc..) while increasing external noise of automobile or bus, and eventually leads to the conclusion that the use of passive methods of noise reduction is pointless. At the present time in Russian Federation in conditions of operation MVs, only the noise of engine exhaust system is controlled for the stationary position of ICE, by use of the method according to ECE Regulation № 51-02. [4].

5. FACTORS INFLUENCING THE FORMATION OF STRUCTURAL NOISE OF AUTOMOBILE ICE

5.1 The Organization Workflow

(Below there are data on the example of the results of experimental work carried out with the prototype V-type diesel engine, designed for heavy trucks). With the direct fuel injection, the degree of pressure increases over time in the cylinder at the time of the explosion of the working mixture is usually determined by the maximum value of structural noise rate.

This is shown by use of flow indicator diagrams obtained experimentally and the character of variation of noise in the first seconds after the explosion of the working mixture. The shorter the duration of this period, the higher the level of structural noise rate. The essential value of variation of flow indicator diagrams and noise over time relies on the fuel system design and characteristics of the fuel supply. As experience has shown in recent years, the use of Common Rail fuel system contributes both to reduce the toxicity of exhaust gases and a decrease structural noise rate of ICE. This is confirmed by the experimental work on samples of new diesel engines of Yaroslav motor plant -JAMaZ (P-4). and the report is given in [5].

5.2. Relining the piston

Reduction of structural noise, by reducing side clearance between the piston and the cylinder, can be carried out in a very limited extent.

5.3. The angle of fuel pre-injection

Earlier in the USSR, when there were not in power the conditions of performance standards for toxicity, one of the priorities was to reduce fuel consumption. The maximum value of pressure on the indicator diagram should be located as close to TDC (Top Dead Center), and in this case, the major impact on structural noise is done by even a slight change in the angle of fuel pre-injection.

In those years, this angle is equal to 16-18 deg. to TDC for a diesel KAMAZ (Kamsky Automobile Factory) and JMZ. Structural noise rate was very sensitive to a variation of the angle of fuel pre-injection and, accordingly, the rigidity of the flow of the working process in a diesel engine.

Currently, in striving to achieve modern standards for toxicity, the character of the flow of indicator diagrams in the Russian diesel engines has virtually changed, the fuel pre-injection angle was positioned closer to TDC, and as shown by recent experience, the variation of the angle of fuel pre-injection did not provoke a significant change of structural noise rate of KAMAZ-type engine.

5.4 Turbocharging

Turbocharging increases the energy performance of ICE, which in turn can lower the maximum speed of diesel engine crankshaft. Every drop of crankshaft rotation shaft for 100 rpm leads to a noise reduction for about 0,8-1,0 dBA. Turbocharging increases the maximum pressure in the cylinder, but at the same time, it reduces the rigidity of the workflow, which also contributes to a decrease of structural noise.

So, for example, diesel engine KAMAZ-740, manufactured before 1995., with n = 2600 rpm without turbocharging, produced noise level 4-6 dBA higher than noise produced now with the turbo diesel KAMAZ engines (n = 2100 rpm) of the same displacement.

5.5 Engine crankshaft speed

As the speed of rotation of the crankshaft varies, with the fixed values of load and angle of fuel pre-injection, the shape of the pressure curve in a cylinder fixed on the angle of rotation of the crankshaft (the indicator diagram) varies only slightly. Minor changes are associated with different values of turbocharging, due to the variation of crankshaft speed of rotation.

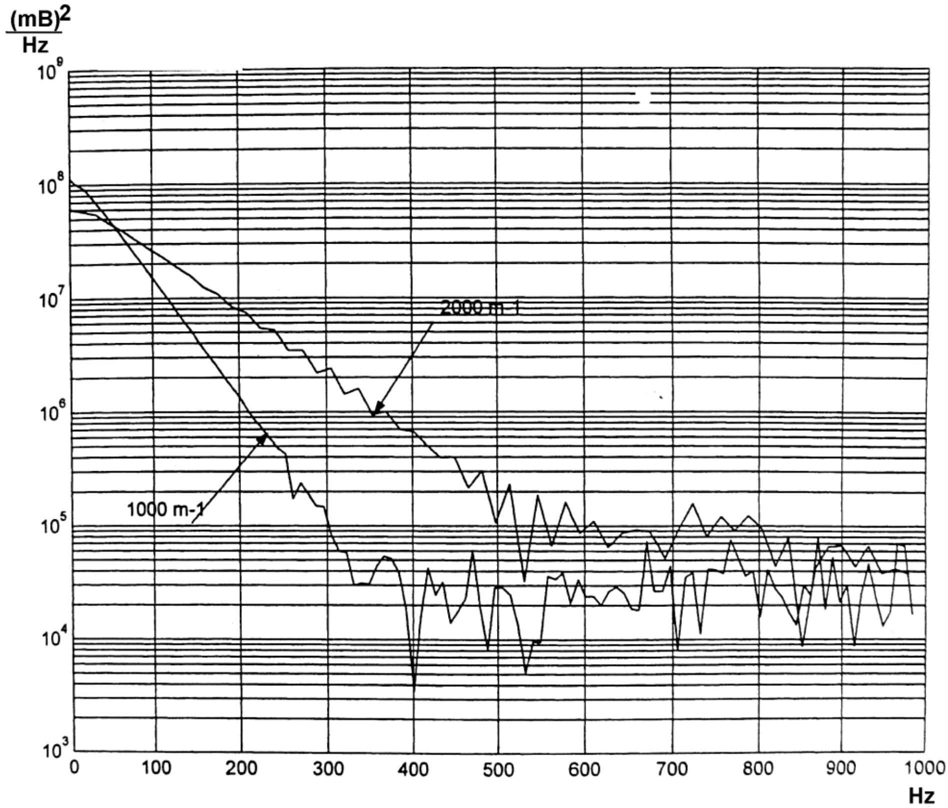

Figure 2: *Frequency content of the pressure pulse in cylinder for different crankshaft speeds*

Basic attention in the following text will be paid to the frequency analysis in time domain. Frequency of changes in pressure in the cylinder should be investigated in the absence of fuel, since maintaining the same cycle of fuel supply at different engine speeds presents certain difficulties. Performed studies (without fuel supply) have shown that the increase of the engine crankshaft speed from 1000 to 2000 rpm will *reduce* duration of pressure pulse. It is obvious that reducing of the duration of pulse leads to an *expansion of its frequency content* to the area of higher frequencies (pulse becomes more "sharp"). This phenomenon is confirmed by the analysis of the frequency of the pressure pulse in the cylinder. (Figure 2).

The above results explain the reason for increasing noise with the increase of engine crankshaft speed.

5.6 Load of diesel engine

Effect of engine load was investigated under the conditions of engine speed at 2200 rpm and the fuel supply from 25% to total 100%. The angle of the start of fuel injection was 18 degrees before TDC.

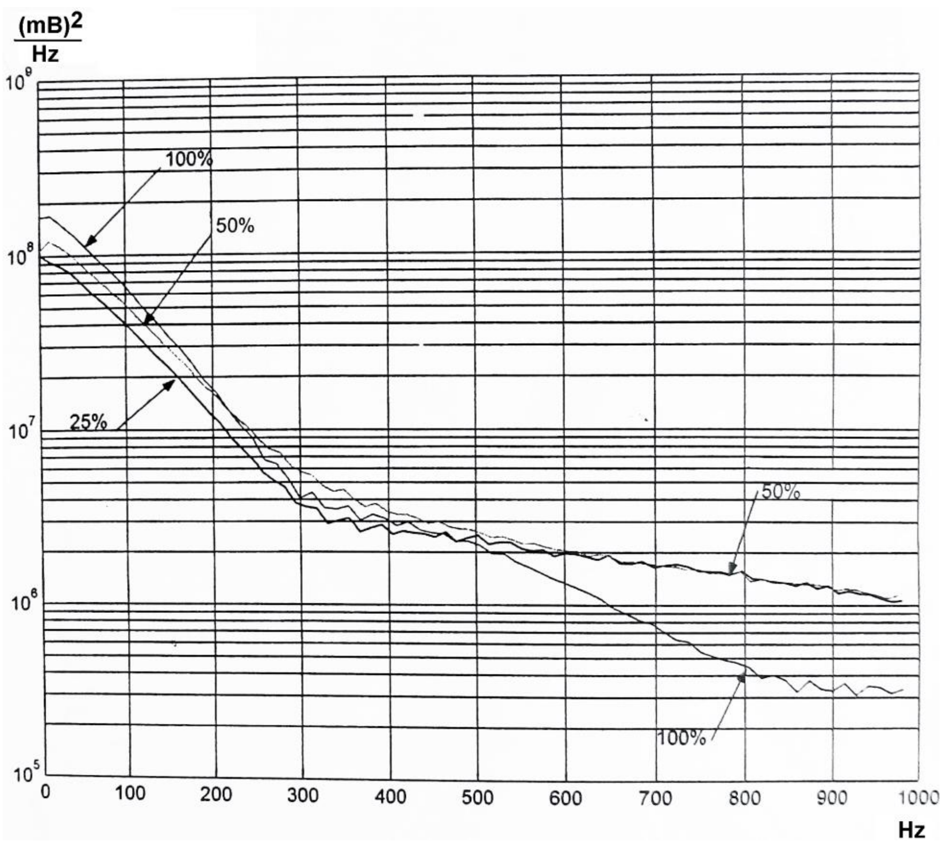

Figure 3: *The frequency content of the pressure pulse in the cylinder of a diesel engine with different fuel supply*

It turned out that an increase in fuel supply will lead to the *reduction* of gradient of the pressure front in cylinder, caused by the start of combustion. It is known that the gradient of combustion front determines the rigidity of the engine work, which affects the noise level of the combustion process. This phenomenon is also reflected in the spectral composition of the pressure pulse in the cylinder (Figure 3).

When the load increases the high-frequency components in the spectrum of influence of pressure decreases by about 70%, and in the low frequency zone the increase is less than 10%. This indicates a softening of the combustion process by increasing the fuel supply. It is also possible to notice that when the fuel supply is increasing, at the same time the pressure at the end of the compression stroke increases too, due to high boost pressure as a result of higher energy of exhaust gases. This explains the reason for reducing the rigidity of the combustion process. At the beginning of the combustion process, combustion of fuel-air mixture is quicker due to the lower duration of ignition delay. As a result, the accumulated unburned mixture is smaller and the intensity of the explosion in the initial period of combustion is lower. This explains the decrease in rigidity of the process with the increase of the fuel supply.

5.7 Transient regimes of diesel engine (acceleration without load)

Tests of engine transient regimes of operation of ICE are very important, since in this case vehicle acceleration is simulated up to some extent according to the ECE Regulation № 51 for external noise measurement. It should be noted that the noise level does not significantly change with the variation of engine load.

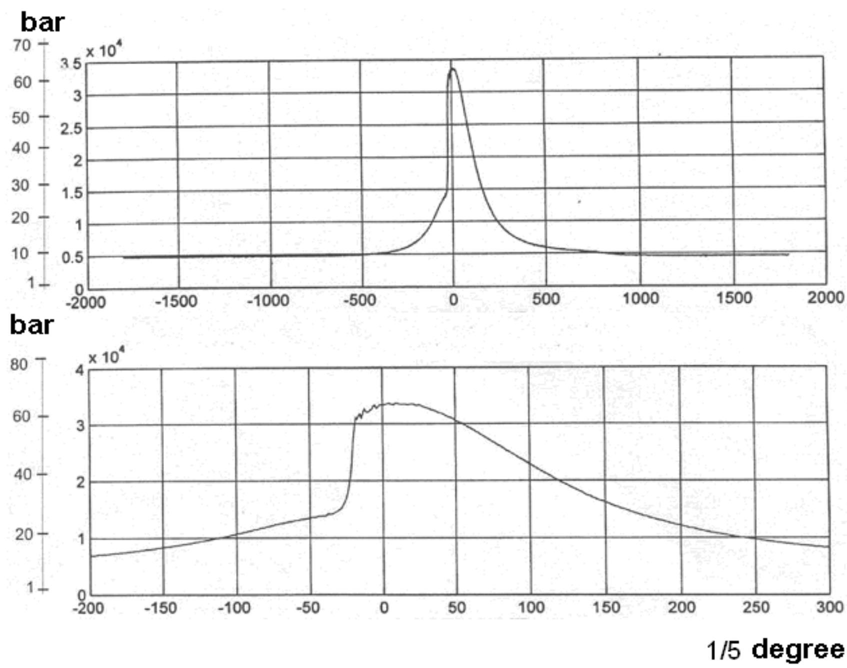

Figure 4: *The first cycle of the engine operation with a sharp increase of fuel at idle*

In our case, a sharp turn of the fuel pump lever is performed from zero (idle) to maximum with no load on the engine crankshaft. These tests simulate the most dramatic changes in the two main operating parameters of the engine: fuel supply cycle and the engine crankshaft speed. Given that the engine was equipped with a gas turbine supercharger, as an inertial element, this kind of test is important because for the automobile engine, such regimes are typical. In terms of noise emissions, the greatest attention should be paid to the indicator diagram of the first cycle after a sharp increase in fuel supply (Figure 4).

At this point, the engine speed and the magnitude of the boost pressure is the same as when idling and the fuel supply is maximal. The diagram shows that the leading edge of the combustion process is very steep and significant in magnitude. Frequency analysis of the process and the corresponding process on the defined regime (i.e. the regime in which the boost pressure reached its defined value) is shown in Figure 5.

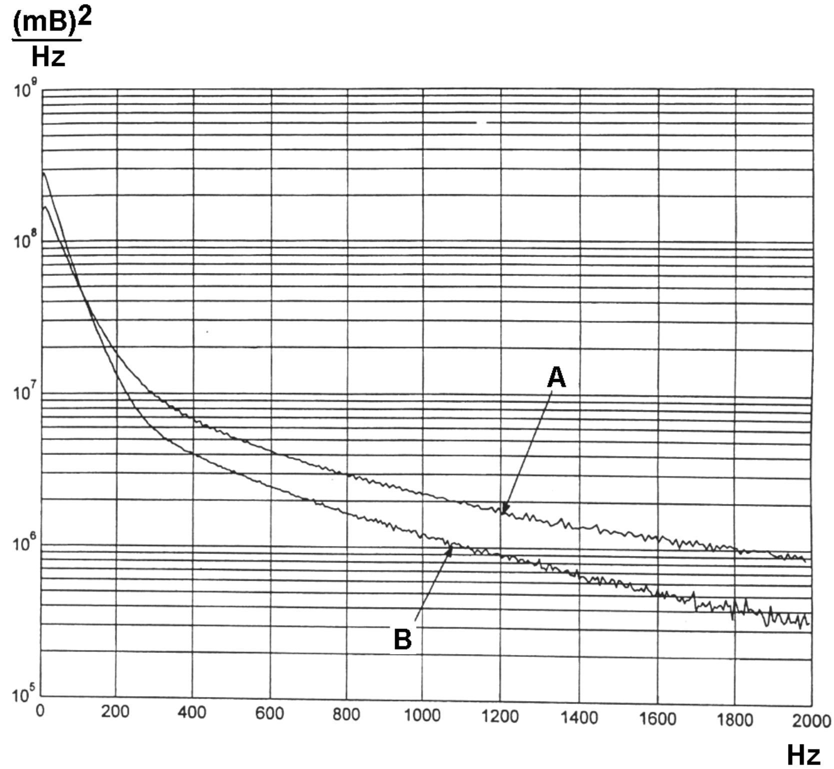

Figure 5: *The frequency content of the pressure pulse in the cylinder at work on the defined regime (n = 1000 rpm, the fuel supply 100% - the curve "B") and with increasing speed of the diesel engine crankshaft - the curve "A"*

It is evident that when there is a sharp increase in fuel supply, the frequency content of the influence of pressure pulse significantly increases in the high frequency domain. This corresponds to an increase in the leading edge of combustion. The reason for that is that the parameters of the pressure at the end of compression are small due to the low boost pressure.

5.8 The design of the external surfaces of ICE

The design of the external surfaces plays a significant role in the formation of structural noise of the engine. The presence of separate cylinder heads, the application of aluminium alloys. insufficient bending stiffness of the block increases the noise level of ICE.

Significant role in the formation of structural noise shows the character of the flow of bending vibrations of the block in the frequency of about 1000Hz, caused by shock loads during the early stage of the operation process. Tightening of the block by increasing its weight and with the application of modern fuel system helps reduce the noise of diesel engine. An example would be the last work JMZ cooperation with the firm AVL (Austria) to reduce the noise of prototype diesel engine P-4.

Currently, there is the increasing application of a calculation-experimental method for studying structural noise of ICE.

Its essence is as follows:

Calculation part consists of two phases

- Calculation of forms of bending vibrations of the external surfaces of ICE by use of Finite Element Method (FEM).

- Application of the Boundary Element Method (BEM) to evaluate directly the nature of structural noise of the engine caused by vibration [6].

CONCLUSION

The above-mentioned method of investigation requires the mandatory identification of computational models based on the results of the first experimental work, only after that the method should be modified, i.e. perform the search for ways to improve the design of ICE.

Such computational-experimental work was carried out with the participation of the authors of the article, which allowed a presentation of specific recommendations for change of the character of bending vibrations by modifying the design of the engine block of the tested diesel ICE, in order to increase its rigidity, as well as changing the design of some of its outer parts. These recommendations were made based on analysis of forms of elastic vibrations received directly on a running diesel engine with multi-channel equipment for vibration measurement.

REFERENCES

[1] GOST P 53838-2010 Automobile engines. Permissible noise levels and methods of measurement M. Standartinform. 2010.

[2] GOST 27408 Noise ratio. The statistical treatment of results of determination and control of noise levels, emitted by machines.
[3] GOST 30691-2001 (ISO 4871-96) Noise of machines. Appearance and control of values of the noise characteristics.
[4] GOST R 52231-2009 External noise of cars in service. Permissible levels and methods of measurement M. Standartinform. 2009.
[5] Khachiyan, A.S., Sinyavsky V.V. Diesel engines of modern light vehicles Features of working processes and systems. Monograph. MADI, M, 2009. pp. 127.
[6] Russinkovsky V.V. Development of a method for calculating the vibration and structural noise of the body parts of automotive diesel engines. Dissertation for the degree of M.Sc., Moscow, 2005.