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Original Study Article

Computational study of the gas-dynamic approach for noise reduction in the two-stroke engine's exhaust system

Andrei A. Chernousov, Rustem D. Enikeev, Reshad E. Dadashov

Ufa University of Science and Technology, Ufa, Russian Federation

ABSTRACT

BACKGROUND: The traditional approach to designing exhaust mufflers relies mainly on energy dissipation. In the gas-dynamic approach, the flow of exhaust gases is equalized by introducing long channels into the muffler to separate impulses and to shift them in time. It is assumed that this ensures noise reduction without generation of significant counterpressure.

AIM: Evaluation of the prospects of the gas-dynamic approach to reducing the noise level of the exhaust system of two-stroke internal combustion engines.

METHODS: The study has a computational and theoretical nature. The study object is the RMZ-551i two-stroke gasoline two-cylinder engine, which exhaust system includes a resonator (ensures gas-dynamic supercharging) and a muffler. The processes in the gas-air circuit of the piston engine were calculated using the 1D model. The noise characteristic was the effective sound pressure at a specified point in the environment, calculated using the 2D model of propagation of disturbances in elastic medium. Initially, the engine parameters and sound pressure level with the stock muffler at full load and close to nominal engine speed were calculated. Then, the structure of the stock muffler was modified by adding a channel between its two chambers. The parameters of the modified muffler were optimized based on the criterion of gas pulsations reduction at the outlet. The noise reduction of the muffler implementing the gas-dynamic approach was evaluated relatively to the stock muffler and expressed in terms of sound pressure levels in dB. The parameters and sound pressure were finally calculated over a wide range of engine speeds.

RESULTS: According to the computational estimation, the optimal implementation of the gas-dynamic approach in the muffler reduces exhaust noise by 7 dB, while engine power decreases by 2.5%. Calculation of the sound pressure level based on the full-load curve showed that at an engine speed of 3000 rpm, the calculated sound pressure exceeds the minimum (99 dB), obtained for the optimally tuned muffler at an engine speed of 5000 rpm, by 8 dB. It is suggested that the gas-dynamic approach with optimization is also applicable for uniform noise reduction over a wide range of engine speeds, with a more complicated design of the exhaust muffler.

CONCLUSION: Theoretical evaluation of the muffler with a tuned channel connecting its two chambers was carried out. The RMZ-551i two-stroke engine with a stock muffler is a basis for comparison. At the optimum point on the full load curve, the exhaust noise was reduced by 7 dB, while the calculated power decrease was insignificant. The authors note the suitability of the methodology for rapid assessments and automated computational optimization of mufflers that utilize wave effects. They also point out the limitations of the models used, which require validation or calibration based on the experimental data. The necessity in the development of applied models of acoustic effects and measuring devices for domestic CAE packages is pointed out as well.

Keywords: two-stroke engines; exhaust noise; mufflers; wave effects; computer modeling; optimization.

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Оригинальное исследование

Расчетное исследование газодинамического подхода для снижения шума выпуска в двухтактном двигателе

А.А. Черноусов, Р.Д. Еникеев, Р.Э. Дадашов

Уфимский университет науки и технологий, Уфа, Российская Федерация

АННОТАЦИЯ

Обоснование. Традиционный подход к проектированию глушителей шума выпуска во многом полагается на диссипацию в них энергии. При «газодинамическом» подходе поток выхлопных газов выравнивают, вводя в глушитель длинные каналы для разделения импульсов и смещения их по времени. Предполагается, что это обеспечит снижение шума без создания существенного противодавления.

Цель работы — оценка потенциала «газодинамического» подхода к уменьшению уровня шума выхлопа двухтактных двигателей внутреннего сгорания.

Методы. Исследование носит расчётно-теоретический характер. Объектом является двухтактный бензиновый двухцилиндровый двигатель РМЗ-551i, выпускная система которого содержит резонатор (обеспечивает газодинамический наддув) и собственно глушитель. Процессы в газовоздушном тракте двигателя рассчитаны по одномерной модели. Характеристикой шума выхлопа было эффективное звуковое давление в заданной точке из 2D расчёта упругих возмущений в окружающей среде. Вначале рассчитаны показатели двигателя и уровень звукового давления с серийным глушителем на полной мощности и частоте вращения, близкой к номинальной. Далее изменена структура глушителя: между двумя его камерами добавлен канал. Параметры такого глушителя оптимизированы, критерием был минимум пульсаций потока на выходе. Снижение шума выхлопа для глушителя, реализующего газодинамический подход, как и для серийного, оценено по уровням звукового давления в дБ. Рассчитаны показатели в широком диапазоне частот вращения вала, в частности — уровень звукового давления.

Результаты. По расчётным оценкам, оптимальная реализация газодинамического подхода в глушителе снижает шум выхлопа на 7 дБ при том что мощность двигателя уменьшается на 2,5%. Расчёт уровня звукового давления по внешней скоростной характеристике показал, что на частоте вращения, равной 3000 об/мин, звуковое давление на 8 дБ превышает минимум (99 дБ), полученный на частоте вращения в 5000 об/мин для оптимально «настроенного» глушителя. Высказано предположение, что газодинамический подход применим и к равномерному снижению шума в широком диапазоне частот вращения (при усложнении структуры глушителя шума выхлопа).

Заключение. Теоретически оценён глушитель с каналом подобранной длины, соединяющим две его камеры; база для сравнения — двухтактный двигатель РМЗ-551i с серийным глушителем. По результатам расчётов, в точке оптимума на скоростной характеристике шум выхлопа снижен на 7 дБ, причём мощность снизилась несущественно. Авторы отметили пригодность методологии для оперативных оценок и для автоматизированной расчётной оптимизации глушителей, использующих волновые эффекты, но также и ограничения моделей, которые требуют подтверждения или калибровки по экспериментальным данным. Отмечена нужда в разработанных специалистами прикладных моделях акустических эффектов и измерительных устройств для отечественных CAE-пакетов.

Ключевые слова: двухтактные двигатели; шум выхлопа; глушители; волновые эффекты; моделирование на ЭВМ; оптимизация.

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BACKGROUND

A reciprocating internal combustion engine (ICE) is a cyclic heat engine. Intense pulsations of gas flow at the outlet of the gas–air flow duct (GAD) create noise characterized by completely unacceptable sound pressure levels unless mufflers are used [1]. Intense wave phenomena in the GAD of modern ICEs induce strong pulsations of pressure and other parameters in the flow at the outlet of the "power" part of the exhaust or intake system. Pressure fluctuations and flow pulsations are especially intense when using gas-dynamic settings. In these cases, exhaust noise mufflers are required to convert a flow with pulsations into a stationary flow (ideally) and with a low flow rate of gases flowing into the atmosphere.

The design of ICE exhaust silencers usually contains chambers connected by holes and short channels. The damping of pulsations of gas parameters in such mufflers is associated with dissipative processes during flow and interaction with the elements of the sound-absorbing packing. This approach to creating noise suppression systems for pulsating flows is called "dissipative" [2].

Another approach (gas-dynamic) can be incorporated into the muffler design [2]. In the flow part of such mufflers, the chambers are also connected by relatively long channels. These channels ensure a delay in the arrival of the pressure wave in the last chamber of the muffler in the antiphase with the disturbance from flowing through holes and short channels. Consequently, pulsations of parameters in the chamber and flow velocity in the outlet pipe are significantly weakened. That is, with this approach, flow pulsations are weakened using mainly wave rather than dissipative effects. Therefore, a muffler implementing this approach with comparable dimensions can presumably be made more efficient without significant complications in its design or without making it heavier.

Computer modeling methods for the intake and exhaust noise of ICEs are traditionally based on one-dimensional models that enable accounting for flow pulsations in GAD sections. Models and techniques for the quick assessment of sound pressure levels and optimization of muffler designs have been developed and tested [3, 4]. Using such techniques and tools [5], exhaust noise mufflers were optimized and then tested.

However, not all actual sources and frequencies of the gas-dynamic noise spectrum of an ICE are accounted for by the technique unless it is based on a detailed three-dimensional (3D) model. Such a model considers real geometry and requires a fine-mesh grid and large computing power. Researchers have been deepening methodologies in this direction for more than two decades. Early works were based on calculations using a one-dimensional (1D) model of pulsating flow in GAD channels coupled with 3D calculations of the flow in the muffler (with a given more or less realistic 3D geometry; e.g., [6]). By calculating the flow in the chambers and channels of the muffler with moderately high detail in 3D, at least large-scale unsteady structures are revealed.

On this basis, the jet unsteady outflow of gases into the environment can be calculated in detail. For the adequacy of the calculation, a wide range of scales of vortex structures must be identified. In areas of the order of the distances where the sound level meter microphone is placed (measuring the spectrum and equivalent sound pressure), the disturbance can also be calculated in detail using the acoustic equation. Such problems are solved in conjunction with solving the equations of a detailed 3D model of flow in a jet using high-precision numerical methods. In this formulation, exhaust noise is studied using both commercial computational fluid dynamics (CFD) solvers and their own development means in aeroacoustics models and methods [7]. These development means can be used to calibrate fast-calculating models of acoustic fields in the environment. These models can then be used to evaluate quickly the spectra and integral noise indicators of engines and other systems in CAE packages [8–10], which implement 1D models of processes in engines, coupled with models of microphones and sound level meters.

In this study, using existing models and methods, the maximum capabilities of a gas-dynamic type muffler were assessed using comparative calculations. Nonlinear processes in the entire GAD of a two-stroke engine with a tuned exhaust system (containing a resonator and a muffler) were calculated using a 1D thermo-gas-dynamic model. The sound pressure level, which characterized the noise caused by the pulsating flow at the outlet of the muffler, was assessed using a technique that included a two-dimensional (2D) numerical calculation of disturbances in the environment. The noise level and performance of an engine with a total power and a rotation speed close to the nominal speed were determined, and a muffler with a change in structure was examined. A long channel connecting its two chambers was added to the 1D model of the muffler. The optimal parameters of a muffler of this design were determined. Then, engine performance and exhaust noise were calculated over a wide range of engine speeds. Calculations using the applied methodology enabled the approximate estimation of the effectiveness of muffler circuits that implement the gas-dynamic approach, as shown in relation to a two-stroke engine with a wave-tuned exhaust system.

AIM

This computational study aimed to estimate theoretically the limits for reducing the exhaust noise level of a two-stroke forced engine when implementing a gas-dynamic approach to reducing gas flow pulsations at the outlet of a muffler.

METHODS

The possibilities of a gas-dynamic approach in reducing the exhaust noise of two-stroke ICEs have been studied. The approach under consideration involved the use of a relatively long connecting channel to provide a time delay in the arrival of the wave in the last of the muffler chambers. The separation of pulses and their temporal displacement weakened fluctuations in gas parameters in the last chamber, bringing the flow through a short exhaust pipe closer to a stationary one.

This study was of a theoretical nature (computational experiment). Using numerical calculations with a 1D model of thermo- and gas-dynamic processes in a two-stroke piston engine and using a special calculation technique, the sound pressure level at the outlet was assessed. For marginal valuation of the approach effectiveness, the parameters of the connecting channel and muffler chambers were computationally optimized, aimed at minimizing exhaust noise while maintaining the power level of the serial engine.

The RMZ-551i engine produced by the Russian Mechanics concern was taken as the study object. This two-stroke two-cylinder engine has a displacement volume of 553 cm3. The engine is applied in various civilian fields, such as in snowmachines, snowmobiles, airboats, and paragliders. A sample engine is at the disposal of the ICE Department of the Ufa University of Science and Technology and is studied on a test bench. Figure 1 presents a general view of the engine. Table 1 presents the engine parameters declared by the manufacturer.

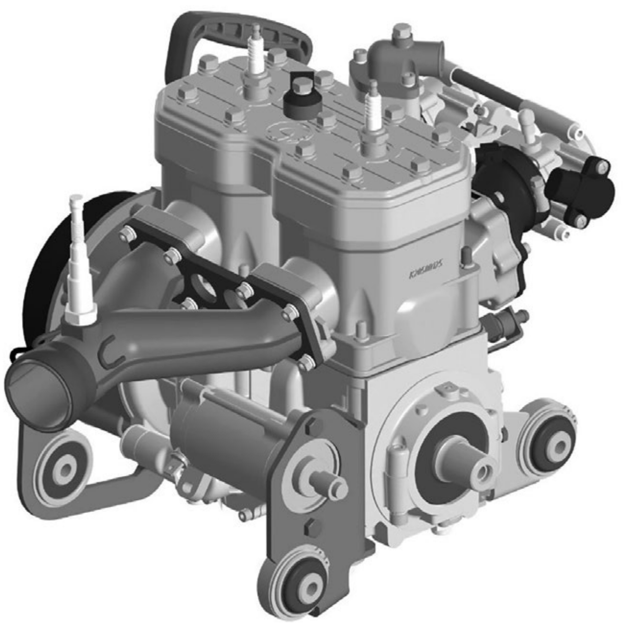

Fig. 1. The RMZ-551i engine.
Рис. 1. Двигатель РМЗ-551i.

Table 1. The key technical specifications of the engine
Таблица 1. Краткая техническая характеристика

Type	Two-stroke
Number of cylinders	2
Cylinder diameter, mm	76
Piston stroke, mm	61
Power, h.p.	65
Fuel supply system	With injector
Lubrication system	Separate
Exhaust system	With resonator

To simulate the engine, the *ALLBEA* software package, released in 2023 and created at the Ufa University of Science and Technology [11], was used, including the *ALLBEA OPTIM* [12] and *ALLBEA NOISE* programs.

The graphical environment of the package contained a block diagram of a 1D model of processes in the GAD of an engine (Fig. 2). The 1D model contained models of individual elements (channels and containers, including the crank and working chambers of the engine), as well as models of connections (local resistances, check plate valves, gas exchange ports, and tees), taken from the library of models implemented in *ALLBEA*.

A 3D geometric model of the engine, including all components of the GAD, was provided by the Russian Mechanics concern. Geometric models were studied to represent adequately the GAD structure in a 1D model (Fig. 2), as well as the geometry of the components and the laws of the opening of the exhaust and blowoff ports. On the basis of 3D models of the flow path parts, calculation areas were created for 3D calculations of the flow characteristics of all groups of ports and the blowoff characteristics of the working chamber during gas exchange. The calculations were performed in a *CFD* package using a proven methodology, with the results processed and inserted into a 1D model in the form of tabulated characteristics.

The engine exhaust system, including exhaust pipes, a tee, a resonator, and a muffler, is presented in Fig. 3. The resonator in the engine was used to increase power and efficiency due to wave effects in the gas flow. It was most effective at the tuning rotation speed, at which a significant part of the air–fuel mixture leaving the working chambers into the exhaust system returned to the chamber before the exhaust ports closed. The resonator of this engine had a complex 3D shape (Fig. 3). It was simplified in the 1D model as a set of profile channels (Fig. 2; the elements

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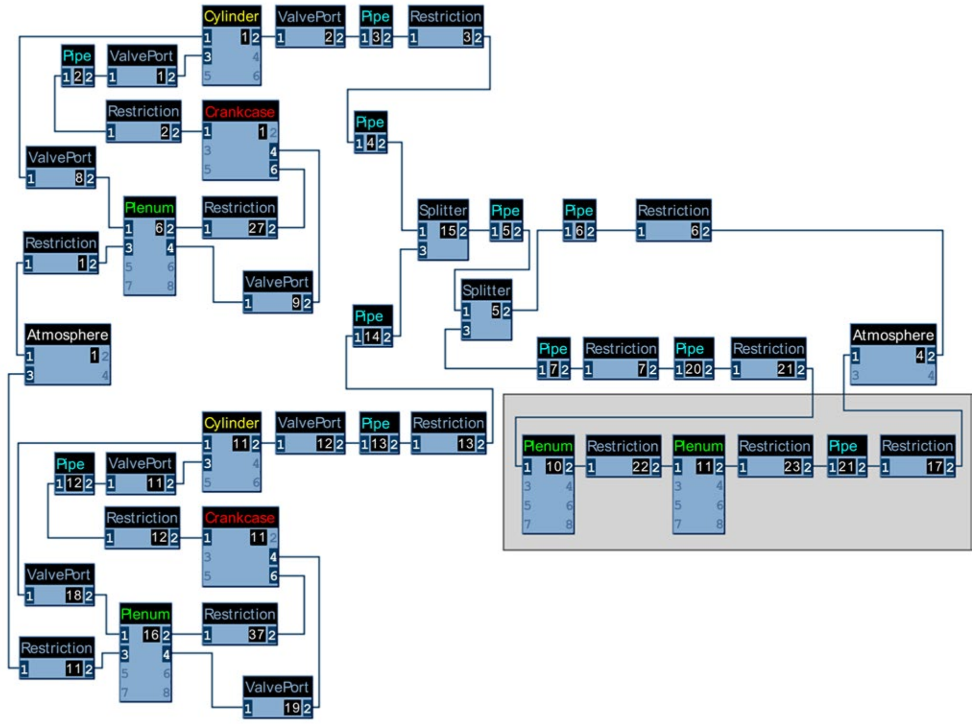

Fig. 2. The structure of the 1D model of the engine in the ALLBEA.
Рис. 2. Структура 1D модели двигателя в ALLBEA.

of the stock muffler were highlighted). The 1D resonator profile included forward and reverse conical sections, as well as a central internal channel in the reverse conical section.

The wave processes in the resonator and the resulting oscillations in the flow at the inlet to the muffler were very intense. To smooth out pulsations in the mufflers, perforated partitions and meshes were used. Gas passing through these obstacles reduced the noise level but created back pressure. In this engine, the muffler consisted of two chambers of different volumes, which were connected by holes in a common partition. The muffler diagram is presented in Fig. 4.

The elements of the 1D model of this (stock) muffler are outlined in Fig. 2.

After a 1D model of the engine was created and all the necessary initial data were entered, the model was tested for accuracy and showed satisfactory agreement between the calculated and measured parameters on the bench in several operating modes. The task of fine-tuning the model was not posed as the model was intended for comparative calculations of the efficiency of exhaust noise mufflers (stock and optimized).

The noise produced by the flow from the exhaust system was assessed using the effective sound pressure, defined as the mean-square deviation of pressure from pressure p_a in an undisturbed environment (Pa):

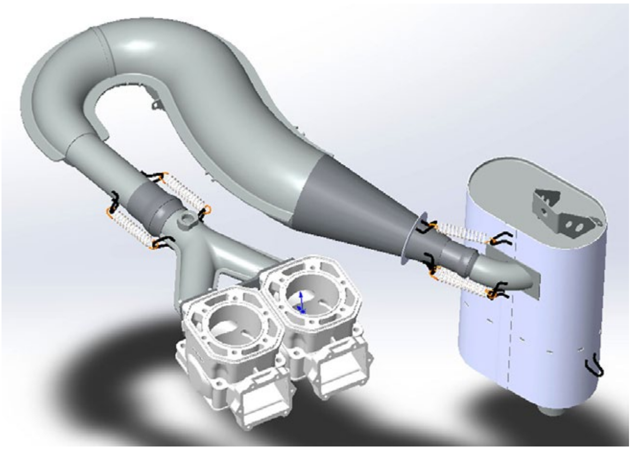

Fig. 3. The 3D model of the exhaust system.
Рис. 3. 3D модель системы выпуска.

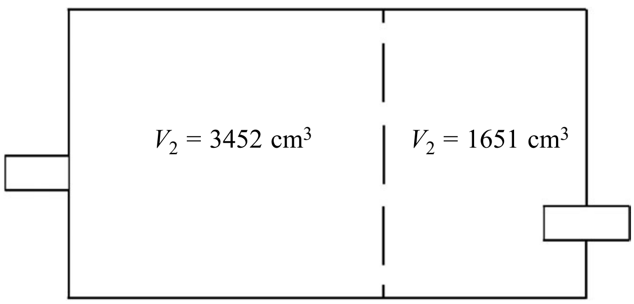

Fig. 4. The scheme of the stock muffler.
Рис. 4. Схема серийного глушителя.

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$$p_{eff} = \sqrt{\frac{1}{\tau}\int_{t_0}^{t_0+\delta}[p(t) - p_a]^2} \approx \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(p_i - p_a\right)^2},$$

where N is the number of nodal pressure values taken with a constant step in the time interval τ (equal to or a multiple of the pulsation period).

In acoustics, the sound pressure level is expressed relative to a characteristic (reference) value (in dB). The accepted equation with the decimal logarithm of this ratio is [2, 13]

$$L = 20\lg(p_{eff} / p_0),$$

where $p_0 = 2 \cdot 10^{-5}$ Pa is the reference value.

The point location was taken at a distance of 500 mm from the section of the outlet pipe and at an angle of 45° to its axis [14].

As the microphone model was not built into *ALLBEA*, a special technique was used to calculate the sound pressure level L at an environmental point based on data on the pulsating flow at the outlet of the muffler (from 1D calculation). This technique was developed at the Department of Internal Combustion Engines at the Ufa State Aviation Technical University and was

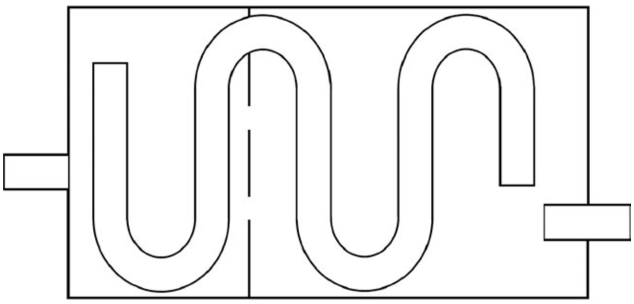

Fig. 5. The scheme of the modified muffler with the extended connecting channel.
Рис. 5. Схема глушителя с длинным соединительным каналом.

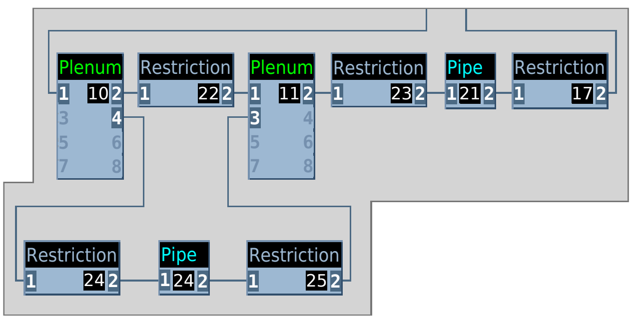

Fig. 6. The 1D submodel of the muffler with the channel connecting two chambers.
Рис. 6. Подмодель глушителя с каналом, соединяющим две камеры.

used for the design of exhaust systems and evaluation and optimization of mufflers (e.g., [3]).

For calculations using this method, the *ALLBEA NOISE* program was used. The program calculated disturbances in the environment using a 2D axisymmetric model. Processing of numerical data gave an estimate of the sound pressure level L at a point.

First, we calculated the indicators and sound pressure level L at the exhaust of an engine with a stock muffler. Several calculations were also performed, where the influence of the volume of the first muffler chamber, the flow sections of the holes, and the replacement of their parts with a short channel on the exhaust noise level and on the engine power was studied. Calculations revealed the futility of optimizing the stock muffler parameters. The results of these calculations are not presented in this work.

Then, a modified scheme was adopted, with the addition of a long connecting channel between the muffler chambers (Fig. 5), implementing a gas-dynamic approach for reducing flow pulsations. The channel fitted into the overall volume and dimensions of the muffler. The elements of the 1D model of the modified muffler are presented in Fig. 6.

The main dimensions $L_т$ and $D_т$ of the channel (*Pipe* element No. 24 in Fig. 6) were made with optimized parameters, as was the diameter D_{hole} of each of the two holes left in the partition between the chambers. The total volume of the two chambers of the muffler V was left equal to 5,103 cm^3, which corresponded to the volume of a commercially produced muffler. The channel volume (considering the thickness of its walls of 0.8 mm) in the 1D model was subtracted from the volumes of the chambers in proportion to their initial values, for which $V_1 + V_2 = V$. The initial volume V_1 of the first muffler chamber along the gas flow was also selected.

The optimization problem was associated with finding the maximum of the objective function (OF), defined as

$$f(L_т, D_т, D_{hole}, V_1) = (\Delta u_{mean.sq.})^{-1},$$

where $\Delta u_{mean.sq.}$ is the mean-square deviation of the gas flow speed at the section of the muffler outlet pipe from the average flow speed at this section:

$$\Delta u_{mean.sq.} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(u_i - u_{av.})^2},$$

$$u_{av.} = \frac{1}{N}\sum_{i=1}^{N}u_i.$$

OF, inversely proportional to $\Delta u_{mean.sq.}$, was an optimality criterion (instead of L) due to the lack of an adequate microphone model in *ALLBEA*.

In addition to OF, a limitation was considered; that is, the calculated engine power should not be more than 3% lower than the calculated power with a stock muffler

(41.09 kW). When calculating OF for an option that violated the limitation, a penalty value (a sign of an unacceptable option) was transmitted to the optimization algorithm instead of the OF value.

Thus, the muffler parameters were selected with the smallest (according to the OF) speed pulsations at the outlet to the atmosphere but without a significant loss of engine power. The described optimization problem was solved for the engine at full power at a shaft speed n of 5,000 rpm. The optimization problem involved determining such values of variables that induce the maximum reduction in noise level with minimal changes in the design of the muffler and power at a specified frequency.

The optimization calculation was automated using the *ALLBEA OPTIM* program [12]. The program uses a genetic algorithm for searching the OF global maximum with restrictions. The program is configured for a specific optimization problem by setting the algorithm parameters and connecting an external software module in C or $C{+}{+}$. With each call to calculate the OF, the module takes the current values of the optimized parameters, substitutes them into the process calculation and, based on the results, calculates and returns the OF value or penalty value. In this work, for a 1D calculation of the process in the engine GAD, including the muffler, the module called a calculation program: the *ALLBEA* package solver.

RESULTS

Calculations assessed the marginal effect of a relative change in the volume of the muffler chambers and the addition of a connecting channel between them. Using the described methodology, engine performance and noise levels were calculated when using a stock muffler. Then, the muffler design was modified by introducing a tuned connecting channel, and the main dimensions of the muffler of the modified design were optimized. For the optimal muffler option determined, the engine performance and exhaust sound pressure were calculated in the crankshaft speed range. The data obtained were analyzed.

CALCULATION OF POWER AND NOISE LEVEL WITH A STOCK MUFFLER

For a stock muffler (Figs. 2–4), the calculated value of the sound pressure level L at the outlet was 105.9 dB at full power and n of 5,000 rpm. The estimated value of effective engine power was 41.09 kW.

OPTIMIZATION OF MUFFLER STRUCTURE AND PARAMETERS

A computational optimization was performed for a muffler with a tuned channel connecting two chambers parallel to the holes in the partition (Figs. 5 and 6). The determined maximum of corresponded to a minimum $\Delta u_{\text{mean.sq.}}$ of 1.812 m/s with the values of the muffler parameters of L_{T} = 1,810 mm, D_{T} = 31,0 mm, D_{hole} = 20,5 mm, and V_1 = 1786 cm^3.

Calculated dependences of the flow rate and temperature of the exhaust gases at the outlet of the stock and optimized muffler in Fig. 7 are presented for comparison in the form of graphs of the shaft rotation angle within one pulsation period (½ revolution for a two-cylinder engine). The estimated effective engine power was 40.06 kW at n of 5,000 rpm.

With the optimal muffler parameters detected, engine performance was calculated at several rotation speeds at full power (i.e., according to the external speed characteristic). At the calculated operating points, the sound pressure levels L were determined using the method described above. The graphs of the effective power and L are presented in Fig. 8.

DISCUSSION

Calculation estimates showed the possibility of reducing the exhaust noise of the RMZ-551i engine by approximately 7 dB by adding a tuned channel between the two muffler chambers. The optimized muffler was fitted within the dimensions of a stock muffler and reduced the calculated effective engine power by only 2.5% (for the same speed of 5,000 rpm).

Notably, at a frequency of 3,000 rpm, the calculated sound pressure level was approximately 8 dB higher than the minimum; that is, the gas-dynamic setting ceased to have an effect. This was an expected result, similar to reducing the effect of wave tuning of the inlet and outlet channels of the main (power) part of the GAD.

Complicated structural diagrams of the muffler (e.g., with two parallel connecting channels of different lengths) remained beyond the scope of this study. The structure and parameters of such mufflers could also be optimized to reduce uniformly the exhaust noise over a wide range of shaft speeds.

Limitations of the methodology and instruments could significantly affect the results as some physical processes in the muffler and the outflowing stream were not considered. Thus, flow pulsations at the outlet of the exhaust pipe were calculated using a global 1D model, where the muffler chambers were represented by zero-dimensional models of containers that filtered out the high-frequency component of the pulsations. To calculate the sound pressure, a technique was used based on the calculation of disturbances in the environment produced by flow pulsations at the muffler outlet. However, the numerical calculation of disturbances using a 2D model of air movement as an inviscid elastic medium does not convey the effects of vortex generation in a turbulent jet. For these reasons, the calculated

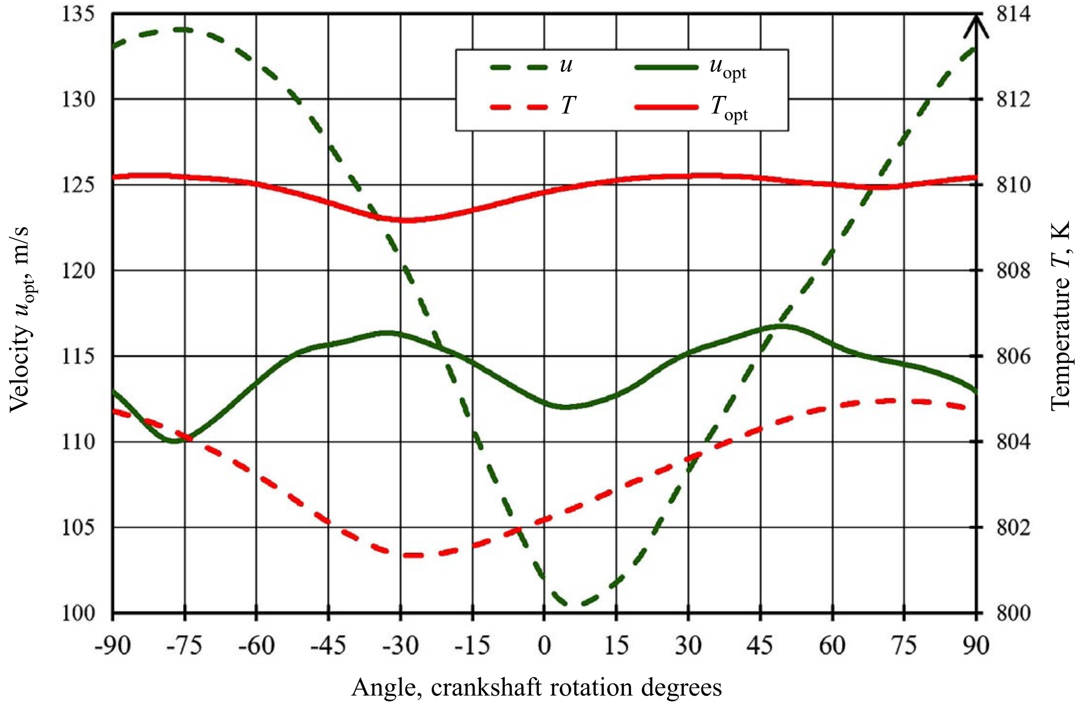

Fig. 7. Values at the outlet of the stock (- - -) and the optimized (––) muffler.
Рис. 7. Величины на срезе серийного (- - -) и оптимизированного (––) глушителя.

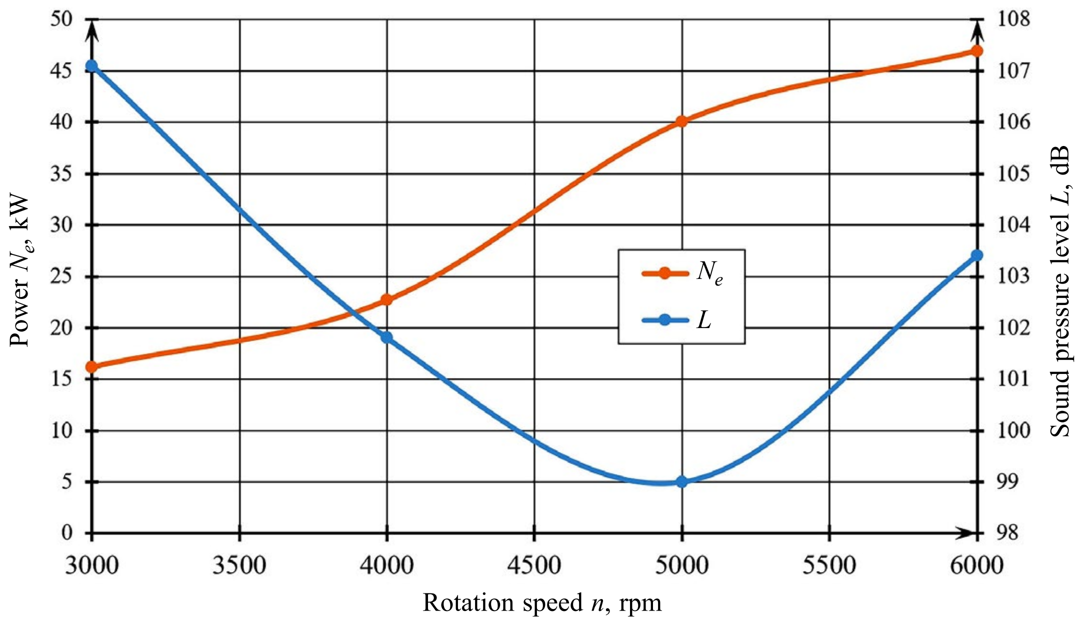

Fig. 8. Calculated characteristic curves for the engine with the optimized muffler.
Рис. 8. Расчётные показатели для двигателя с оптимизированным глушителем.

estimate of the reserves of the gas-dynamic approach to the creation of exhaust noise mufflers is quite approximate even for the case of comparative calculations, the results of which are expressed in relative values (dB).

Thus, additional experimental studies are required to confirm the results obtained or to tune the models used. Further, comprehensively improving the models of acoustic effects and measuring instruments for application software are more promising.

CONCLUSION

The efficiency of a muffler with a tuned long channel between the chambers was theoretically assessed using an RMZ-551i two-stroke engine as an example. The results of numerical calculations based on a 1D model of the process and a method for calculating 2D disturbances in the environment showed the possibility of reducing exhaust noise by 7 dB compared with that of a stock two-chamber muffler. The estimated engine power decreased insignificantly (by 2.5%).

The methodology and tools impose limitations that can significantly influence the results. Therefore, the models and methodology require additional experimental studies for confirmation (as well as theoretical studies for clarification). However, the applied methodology and tools can be recommended for immediate assessments and computational optimization of mufflers using wave effects. The optimization of multichamber mufflers should be automated according to the necessary criteria using 1D models of processes in the GADs of engines.

Software in several aspects must be improved to increase significantly the adequacy of calculated estimates of the ICE acoustic performance. The development of applied models of acoustic effects and measuring devices can be performed by specialists in the field of computational and technical acoustics. The backlog of mathematical support for Russian CAE packages in this field must thus be eliminated.

ADDITIONAL INFORMATION

Authors' contribution. A.A. Chernousov — search and analysis of literary sources, writing and editing the text of the manuscript; R.D. Enikeev — task formulation, expert opinion and approval the final version; R.E. Dadashov — performing computer simulations. All authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work.

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AUTHORS' INFO

*** Andrei A. Chernousov,**
Cand. Sci. (Engineering),
Associate Professor of the Internal Combustion Engines Department;
address: 12 K. Marx street, 450008 Ufa, Russian Federation;
ORCID: 0000-0001-5541-8082;
eLibrary SPIN: 2885-6338;
e-mail: andrei.chernousov@mail.ru

Rustem D. Enikeev,
Professor, Dr. Sci. (Engineering),
Head of the Internal Combustion Engines Department;
ORCID: 0009-0001-4683-1657;
eLibrary SPIN: 8556-3237;
e-mail: rust_en@mail.ru

Reshad E. Dadashov,
Postgraduate at the Internal Combustion Engines Department;
ORCID: 0009-0006-1429-8436;
eLibrary SPIN: 1957-4650;
e-mail: reshad.dadashov85@mail.ru

ОБ АВТОРАХ

*** Черноусов Андрей Александрович,**
канд. техн. наук,
доцент кафедры «Двигатели внутреннего сгорания»;
адрес: Российская Федерация, 450008,
Уфа, ул. К. Маркса, д. 12;
ORCID: 0000-0001-5541-8082;
eLibrary SPIN: 2885-6338;
e-mail: andrei.chernousov@mail.ru

Еникеев Рустэм Далилович,
профессор, д-р техн. наук,
заведующий кафедрой «Двигатели внутреннего сгорания»;
ORCID: 0009-0001-4683-1657;
eLibrary SPIN: 8556-3237;
e-mail: rust_en@mail.ru

Дадашов Решад Эльманович,
аспирант кафедры «Двигатели внутреннего сгорания»;
ORCID: 0009-0006-1429-8436;
eLibrary SPIN: 1957-4650;
e-mail: reshad.dadashov85@mail.ru

* Corresponding author / Автор, ответственный за переписку