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Active system for reduction of noise parameters of car muffler with the use of pressure sensors based on silicon microcrystals

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ABSTRACT

Purpose: The article contains the results of research and development of a system for active noise damping of an automobile engine. The proposed system of active noise suppression can significantly reduce the sound pressure level in the frequency band up to 500 Hz. The robotic principle of the developed system is based on the addition of an additional buffer tank with a variable volume in the silencer system. The use of high-temperature sensors with strain gauges based on silicon microcrystals to obtain information on the parameters of sound vibrations arising during the exhaust gas outflow made it possible to create a control system for changing the volume of the buffer tank. The results of testing the proposed system of active noise suppression of an internal combustion engine are presented.

Design/methodology/approach: The active noise suppression system based on the Helmholtz resonator used tools to control general noise levels, experimental tests, complex mathematical modelling of acoustic processes in Solidworks, taking into account the conditions of propagation and attenuation of sound energy by intermediate closed volumes.

Findings: The use of an additional resonator chamber with variable volume in the exhaust muffler of the internal combustion engine allowed to reduce the resonant phenomena in the zone of low-frequency pulsations of exhaust gas pressure from 57 Hz to 43 Hz at frequency drift in the range of 310… 350 Hz, which significantly improved its noise characteristics.

Research limitations/implications: For further research, to improve the characteristics of the active noise suppression system, it is advisable to consider the use of several in additional cameras of the Helmholtz resonator and to clarify the algorithm of the controller in transient modes of engine operation.

Practical implications: The developed design of active noise reduction is simpler in comparison with analogs and allows reducing the noise of exhaust gases in a low-frequency range.

Originality/value: To reduce the noise, a variable-volume Helmholtz resonator was used, the efficiency of which is provided by high-temperature sensors of the original design.

Keywords: Active noise damping, Car mufflers, Noise reduction, High-temperature pressure sensors, Filamentary crystals, Loss of sound wave transmission

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

An important stage in the creation of modern cars with improved environmental and consumer qualities is their vibroacoustic characteristics improvement. This fact encourages manufacturers to use methods to reduce both external and internal noise generated by cars [1].

The main noise source of the active engine is the exhaust gas noise, and the acoustic power of the attenuated exhaust noise reaches 100 W (up to 140 dBA) and many times higher than the noise power of other elements and systems of the engine [2].

The frequency sound spectrum of this source has a pronounced low-frequency nature, which determines its weak absorption during open-air propagation. To reduce the sound pressure levels in the frequency bands to 500 Hz, it is necessary to use mufflers with huge dimensions and weight. This contradicts the special requirements for mufflers, so the development of new mufflers' designs, which would combine high efficiency over the entire frequency range, low opposite pressure, and small mass and size parameters, is a very important task.

Noise mufflers are divided according to the operational principle into dissipative, reactive, combined, active and hybrid [3].

Dissipative mufflers (tubular or plated) containing channels filled with sound-absorbing material is the most popular. These are absorption-type mufflers, where sound energy is converted into heat in a sound-absorbing material layer. The use of such mufflers is limited by the high packing costs, their clogging and operation burnout, etc.

Reactive mufflers reflect sound due to the formation of a "wave plug", which makes it difficult to transmit acoustic vibrations. In such mufflers, the damping effect is achieved mainly by reflecting the sound energy back to the source. They are effective for reducing noise in narrow frequency bands and in tonal components.

Combined mufflers use both the sound absorption property and the sound energy reflection property. An example of a combined muffler is a chambered muffler, the inner surface of the walls of which is filled with sound-absorbing material.

Recently, active mufflers are increasingly used, the principle of which is to form a sound signal of the same amplitude and frequency as unwanted sound, but opposite in phase, and hybrid (active-passive) [4]. Active compensation is based on the superposition and interference principles – the imposition in space (on the surface) of two or more sound (vibration) waves, in which at different space points (surface) is the resulting wave damping.

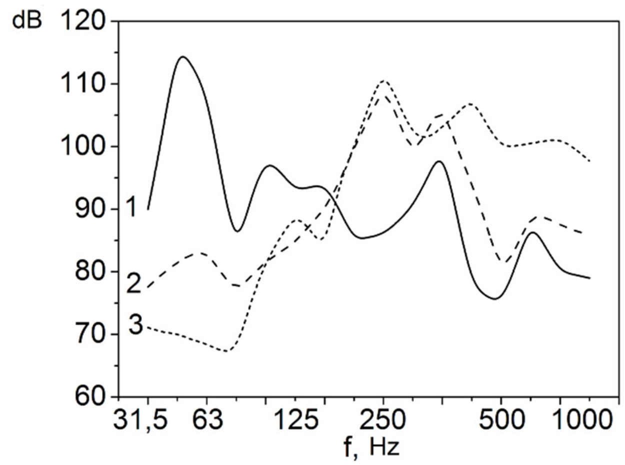

Fig. 1. 1/3-octave spectrum equal to the sound pressure of the VAZ 2111 engines at low robotic modes: 1 – 1600 rpm; 2 – 5600 rpm; 3 – 5500 rpm

Changing the engine speed causes a significant change in the operational noise (Fig. 1). Therefore, mufflers with constant characteristics calculated for a given resonant frequency are not always effective, because the resonant frequency drift can overflow the range of displacement for which the muffler is designed [5].

A Helmholtz resonator is usually used for different resonant frequencies. But this method is not always effective in the case of significant frequency drift.

2. Sample development

A possible solution is to use an active muffler resonant frequency suppression system using strain gauges to capture primary information about the dynamic processes that determine the noise level.

To take into account the resonance frequency drift, reduce pulsations in the muffler and adjust the active noise dumping system to the frequency that is extinguished by the muffler, it is proposed to use a buffer tank of variable volume (Fig. 2).

The combined system of noise dumping in the muffler is presented in Figure 2. The sensor of the reference sound signal 1 at the input of the muffler and the sensor of the residual sound signal 6 in the output zone of the exhaust gas flow detects the noise level. As a result of processing the control unit 2 of these signals, an additional signal is formed, which is transmit through the amplifier to the solenoid 5, which controls the position of the diaphragm 4, which changes the volume of the buffer tank 3. This design allows to dynamically change the resonant frequency of the buffer tank depending on the operating modes of the engine, which reduces its noise characteristics.

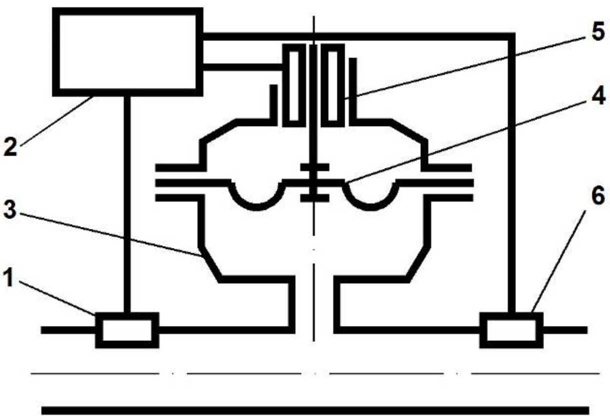

Fig. 2. Combined noise suppression system in the muffler: 1 – strain gauge reference signal; 2 – control unit; 3 – additional buffer tank; 4 – diaphragm; 5 – electromagnet-solenoid; 6 – strain gauge residual signal

For efficient operation of the proposed design, the parameters of the additional buffer tank for the first harmonic of the engine noise should be determined [6].

The internal combustion engine emits noise, the first harmonic of which has a frequency:

$$f_1 = \frac{ni}{60\tau},$$

where τ is the frequency factor (for four-stroke internal combustion engines τ = 2).

Given the crankshaft frequency n = 1200 min^{-1}, the frequency of the first noise harmonic will be

$$f_1^w = \frac{1200 \cdot 8}{60 \cdot 2} = 80\ Hz$$

The resonance frequency of the resonant muffler is calculated by the formula [7]:

$$f_0 = (c/2\pi)\sqrt{\frac{S_0}{l_c V}},$$

where c is the speed of sound in the environment; V – is the volume of additional buffer tank; $S_0 = \pi d_0^2/4$ – is the cross-sectional area of the additional buffer tank neck; d_0 – is the diameter of the additional buffer tank neck; $l_e = l + l_{att}$ – is the effective length of the additional buffer tank neck, determined in addition to the actual length of the neck by its attached length, which is determined by the presence of rapidly damping inhomogeneous waves in the vicinity of the additional buffer tank neck.

After a series of transformations and taking into account the symbols of Figure 2 will look like this:

$$\frac{S}{lV} = \left(\frac{2\pi f_1^p}{c}\right)^2. \tag{1}$$

For = 80 Hz we have:

$$\frac{S}{lV} = \left(\frac{2\pi f_1^p}{c}\right)^2 = 2{,}19 \tag{2}$$

It is necessary to select the effective parameters of the additional buffer tank of the resonant muffler: l, S, V. And they must be related by equality (1). Let the neck radius $r = 0{,}01$, then:

$$S = \pi r^2 = \pi 0{,}01^2 = 3{,}14 \cdot 10^{-4}\ m$$

Let the length of the neck is $l = 0{,}05m$. Then, given (2):

$$V = \frac{S}{2{,}19l} = \frac{3{,}14 \cdot 10^{-4}}{2{,}19 \cdot 0{,}05} = 2{,}87 \cdot 10^{-3} m$$

Let the height of the additional buffer tank H = 0,1 m, then its area:

$$S^{ч} = \frac{V}{H} = \frac{2,87 \cdot 10^{-3}}{0,1} = 2,87 \cdot 10^{-2} m^2$$

Hence we have the radius of the additional buffer tank R:

$$R = \sqrt{\frac{S^{ч}}{\pi}} = \sqrt{\frac{2,87 \cdot 10^{-2}}{\pi}} = 9,56 \cdot 10^{-2} m$$

To ensure reliable obtaining of primary information about the dynamic processes in the muffler, which determine its noise characteristics, sensors that were operational in a very aggressive environment are needed. For example, the temperature of the exhaust gases of a diesel engine varies in the range of 500…700°C, carburettor – 700… 1000°C. When entering the muffler, the exhaust flow rate changes in the range V = 50… 130 m/s, and the pressure in the volume reaches 0.1 MPa when the temperature changes in the range T_0 = 290… 500°C. [8].

For use in the active noise suppression system, a high-temperature pressure sensor based on strain gages made of silicon microcrystals (SC) has been developed [9,10]. Such strain gages have unique mechanical properties, are characterized by high sensitivity and the ability to work in different amplitude-frequency and temperature ranges up to 500°C.

The design of the sensor is based on the membrane-rod-beam system (Fig. 3).

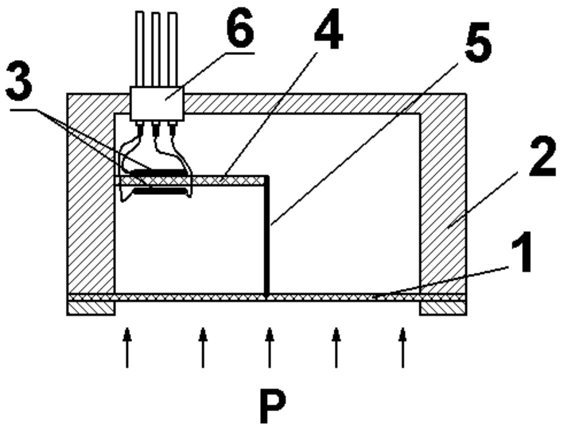

Fig. 3. Design of pressure sensor of membrane-rod-beam system: 1 – membrane; 2 – housing; 3 – strain gages; 4 – beam; 5 – stock; 6 – current terminals

The robotic principle of such a pressure sensor is as follows. Under the pressure P there is a deflection of the membrane 1. The movement of the centre of the membrane through the rod 5 is transmitted to the beam 4 with fixed strain gauges 3. In this case, the beam is deflected and fixed strain gauges strain gages are compressed or stretched, according to the place of their fixing.

Both strain gages are included in the bridge circuit, the output signal of which is proportional to the measured pressure. Strain gages based on SC p-type conductivity with a resistivity of 0.005 Ohm×cm, which has a linear temperature dependence of the resistance in a wide temperature range, selected in pairs by the value of the nominal resistance and the temperature coefficient of resistance.

They are fixed on the upper and lower surfaces of the beam of the strain gage, and current terminals made of platinum wire with a diameter of 30 μm are welded to a metal-glass lead built into the strain gage module. The strain gauges are connected in a bridge circuit, the output signal of which varies depending on the pressure received by the sensor membrane.

To create an elastic element of the high-temperature sensor, a 29NK alloy with a coefficient of thermal expansion (CTE) close to silicon was used. C51-1 glass solder with CTE ≈ 4.9×10^{-6} deg^{-1} at a melting point of ~ 750°C was chosen for fixing the strain gages. The use of a combination of silicon strain gage-solder-kovar with close CTE allowed minimizing temperature stresses and ensuring the stability of the sensor at high temperatures.

To optimize the design of the pressure sensor, computer simulation of the distribution of mechanical stresses and strains in the membrane-rod-beam system was performed, which was performed by the finite element method using the program ANSYS [11]. The calculation was performed in the isotropic approximation: it was assumed that all elements of the sensor design were made of 29NK covariance with a Young's modulus $E=140 \times 10^9$ Pa and a Poisson's ratio ν = 0.3. Figure 4 shows the results of calculations of mechanical stresses in the structural elements of the pressure sensor. Such calculations made it possible to select the optimal configuration and size of the rod to provide the required frequency characteristics of the system, as well as to reduce its nonlinearity.

To eliminate the effects of high vibration loads and the acidic action of the environment, the sensor housing is made of an alloy and is connected to other elements by laser welding. Such a rigid connection of all elements of the sensor helps to increase its natural frequency and resistance to vibration. The sensor membrane is made of 44NHTYu type alloy with high elastic properties and low temperature coefficient of modulus of elasticity. Figure 5 shows the appearance of the pressure sensor designed to measure pressures in the range 0…400 kPa at temperatures up to 450°C.

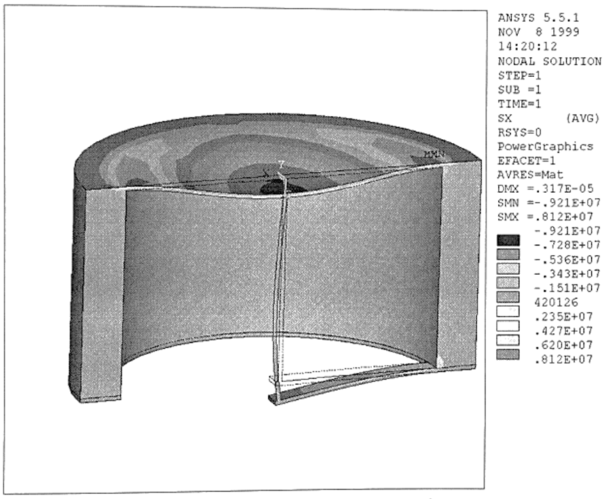

Fig. 4. Mechanical stresses distribution in the pressure sensor

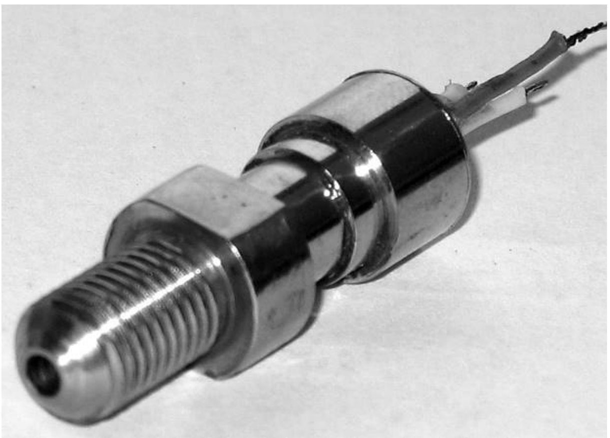

Fig. 5. External inspection of the pressure sensor

3. Experimental results and discussions

Based on the research, the dependences of the output signal of the sensor on the pressure at different temperatures in the range of 20…450°C were obtained (Fig. 6). From the above characteristics it is clear that in the static measurement mode the output signal of the sensor has a linear dependence on the pressure at different temperatures. The calculated nonlinearity of the initial characteristic is ~ 0.1%.

The study of the dynamic characteristics of pressure sensors was performed on a special stand designed to measure the amplitude and phase-frequency characteristics of pressure sensors in the frequency range from 30 Hz to 8 kHz [12]. The system of pressure pulsation measurement consists of pressure sensors (controlled and tested), measuring amplifiers and multi-channel recording device TESLA EAM-500. The study of the amplitude-frequency characteristics (AFC) of the pressure sensor was carried out by the method of comparison with the AFC of the control pressure sensor, which was used as a sensor "Kulite" company [13]. The AFC is shown in Figure 7 and is defined as the ratio of the amplitudes between the control and test pressure sensors. The resonant frequency of the investigated pressure sensor is ~ 4400 Hz.

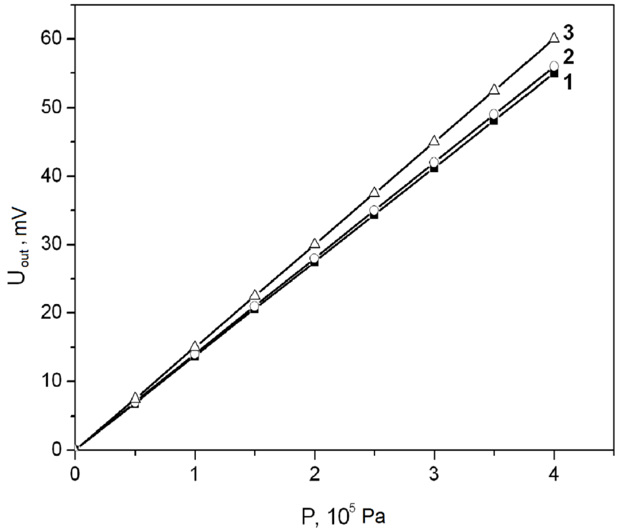

Fig. 6. Output characteristics of the high-temperature pressure sensor at different temperatures: 1 – 20°C; 2 – 300°C; 3 – 450°C

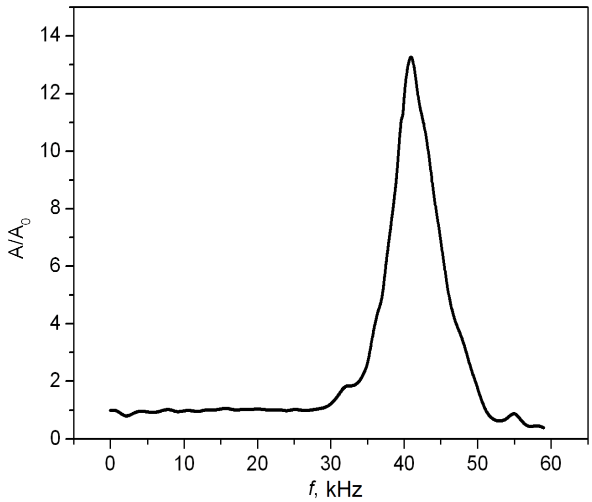

Fig. 7. Amplitude-frequency characteristics of the pressure sensor

Calibration of the pressure sensor allowed to make a conclusion about the quality of its electromechanical part and to determine the measurement error of the sensor in the temperature range 20… 900 °C, which is ± 0,5%, and the additional temperature error is less than 0.03%/deg.

To assess the efficiency of both the entire exhaust system and its individual elements, the most informative parameter is the loss of transmission TL, because it does not depend on the acoustic conditions at the input and output of the exhaust system:

$$TL = 10\lg\left(W_{in} / W_{out}\right),$$

where W_{out} and W_{in} are the powers of the sound waves, respectively, at the input and output of the muffler at the agreed input and output load.

Accepted as an estimated transmission loss TL parameter (Fig. 8), which is determined in the analysed speed range of the internal combustion engine, is determined (formed) not only by the total volume of the cavities of the muffler, but also the specific design of their internal components, their level of perfection "acoustic settings", the presence or absence in the design of the muffler fibrous sound-absorbing packing, the influence of a given layout (specific location of the housings) of the exhaust system, the design of the collector unit (including the arrangement of the module catalytic collector and cross-sections), geometric parameters of connecting pipeline elements (lengths and cross-sections).

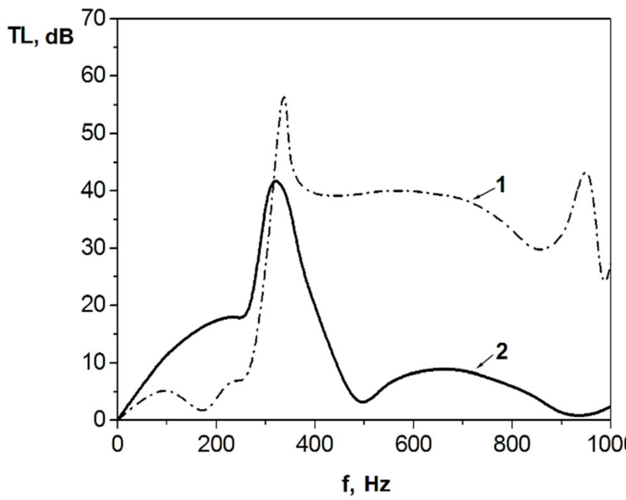

Fig. 8. Muffler transmission losses: 1 – without additional buffer tank; 2 – with additional buffer tank

4. Results and discussion

Noise dumping, as the acoustic efficiency of the exhaust system, depends on many factors, including the technical parameters of the internal combustion engine and the design of system elements that are in complex relationships, so far have no unambiguous functional expression.

The application of the developed high-temperature pressure sensors based on strain gages with silicon micro-crystals made it possible to implement a system of dynamic change of the resonator chamber volume, which occurs with the help of a diaphragm controlled by an electromagnetic drive. The developed sensors due to the use of strain gages made of silicon microcrystals can withstand more than 10^7 cycles of load – unloading during deformation of strain gages 1×10^{-3} relative units. The use of special 29NK alloys type, for the manufacture of elastic elements, and glass solder C51-1, for fixing strain gages, provided the efficiency of pressure sensors at high temperatures (up to 450°C) while maintaining their high metrological parameters.

The use of an additional resonator chamber with variable volume in the exhaust muffler of the internal combustion engine allowed to reduce the resonant phenomena in the zone of low-frequency pulsations of exhaust gas pressure from 57 Hz to 43 Hz at frequency drift in the range of 310…350 Hz, which significantly improved its noise characteristics.

The active noise suppression system based on the Helmholtz resonator used tools to control general noise levels, experimental tests, complex mathematical modelling of acoustic processes in Solidworks, taking into account the conditions of propagation and attenuation of sound energy by intermediate closed volumes.

The developed design of active noise reduction is simpler in comparison with analogues and allows reducing the noise of exhaust gases in a low-frequency range.

For further research, to improve the characteristics of the active noise suppression system, it is advisable to consider the use of several additional cameras of the Helmholtz resonator and to clarify the algorithm of the controller in transient modes of engine operation.

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