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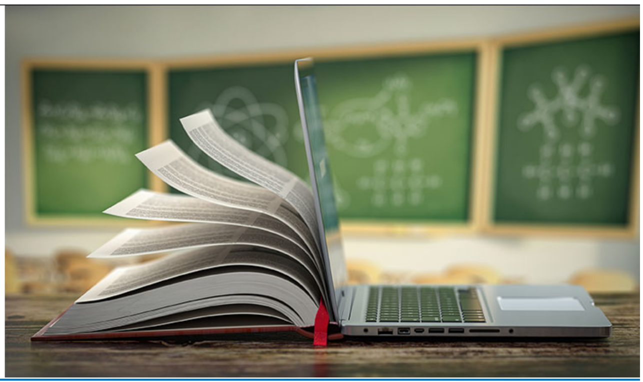

Spectral analysis of gas-dynamic processes in the exhaust system of piston engine (82/71)

L V Plotnikov[1], B P Zhilkin[1] and L E Osipov[1]

[1]Ural Federal University named after the first President of Russia B.N. Yeltsin, ul. Mira 19, Ekaterinburg 620002, Russia

E-mail: leonplot@mail.ru

Abstract. Batch machines are actively used in industry and energy. Internal combustion engines are a prime example of such machines. A feature of the operation of engines is that a certain amount of the working fluid is supplied to the working chamber, and upon completion of the process, the combustion products are removed from the chamber. Therefore, the aeromechanics of pulsating gas flows in the exhaust system significantly determines the efficiency of the engine. A distinctive feature of the processes in the exhaust system is their high dynamics (high-frequency pulsations due to the operation of valves with external disturbance from the turbine blades of the turbocharger). The article describes laboratory equipment (piston engine model), measuring system (main sensors and determined physical quantities) and data processing methods (spectral analysis). The boundary conditions during experimental studies are described. The aeromechanical characteristics of non-stationary flows in the exhaust system of the engine with and without a turbocharger are compared. Qualitative and quantitative differences in aeromechanics and thermophysics of processes in exhaust systems of various configurations are shown. A method for aeromechanical improvement of the exhaust system by creating an ejection effect is proposed. It was found that the ejection effect in the exhaust system of the engine leads to stabilization of the flow, an increase in air consumption by 6-12% and an improvement in reliability indicators by 1.11-1.74%.

1. Introduction

Batch devices are widespread in industry and energy. The principle of operation of these devices is that a portion of the working fluid is introduced into the chamber, work is carried out inside, and then the exhaust gases are removed from the chamber upon completion of the process. A well-known example of batch apparatuses is reciprocating internal combustion engines (RICE). The working process in the RICE is carried out in the cylinder, into which the working fluid is supplied through the intake system, and the exhaust gases are removed from the cylinder through the exhaust system.

The efficiency of the working cycle of engines is determined by the aeromechanical perfection of the processes in the exhaust system [1-3]. For example, results on tuning the design of exhaust systems in order to improve the efficiency and environmental friendliness of gasoline and diesel engines are given in some articles [4, 5]. The main idea of finishing exhaust systems is to improve the aeromechanics of flow movement in order to reduce hydraulic resistance and, accordingly, to increase the flow characteristics. Additionally, a number of articles on the creation of mathematical models of gas flows in exhaust systems can be distinguished [6-8]. These models were created with the aim of predicting the gas-dynamic, heat-exchange and flow characteristics of exhaust systems in order to improve the performance of engines. A separate area of research is the processes in a turbocharger (TC) for boosting a RICE. It is known that TC has a significant effect on the engine's duty cycle [9-11]. It should be noted that there is a relatively small amount of work on the detailed study of the influence of TC blades on gas dynamics and heat exchange in gas-dynamic engine systems.

One of the most famous and effective methods for assessing the aeromechanics of pulsating flows in complex gas-dynamic systems is spectral analysis [12, 13]. It is actively used in all branches of science and technology, including piston engine manufacturing [14, 15]. Therefore, this method was chosen as the basis for processing experimental data in this study.

Thus, the objectives of this study were: 1) to assess the effect of installing a turbocharger turbine on the aeromechanics of pulsating gas flows in the exhaust system of the engine based on spectral analysis; 2) to propose a method for controlling the gas-dynamic and heat transfer characteristics of gas flows by creating an ejection effect in the exhaust system.

2. Laboratory equipment, measuring system, data processing methods and task description

The studies were carried out on a dynamic bench simulating the exhaust process in a turbocharged piston engine (Figure 1). The stand included a source of compressed air, which fed it into the cylinder with a pressure of 50 to 250 kPa. Stabilization of compressed air (pressure equalization) was carried out in a special tank before it was fed into the cylinder. From the cylinder, air was supplied to the valve head with a valve mechanism. The inlet and outlet valves were driven by an electric motor with a control system. he camshaft speed varied from 300 to 1500 rpm, which corresponds to a crankshaft speed of 600 to 3000 rpm. From the block head, air entered the exhaust pipe with a length of 400 mm with an internal diameter of 30 mm. The turbocharger was installed at the outlet of the exhaust pipe. The total length of the exhaust system was about 500 mm. The TC rotor speed was determined by the pressure in the cylinder (outlet pressure) p_{out} and the camshaft speed.

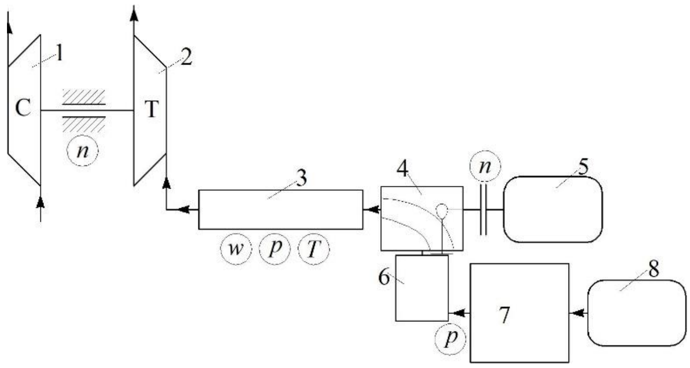

Figure 1. The layout of the laboratory bench and the location of the sensors: 1 – TC compressor; 2 – TC turbine; 3 – exhaust manifold; 4 – cylinder head; 5 – electric camshaft drive; 6 – volume simulating the engine cylinder; 7 – volume for flow stabilization; 8 – compressed air source; *p* – pressure sensor; *n* – speed sensor; *w* – gas flow rate sensor; *T* – temperature sensor.

The following physical quantities were measured in the exhaust pipe: air flow rate w_x, flow pressure p_x, flow temperature *T*, and local heat transfer coefficient α_x. Additionally, the cylinder pressure (outlet pressure) p_{out} was measured. The rotor speeds of the turbocharger and the engine crankshaft were also determined. The air flow rate was measured using a constant temperature hot-wire anemometer, the flow pressure using a high-speed pressure sensor, and the temperature using a thermocouple. The local heat transfer coefficient was also determined using a hot-wire anemometer and a sensor with sensitive elements in the form of a thin filament. The method of indirect calibration of the sensor based on the

Reynolds analogy was used to determine the quantitative values of the heat transfer coefficient. The measurement system is described in more detail in [16].

The studies were carried out in two stages in this work. At the first stage, the influence of the presence of a turbine of a turbocharger in the exhaust system of the engine on the pulsating components of the velocity and pressure of the flow was evaluated. Obviously, the turbine blades in the exhaust system have a mechanical effect on the flow in the gas-dynamic system and at the same time the turbine is a source of aerodynamic drag. The paper compares the spectral graphs for $w_x = f(\tau)$ and $p_x = f(\tau)$.

At the second stage of the study, a method of gas-dynamic improvement of the RICE exhaust system was proposed. The ejection effect was used as a method for improving the aeromechanics of flows in the exhaust system [17]. This effect is usually used to equalize the velocity field and increase the flow characteristics through the system. In this case, the influence of the ejection effect on the pulsating components of the gas flows in the exhaust system of the engine was estimated using spectral analysis.

Based on the data on the flow mechanics in the systems under consideration, the spectral analysis of the velocity and pressure functions of the flow in time was carried out using the PowerGraph program based on the fast Fourier transform algorithm. The main indicators of the spectrum during processing were: 1) the type of spectrum was amplitude; 2) the number of spectrum values during the fast Fourier transform was 1059687; 3) the type of weight function was rectangular. Spectral analysis of the harmonic functions of velocity and pressure is a classical approach for studying the flow characteristics under various boundary conditions.

3. Analysis of experimental data on the effect of the turbocharger turbine

The primary data on the change in the flow velocity and pressure, as well as the local heat transfer coefficient in time in the exhaust system of the engine with and without TC for one of the operating modes of the RICE and TC are presented in Figure 2. A spectral analysis of the primary functions $w_x = f(\tau)$ and $p_x = f(\tau)$ also for one of the operating modes of the bench is shown in Figure 3.

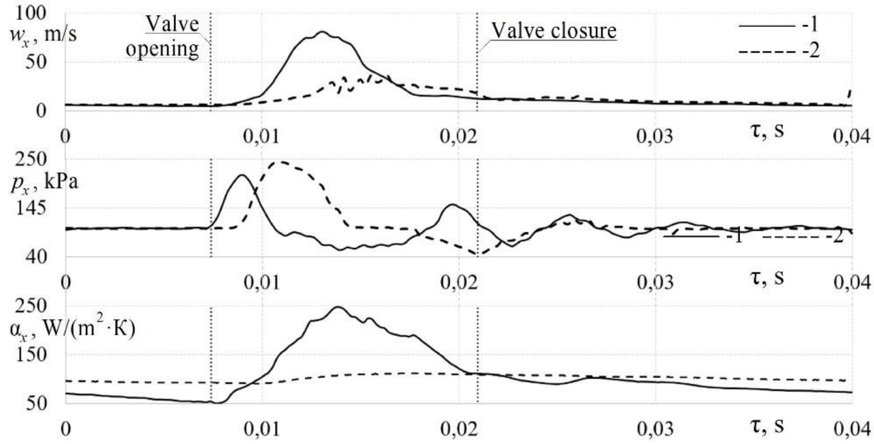

Figure 2. Dependences of the local flow velocity w_x and pressure p_x, as well as the local heat transfer coefficient α_x in time for the exhaust system without TC (1) and the system with TC (2) for n = 3000 rpm and p_{out} = 200 kPa.

Figure 2 shows that equipping the engine with a turbocharger leads to major changes in the aeromechanics of pulsating gas flows. For example, there is a decrease in the maximum air flow rate by 10-55% if there is a TC in the system. In this case, the maximum flow pressure in the exhaust channel increases. This indicates an increase in aerodynamic drag of the system. The drag coefficient ξ for the base exhaust system was 2.5 (average), and in the presence of a TC ξ was 4.4 (also average). It can also be noted that there is a more rapid damping of vibrational phenomena in the exhaust system in the presence of a TC (Figure 2). The greatest visual differences are observed for function $\alpha_x = f(\tau)$. There is a significant smoothing of curve $\alpha_x = f(\tau)$ in the exhaust system with TC compared with the base system. Moreover, the maximum values of the local heat transfer coefficient are reduced by more than 2 times.

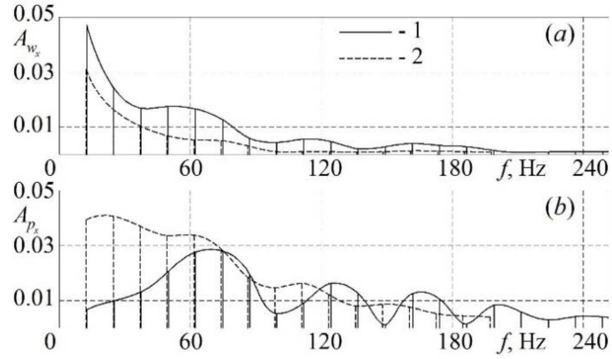

Figure 3. The graphs of the amplitudes of the spectrum of the velocity w_x (*a*) and pressure p_x (*b*) of the air flow in the exhaust system of the engine without a turbocharger (1) and with a TC (2) at n = 1500 rpm and p_{out} = 200 kPa.

The installation of a TC in the exhaust system of the engine has a noticeable effect on the graph of the amplitudes of the flow velocity spectrum (Figure 3). There is a decrease in significant amplitudes of velocity pulsations up to two times, which is typical for both low-frequency pulsations and high-frequency ones. At the same time, the multiplicity of significant frequencies remains unchanged for the base exhaust system and the TC system. Significant frequencies of the speed spectrum are: 12.58 Hz, 25.01 Hz, 37.46 Hz, etc., i.e. the multiplicity has a value of ~ 12.5 Hz. Moreover, the significant frequencies of the pressure spectrum have almost the same values: 12.4 Hz, 24.8 Hz, 37.1 Hz, etc., i.e. in this case, the multiplicity is ~ 12.4 Hz. However, the pulsation amplitudes of the significant frequencies of the spectrum of function $p_x = f(\tau)$ for flows in the exhaust system with TC are 1.2-1.5 times higher than for the base system. Opposite data on the spectra of functions $w_x = f(\tau)$ and $p_x = f(\tau)$ indicate that when there is a TC in the exhaust system, the structure of the pulsating air flow changes, there are external disturbances, and the spatial development of the flow is complex.

4. Analysis of experimental data on the influence of the ejection effect

The primary data on the change in the flow velocity and the local heat transfer coefficient with time in the base exhaust system and the system with the ejection effect are presented in Figure 4. The graphs of the spectra of the primary function $w_x = f(\tau)$ for different frequencies of the crankshaft rotation are shown in Figure 5.

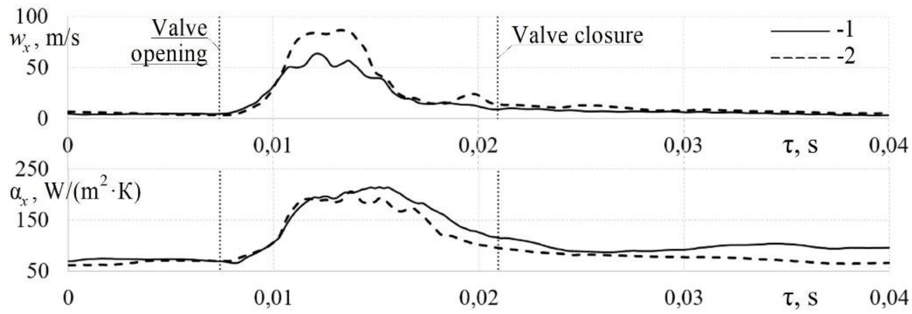

Figure 4. Dependences of the local flow rate w_x and the local heat transfer coefficient α_x in time for the exhaust system with TC (1) and the exhaust system with ejection (2) for n = 3000 rpm and p_{out} = 100 kPa.

Figure 4 shows that ejection in the exhaust system leads to a slight increase in the maximum flow rate in the range of 5-25% compared to the base system. There is also an increase in some vibrational phenomena during the exhaust process and after valve closure. This may be due to the lack of stabilization of the flow through the ejection tube. It should be noted that the air flow through the exhaust system with ejection increases by about 6-12%. At the same time, there is a slight decrease in the local heat transfer coefficient in the range of 3-15% when the ejection effect is created in the exhaust system (Figure 4).

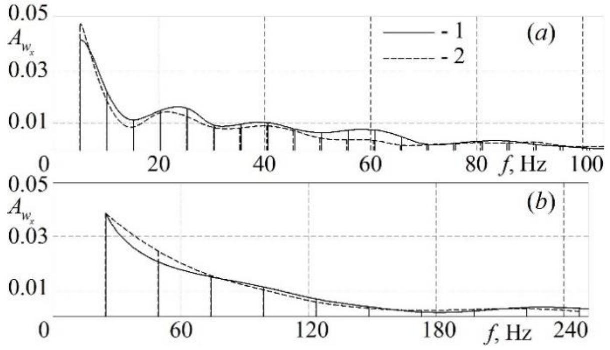

Figure 5. The graphs of the amplitudes of the spectrum of the air flow velocity w_x in the exhaust pipe of the engine without an ejection system (1) and with an ejection (2) at p_{out} = 100 kPa and different frequencies n: a – n = 600 rpm; b – 3000 rpm.

The presence of an ejection effect in the exhaust system does not have a noticeable effect on the graphs of the amplitudes of the flow velocity spectrum (Figure 5). The significant frequencies of the spectrum at n = 600 rpm are: 5.11 Hz, 10.18 Hz, 15.25 Hz, etc., i.e. the multiplicity has a value of 5.07 Hz. Significant spectrum frequencies at n = 3000 rpm are: 24.9 Hz, 49.6 Hz, 74.3 Hz, i.e. the multiplicity has a value of 24.7 Hz. It was found that the pulsation amplitudes of significant frequencies in the exhaust system with ejection are reduced up to 9% compared with the base system at crankshaft speeds of up to 1500 rpm. The differences in amplitudes do not exceed 5% (which is within the experimental uncertainty) at shaft frequencies of more than 1500 rpm.

In the applied aspect, a computational and analytical assessment of the positive effects was performed to improve the reliability from heat transfer suppression in the exhaust system with ejection. The failure rate for the basic and modernized exhaust systems was calculated in relation to a diesel engine (dimension 215/185). Based on these data, the probability of failure-free operation for the considered diesel engine at 3000 hours of operation was recalculated; it was found that it increased by 1.11-1.74 %.

5. Conclusions

The following conclusions can be made based on the analysis of the data presented in the article.

1. The turbocharger turbine has a significant impact on the aeromechanical characteristics of the flows in the exhaust system. There is a significant decrease in the maximum flow rate in the exhaust channel (up to 3 times) when installing the TC. There is also a more rapid attenuation of the oscillatory phenomena of function $p_x = f(\tau)$. There is a decrease in flow characteristics through the system under consideration. This indicates that the turbine TC acts on the gas-dynamic system as a powerful aerodynamic drag. At the same time, spectral analysis of functions $w_x = f(\tau)$ and $p_x = f(\tau)$ shows that the influence of TC on the flow has a more complex physical mechanism. There is a noticeable damping of the pulsation components in function $w_x = f(\tau)$ (the amplitude of the spectrum decreases up to 2 times) in the presence of a TC in the exhaust system. However, the pulsation components in function $p_x = f(\tau)$ increase by 2-3 times, which is especially typical for low-frequency components. This indicates a change

in the flow structure, the presence of disturbing factors (turbine blades) and an increase in the overall dynamics of the exhaust process.

2. A method for controlling the aeromechanical characteristics of flows in a gas-dynamic system of a piston engine with and without a TC is proposed. It is shown that the creation of the ejection effect in the exhaust system leads to a significant change in the flow mechanics. There is an increase in the maximum flow rate in the exhaust channel. Consumption characteristics through the system in question increase by 6-12% when creating an ejection effect. A spectral analysis of function $w_x = f(\tau)$ showed that the ejection effect leads to a decrease in the pulsation components of the flow velocity at crankshaft rotation frequencies of up to 1500 rpm (a decrease of up to 9% compared to the base system). Then, as there are no significant differences in the graphs of the amplitudes of the velocity spectrum (maximum differences ± 3.3%) at high rotation frequencies (at n ≈ 3000 rpm).

3. In the applied aspect of the study, it was found that the use of the ejection effect in a diesel engine (dimension 215/185) will increase the reliability of the exhaust system parts by an average of 1.5% compared to the basic RICE.

4. Data on aeromechanical processes in gas-dynamic systems of complex configuration expand the knowledge base in the field of fluid and gas mechanics, and can also find practical application in the development of unique gas exchange systems for engines with and without turbocharging.

Acknowledgments
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