TECHNICAL CONDITION ASSESSMENT AND MODELLING OF REED VALVES IN VEHICLE ENGINE INTAKE SYSTEMS

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Resume

The purpose of the study was to evaluate the effectiveness of using a simple reed valve model of an engine with periodic workflow. To achieve this purpose, models of the reed valve have been developed and determined that the quasi-stationary model allows one to find the air flow through the reed valve with an accuracy of 5-6%. The limits of permissible values, at which the model has a minimal error, correspond to Strouhal number of 0.2-0.3. This data confirmed that with proper consideration of the existing limitations, the quasi-stationary model gives results close to those provided by the complex dynamic models.

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1 Introduction.

A reed-type check valve is a fairly common design element that is used in the intake systems of some types of engines. The operating principle of a reed valve is quite simple. The petal is affected by the pressure drop between the inlet channel and the control volume (chamber). The vacuum in the chamber causes the petal to bend (lift) and open the inlet to allow air or the air/fuel mixture to pass through. When the pressure in the chamber subsequently increases, the valve closes, which stops the air supply and also prevents its reverse flow (ejection) from the chamber.

Despite its simple principle, the reed valve operates under dynamic loads that affect its performance. In addition, reed valves are known to be damaged by such loads. This raises the problem of mathematical modelling of the valve operation, including when creating mathematical models of engines.

Modelling a reed valve has its own characteristics, which is especially important when pairing (integrating) its model with the entire engine model. This requires solving the problem of correct selection and construction of a valve model. There is also the question of the dimensionality of the valve model if it is to be included in the overall engine cycle model, especially at the initial stage of its development.

2 Literature review and problem statement

Currently, the reed valve (Figure 1) is found as an element for controling the flow of working fluid in various machines and units. Thus, in 2-stroke spark-ignition gasoline engines, the reed valve controls the intake directly into the crank chamber [1], and numerous experimental [2] and theoretical studies [3] are dedicated to this process. Besides that, the reed valve provides the flow control in air compressors [4-6] and hydraulic units [7].

Valved pulse jet engines, which became widespread in the past [8], also incorporate similar types of reed

a b

c

Figure 1 *Reed valves: a - of a 2-stroke internal combustion engine (similar valves were used on full-size valved pulse jet engines), b - of a small-sized valved pulse jet engine, c - of an air compressor*

valves [9]. Unlike the compressors and 2-stroke engines, there are not too many studies on the reed valves for the pulse jet engines [10]. Known sources are often limited to technical data of valve mechanisms of various pulse jet engine models and experimental data [11]. However, research on reed valves has been carried out for a number of years in relation to pulse detonation engines [12].

The reed valve is a common modelling object, and a significant number of works are devoted to this topic [13-14]. When creating new engines and units, it is necessary to determine the parameters of elements and assemblies, including the reed valve, which determines the practical need for a detailed study of its operation. In this case, the greatest difficulties usually arise in ensuring the specified durability of the structure due to significant impact loads when the petal is seated on the support plate, as a result of which its fatigue cracking is observed (Figure 2a, b, c). At the same time, the most severe operating conditions arise when the reed valve is exposed to a high temperature of the working environment, which significantly accelerates destructive processes (Figure 2d).

It is obvious that these problems can be solved in general by simulating the valve operation under various conditions. In this case, it is advisable to use the valve model, not only to test the valve itself, but to study the cause of its destruction, as well. In addition, the development of a valve model is also of practical interest from the point of view of creating the engine model as a whole, in which the valve model is included as an integral part.

The simplest one is the so-called quasi-stationary or quasi-static model [7], in which the valve petal is assumed to be statically loaded, and dynamic processes are not taken into account. In such a model, obviously, the lift of the valve petal depends only on the instantaneous pressure drop across the valve.

As the frequency of forced oscillations increases, dynamic phenomena begin to influence the petal motion. This is, first of all, the rebound of the petal from the limiter and the valve plate [7]. In addition, the elastic line of the petal can bend [15], which can also affect the area opened by the reed valve and the air flow for a given drop. For these reasons, the vast majority of studies solve the dynamic problems of reed valve motion.

When studying a reed valve, it is customary to imagine it in the form of a beam (Figure 3a) with a fixed seal [5] and a distributed mass [4]. This model is used both in quasi-stationary [12] and dynamic formulations [7]. The hybrid models are also used, when the valve lift is calculated using one model, and the elastic line of the petal is determined using another [15]. At the same time, the simpler models also became widespread, for

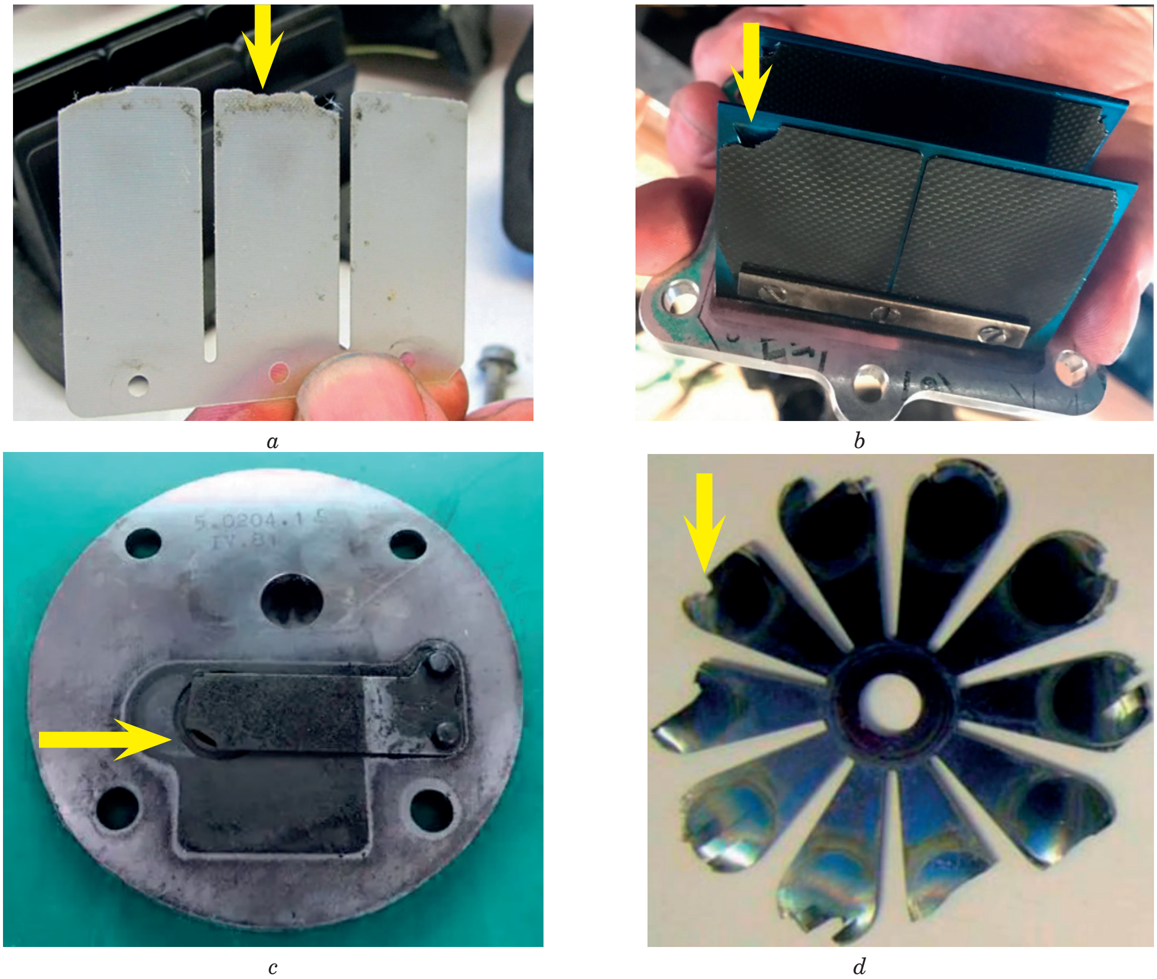
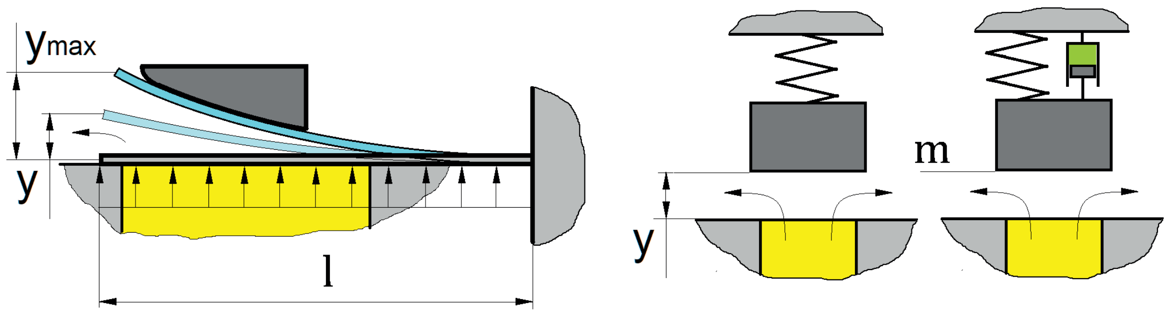


***Figure 2** The most common damage to petal valves in operation: fatigue cracking of petals in two-stroke gasoline engines with crank-chamber purging of cylinders (a - metal petals, b - plastic petals), in air compressors (c) and in pulse-jet engines (d - result of thermo-mechanical impact)*



a b c

***Figure 3** Possible simplified representations of a reed valve as a beam with a fixed embedment (a) and as a spring-loaded mass (b), including damping (c)*

example, in the form of a spring-loaded mass (Figure 3b, c), including those with damping [7]. In this case, the reed valve can be shown either as a simple mass on an elastic spring [6, 13], or as the same mass on an elastic beam [16-17]. In the latter case, the movement of the petal can be described by equations not of the first or second [12], but of the fourth order, as well [15].

A special place in the reed valve research is occupied by modelling of gas-dynamic processes. It is necessary to calculate the air flow through the valve, since the air flow is then included in the general object model for calculating the parameters of the control volume (cylinder, combustion chamber). For this purpose, the 3D flow modelling has become widespread as the most accurate method [16]. At the same time, a 3-dimensional model of the reed valve itself is often created [14, 18].

However, despite the advances in the reed valve modelling, the complex representation of the reed valve in various models does not always correspond to the overall modelling task. For example, if a detailed study of the operating process of the reed valve itself is being carried out, a 3D model is indeed justified. However, often we are talking about a complete model of the object, which in many cases is thermodynamic, that is, 0-dimensional, and the channels adjacent to the control volume are modeled using 1-dimensional gas-dynamic models [19-20]. For such conditions, the use of complex 3-dimensional models is completely inconvenient, and in some cases, when it comes to developing and debugging the new object models and calculation programs, it is generally unacceptable.

At the same time, some simpler reed valve models have been made, including quasi-stationary ones, and those based on the representation of the petal in the form of a beam fixed at one end or a spring-loaded mass (Figure 3). However, that work was not always completed. In many cases, it is not entirely clear what the reliability of certain models is and where their acceptable areas of application are. It is also not completely clear which of the known reed valve models can be integrated into the overall object model, and how model error can affect the modelling results of the entire object.

3 The aim and objectives of the study

The purpose of this study was to justify the choice of a reed valve model to effectively describe its motion - both as a part of a general model of an engine with periodic workflow, and as a separate model to determine the causes of reed valve damage.

To achieve this goal, it seems appropriate to solve the following problems:

- analyze the operating cycle of an engine with periodic workflow, determine the pattern of the reed valve influence on it,
- select the parameter most suitable for subsequent comparative analysis of different reed valve models,
- consider in detail the quasi-static and dynamic models of the reed valve, create a calculation algorithm,
- perform modelling of the reed valve motion in different operating modes of the engine type under consideration and
- conduct a comparative analysis of the models' reliability and accuracy, determine the conditions for their most effective use when modelling processes in the engines with periodic workflow.

4 The study materials and methods

The object of the study was a reed valve of an engine with periodic workflow. An engine of this type has a control volume in the form of a cylinder or combustion chamber [20], with channels (pipes) of air intake and gas exhaust systems. The reed valve is a control element of the engine intake system (Figure 4). With a positive pressure drop between the volume and the environment, the valve takes a closed position. However, with a negative pressure drop, when pressure in the control volume falls down below the ambient pressure, the petal lifts and passes air from the environment into the control volume.

Determination of the air flow parameters in a reed valve, when modelling engines with periodic workflow, is possible by analytical solution and/or numerical integration of differential equations that describe this process. In a specific task, a numerical-analytical method was chosen, when, using simplifying assumptions, an analytical determination of the petal lift as a function of the pressure drop was first carried out, and then a numerical solution was performed for the differential equation of the petal motion over the process time. In this case, the numerical simulation method was used as a test method to evaluate the results obtained by the analytical method.

The initial data were approximate geometric dimensions, their relationships and characteristics of elements of engines with periodic workflow [8, 11, 20].

The main hypothesis in the analytical solution was the assumption that under certain conditions, determined by the frequency of the process, the petal motion and air flow on the valve can be considered as a quasi-stationary process [7]. To implement the numerical method, a number of additional simplifying assumptions were made. The derivation of the petal motion equations was carried out within the framework

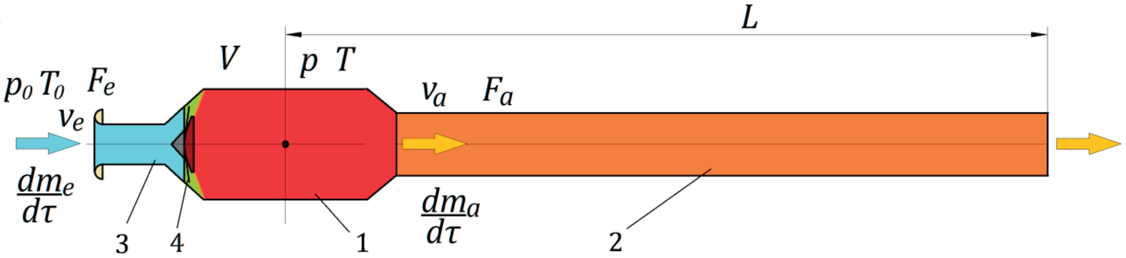


Figure 4 *A simplified diagram of an engine with periodic workflow: 1 - control volume, 2 - resonant exhaust pipe, 3 - inlet pipe, 4 - check reed valve*

of the analogy of the petal movement as a concentrated and spring-loaded mass. The concept also took into account the possible elastic dynamic rebound of the petal in extreme positions.

All the calculations and modelling were carried out in an Excel environment with the XLfit extension [20]. The software choice was due to the limited volume of calculations (no more than 400 time points per cycle), their test nature, and the lack of ready-made standard programs for solving the problem under consideration.

5 The results of studying the reed valve working process in the engine with periodic workflow

5.1 The reed valve effect on the operating cycle of an engine with periodic workflow

When solving the problem, it is important that the air flow through the inlet reed valve is associated with a thermodynamic model that describes the state of the gas in the control volume into which the air flows through the valve. The control volume V within the framework of a 0-dimensional theory [21-22] can always be described by a system of 2 differential equations of the 1st order for gas temperatureand pressure, which can be obtained from the equation of the first law of thermodynamics (energy) and the equation of state of an ideal gas in the form [23-24]:

$$\begin{cases} \dfrac{d\bar{T}}{d\bar{t}} = f_1\left(\bar{T},\bar{p},\dfrac{d\bar{m}}{d\bar{t}},\dfrac{d\bar{Q}}{d\bar{t}},V...\right) \\ \dfrac{d\bar{p}}{d\bar{t}} = f_2\left(\bar{T},\bar{p},\dfrac{d\bar{m}}{d\bar{t}},\dfrac{d\bar{Q}}{d\bar{t}},V...\right) \end{cases}, \tag{1}$$

where V is the volume, $\bar{T}$ is the temperature, $d\bar{m}/d\bar{t}$ is the mass flow of gas from or into the control volume (through the corresponding pipes), $d\bar{Q}/d\bar{t}$ is the rate of heat release in the volume.

The system of equations in Equation (1) includes the air flow rate into the volume under consideration or out of it. It directly depends on the pressure drop and the nature of the flow of air and gas at the inlet and outlet of the volume [20], including the characteristics of the reed valve. Therefore, the reed valve model must be a part of a 0-dimensional thermodynamic model of an engine with periodic workflow. Accordingly, not only the accuracy of engine modelling, but the ability to simulate self-oscillations and the stability of its operating cycle, as well, depend on the reed valve model.

It is obvious that the air flow rate is also the resulting (integral) parameter of the entire process of the air flow through the reed valve. In this case, both the instantaneous and the total air flow rate per cycle are equally important for the same given air parameters in front of the valve and valve geometry itself.

5.2 Determination of air flow rate through the reed valve

In general, the flow rate can be determined by the air parameters in the channel in front of the reed valve as:

$$\frac{d\bar{m}_e}{d\bar{t}} = \mu\bar{\rho}_e\bar{\upsilon}_e F_e\,, \tag{2}$$

where ρ_e is the air density and velocity in front of the valve; F_e is the cross-sectional area of the input channel; $\mu = 1/\sqrt{1+\xi_\Sigma}$ is a flow coefficient [25], which depends on the hydraulic resistance of the channel and reed valve (valve system) ξ_Σ [26].

When developing the models, equations written in dimensionless form were used. To do this, one should move on to dimensionless variables: pressure $p = \bar{p}/\bar{p}_o$, temperature $T = \bar{T}/\bar{T}_o$, velocity $\upsilon = \bar{\upsilon}/\bar{\upsilon}_o$, time $t = \bar{t}\bar{\alpha}_o/L$, coordinate $x = \bar{x}/L$, where $\bar{p}_o, \bar{T}_o$ are the ambient pressure and temperature, respectively; $\bar{\alpha}_o = \sqrt{\gamma_o\bar{R}_o\bar{T}_o}$ is the speed of sound in the environment; $\bar{R}$ is a gas constant; $\gamma_o = 1.4$ is the heat capacity ratio; L is the characteristic size of the engine (hereinafter, the overbar indicates dimensional values).

If one takes the length of the exhaust pipe L as the characteristic size of the engine, which determines the cyclic operation, then the cross-sectional area of the exhaust pipe F_a can be chosen as the characteristic area. In addition, if one does not take into account the dynamic pressure [27] at the inlet (in some types of engines with periodic workflow it is not present), then Equation (2) can be approximately written as follows:

$$\frac{dm_e}{dt} = \frac{1}{\sqrt{1+\xi_\Sigma}}\varPhi p^{\frac{1}{k_o}}\sqrt{\frac{2}{\gamma_o-1}\left(1-p^{\frac{\gamma_o}{\gamma_o-1}}\right)}\,, \tag{3}$$

where the dimensionless parameter is:

$$\varPhi = \frac{F_e}{F_a} = \left(\frac{D_e}{D_a}\right)^2, \tag{4}$$

and D_e, D_a are the diameters of the input channel and the resonance pipe of an engine with a periodic workflow, respectively.

Obviously, to determine the flow rate, it is necessary to find the hydraulic resistance of the reed valve. In the absence of more accurate data, one can use the known dependencies for the hydraulic resistance coefficient on the valve lift value. Thus, for a poppet valve, there is an approximate formula [25]:

$$\xi_\Sigma = 0.55 + 4\left(\frac{b}{d} - 0.1\right) + \frac{0.155}{(\bar{y}/d)^2}\,, \tag{5}$$

where $\bar{y}$ is the lift of the valve petal, d is the characteristic diameter of the hole opened by the petal, b is the amount of overlap of the hole by the petal when completely closed (Figure 5).

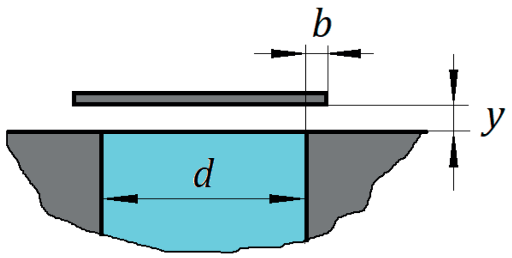


Figure 5 *The diagram of a poppet valve analogy, accepted for determining the hydraulic resistance coefficient of the reed valve*

5.3 Reed valve models of an engine with periodic workflow

The quasi-stationary reed valve model is obviously the simplest and assumes that the frequency of natural oscillations of the valve petal is many times greater than the frequency of forced oscillations corresponding to the engine process frequency. In this case, the inertia of the valve petal motion and, first of all, its delay when the pressure drop changes, can be neglected and the problem can be considered quasi-stationary.

Within the framework of the quasi-stationary model, the petal lifting height does not depend on its speed and acceleration, but is determined only by stationary parameters. These are the pressure drop Δp and the petal toughness. It means, that the petal can be considered as a beam with one-sided embedding and a load distributed along the length (Figure 2a). For such conditions, the petal lifting from the distributed load [28] can be written as:

$$\bar{y} = \frac{\bar{q}l^4}{8\bar{E}I_x}, \tag{6}$$

where $\bar{E}$ is the elastic modulus of the valve petal material; I_x is the moment of inertia of the section along the axis; l is the length of the valve petal.

Considering that $I_x = \delta^3 b/12$, where δ and b are the thickness and width of the valve petal, respectively, and $\bar{q} = \Delta\bar{p}l$, after substituting into Equation (6) and transformations, the formula was obtained:

$$y = \frac{\bar{y}}{l} = 1.5\frac{\Delta p}{S}, \tag{7}$$

where $\Delta p = \Delta\bar{p}/\bar{p}_o$ is the dimensionless pressure drop across the reed valve; $\bar{p}_o$ is the ambient pressure, and the dimensionless parameter Sactually determines the valve petal stiffness:

$$S = \frac{\bar{E}}{\bar{p}_o}\left(\frac{\delta}{l}\right)^3, \tag{8}$$

where $\bar{E}$ is the modulus of elasticity, δ is the thickness, l is the length.

Equation (7) establishes the desired dependence of the valve petal lift on the pressure drop.

To assess the applicability of the quasi-stationary model, it is necessary to know the natural frequency of the valve petal and, at a minimum, compare it with the forced frequency (the cycle frequency of an engine with periodic workflow).

The petal natural vibration frequency f, when it is fixed on one side, can be easily found using the formula given in [29]. Further, taking into account the environment speed of sound and the fact that the pressure $\bar{p}_o$ and temperature $\bar{T}_o$ are related by the equation of state of an ideal gas $\bar{p}_o = \bar{\rho}_o\bar{R}_o\bar{T}_o$, the valve petal natural frequency was obtained in the following final form:

$$\bar{f} = \frac{1}{\bar{\tau}} = 0.1615\frac{\bar{\alpha}_o}{\sqrt{l\delta}}\sqrt{\frac{S}{\gamma_o\rho_m}}, \tag{9}$$

where $\rho_m = \bar{\rho}_m/\bar{\rho}_o$ dimensionless density of the material.

A preliminary analysis of Equation (9), taking into account stiffness in Equation (8), shows that the frequency of natural vibrations is proportional to the stiffness and inversely proportional to the density of the valve petal material. As an example, one can consider a steel valve petal with the following parameters: thickness 0.25 mm, length 25 mm, from which, with an elastic modulus of $2 \cdot 10^{11}$ Pa, from Equations (8) and (9), one can obtain a frequency $\bar{f} = 327$ Hz.

Within the framework of the dimensionless time $t = \bar{t}\alpha_o/L$, adopted above, the dimensionless frequency (equal to the Strouhal number of the process under study [30]) is the inverse of time and amounts to $f = \bar{f}L/\bar{\alpha}_o$. Based on this, it is possible to roughly determine the limitation on the use of a quasi-stationary model depending on the size factor. For example, with a process frequency of 150 Hz and a characteristic length L = 0.8 m, the Strouhal number will be approximately 0.30-0.35. At the same time, the dimensionless natural vibration frequency of the valve petal is two or more times higher.

To determine the scope of application of a quasi-stationary model of a specific reed valve as a part of a general engine model, it is necessary to understand what processes such a model does not take into account, and how this affects to the air flow rate through the valve. To do this, it is necessary to compare the simulation result to what is given by more realistic models that take into account the dynamics of the valve petal motion.

In general, the valve petal can be represented as a beam with one side fixed. The motion of such a beam can be described by a fourth order partial differential equation [4, 13]:

$$\frac{\partial^2}{\partial \bar{x}^2}\left(\bar{E}I_x \frac{\partial^2 \bar{y}}{\partial \bar{t}^2}\right) + m_x \frac{\partial^2 \bar{y}}{\partial \bar{t}^2} = q(\bar{x}, \bar{t}), \tag{10}$$

where m_x, $q(x, t)$ are the distributed mass of the element and the load on the beam, -is the longitudinal coordinate, is the vertical coordinate (lift), $\bar{t}$ is the time.

Equation (10) in the general case allows one to calculate the instantaneous shape of the beam elastic line. However, within the framework of the above-adopted shown of the valve in the form of a spring-loaded and concentrated mass (Figure 3), the equation of Newton's second law is usually used, which determines the acceleration of the valve petal as the second derivative of its lift with respect to time [6, 17, 31]

$$m\frac{d^2\bar{y}}{d\bar{t}^2} = \Sigma \bar{F}_i, \tag{11}$$

where m is the mass of the valve petal; $\bar{F}$ is force acting on the valve petal; $\bar{y}$ is the vertical coordinate (lift); $\bar{t}$ is the time.

Let the Equation (11) be written in the dimensionless form, simultaneously reducing its order. To do this, it is possible to replace the 2nd derivative of the petal lift with the 1st derivative of its velocity (acceleration). Then, this equation with the equation for the petal velocity, as the 1st derivative of its lift, with consideration of rebound [32], forms a system of 1st order differential equations for the petal lift and velocity:

$$\begin{cases} \theta \dfrac{du}{dt} = -\dfrac{2}{3}Sy + \Delta p \\ \lambda \dfrac{dy}{dt} = u \end{cases}, \tag{12}$$

where $\theta = \gamma_o \rho_M \lambda \left(\frac{\delta}{l}\right)$ is a dynamic coefficient; $\rho_M = \bar{\rho}_M / \bar{\rho}_o$ is a dimensionless density of the valve blade material; $\lambda = l/L$ is a relative length of the valve petal.

To solve the problem, some engines with a periodic workflow were analyzed [33] and the necessary geometric characteristics were selected, including the length and diameter of the resonance exhaust pipe L = 0.80 m, D_a = 0.04 m, the diameter of the inlet pipe D_a = 0.035 m, as well as the dimensions of the petal valve $\delta = 0.00025$ m, l = 0.025 m, b = 0.012 m, y_{max} = 0.2 (a block of 10 valves located around a circle was considered).The operation of an engine was modeled by specifying the law of gas pressure change in the control volume. For this, the shape of the pressure oscillations (sinusoid), their amplitude $(\Delta p = 0.3)$ and frequency $(f = Sh = 0.1 - 0.7)$ were specified.

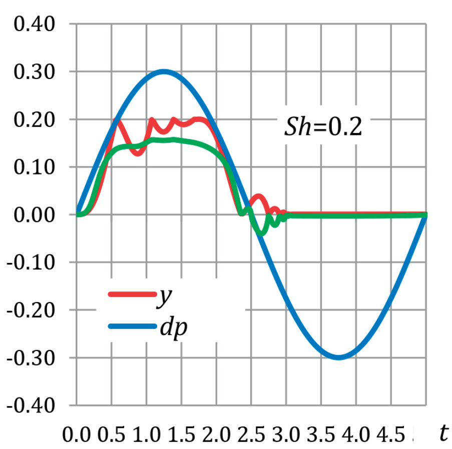
6 Results and discussion

6.1 Results of mathematical modelling of valve the petal motion

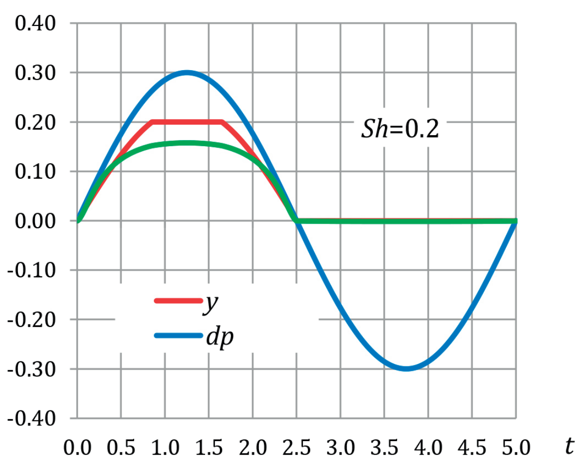
The calculation results show that the petal motion within the dynamic model (Figure 6a) differs significantly from what is given by the quasi-stationary model (Figure 6b). The main difference is the petal rebound from the stop plate and from the valve plate, when the petal position is determined by its inertia, and not just by the pressure drop, as in the quasi-steady model.

However, comparison of models in terms of the air flow rate under these conditions (Figure 7b) did not give a significant difference. Even with the reverse air flow presence, the difference was only 6 % (the dynamic model corrects the air flow rate downward compared to the quasi-stationary one). Such results indicated the need to study the valve petal when operating at other possible frequencies.

The first thing that was revealed, with an increase in the frequency of the engine's operating process, was an increasing dynamic lag in the petal motion when it opens and closes (Figure 8). The influence of the frequency of natural oscillations of the petal in Equation (9) is clearly visible - with an increase in the frequency

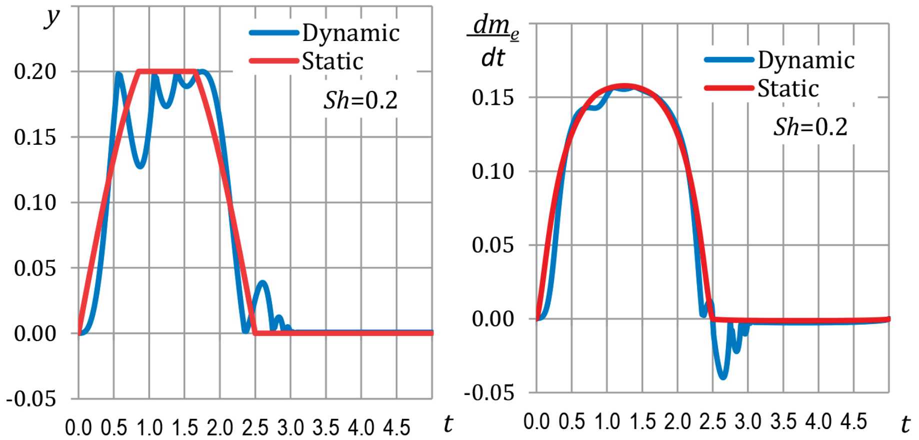


a



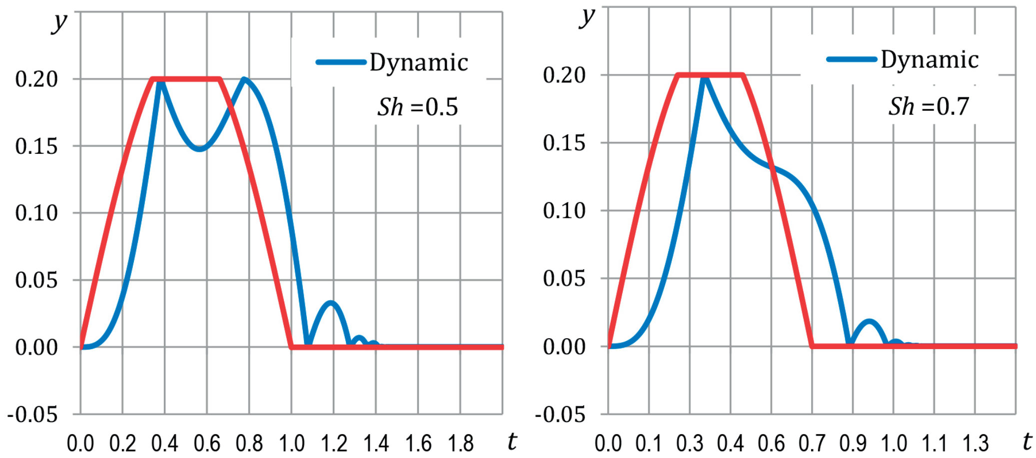
b

Figure 6 *Difference in petal motion calculated by: a - dynamic model; b-quasi-stationary model*



a *b*

Figure 7 *Comparison of instantaneous parameters calculated using the quasi-stationary and dynamic models: a - valve petal lift; b - air flow rate through the reed valve*



a *b*

Figure 8 *Valve petal lift profile at high frequencies: a - Sh =0.5; b - Sh =0.7*

of forced oscillations, the number of complete oscillations of the valve petal near the extreme positions decreases.

At the same time, a significant change in the valve petal velocity profile occurs (Figure 9a). Moreover, a noticeable increase in the petal motion velocity, when rebounding from the valve and stop plates (Figure 10a), causes intense petal vibrations.

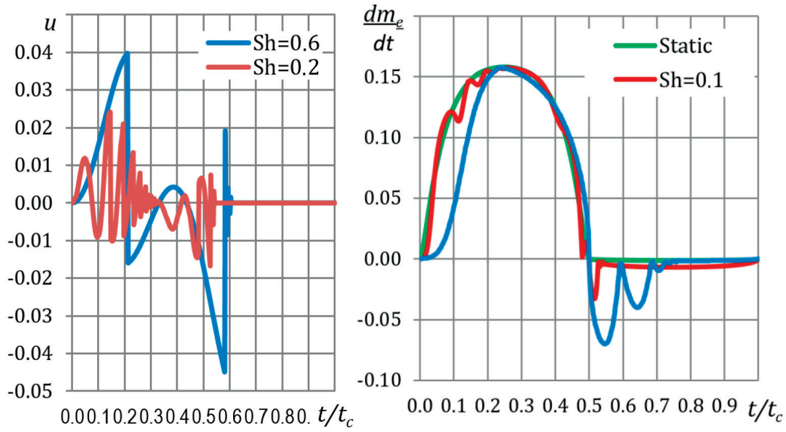
Obviously, this can lead to a decrease in the durability of the valve petal due to the fatigue cracking mentioned above (Figure 2). It is not yet possible to draw unambiguous conclusions based on the valve petal speed alone and, moreover, to obtain any specific figures for its durability without additional research. This is due, among other things, to the influence of the number of impacts during the petal rebound, which may be greater at lower frequencies. However, in any case, the impact speed will be the parameter that determines the durability of the reed valve.

The process of the valve petal lag with increasing frequency of forced oscillations has also a significant effect on the air flow rate (Figure 9b). At a low frequency of the process the flow rate curve over the cycle is close to quasi-stationary, and the difference is made only by the oscillations of the valve petal at the extreme points. At a high frequency the picture is fundamentally different.

Indeed, with increasing frequency of forced oscillations, the difference grows rapidly (Figure 10b). In addition, with increasing frequency, the phase shift of the valve petal lift and air flow rate curves to the late side increases. At small values of the Strouhal number, rather intense oscillations of the valve petal are excited not only during the rebound, but during lifting (Figure 9a), as well, which also causes an increase in the difference in air flow rate (Figure 10b). However, at low frequencies, the result may be affected by the instability of the calculation, as well as the need to clarify the coefficient of recovery for specific structures.

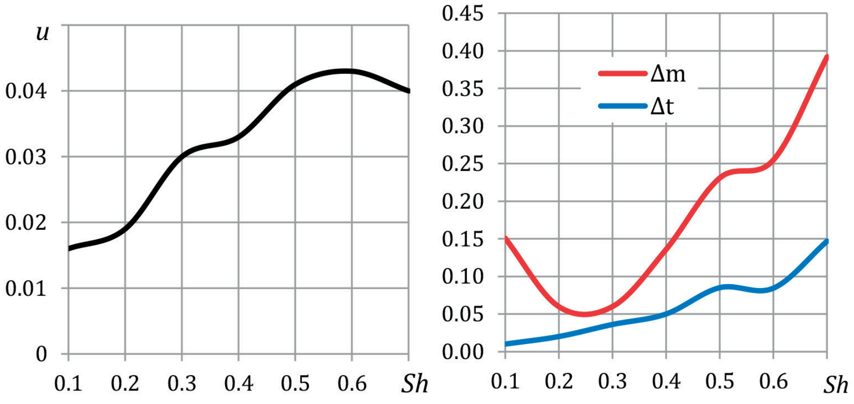
6.2 Comparative analysis of the accuracy and reliability of the models

The modelling results indicate that the Strouhal number can be used to evaluate the range of



a *b*

Figure 9 *Changes in parameters over the cycle with increasing frequency of the process: a - valve petal speed profile; b - air flow rate profile*



a *b*

Figure 10 *The resulting curves of parameters depending on the frequency of the process (Strouhal number): a - the speed of the valve petal at the moment of impact on the valve block; b - error of the quasi-stationary model in terms of air flow rate and oscillation phase*

Table 1 *Basic parameters of known pulse jet engines [34, 35]*

Engine model	Argus As 014[34]	Solar PJ32[35]	Tiger-jet M1[33]	Dyna-jet [33]
Resonant tube length, m*	2.60	1.50	0.406	0.430
Operating frequency, Hz	45	85	250	220
Strouhal number	0.33	0.32	0.30	0.28

*the length of the pipe includes the length of the transition part between the control volumeanda pipe.

applicability of a particular reed valve model. This is especially noticeable when comparing the models under consideration. For example, when the Sh value is above 0.40-0.50 (high frequency of the process), there is a significant discrepancy between the models in air flow rate, which reaches 25% or more with the same law of change in pressure drop and other parameters. The situation is not much better when the Sh value is below 0.10-0.15 (low process frequency), when the discrepancy in flow rate reaches 15%. Overall, this data indicates excessively high errors in the quasi-static model, which significantly overestimates air flow rate compared to the more realistic dynamic model.

However, in the range of Strouhal numbers Sh = 0.20-0.30 (average frequency), on the contrary, there is a satisfactory agreement between the models for air flow rate, with an accuracy of no worse than 5-6%. If one compares this result with the operating frequencies of known types of engines with a periodic workflow, one can note that for valved pulse-jet engines of different sizes (Table 1), the Strouhal number corresponding to the operating frequency falls within the specified range, grouping near the value Sh = 0.30.

For other types of engines, evaluation of methods using the Strouhal number is applicable, as well.

Thus, in known designs of 2-stroke gasoline internal combustion engines with crank-chamber purging of the cylinders [1, 3], the Strouhal number for the reed valve is close to those indicated in Table 1 at maximum mode. Accordingly, as the crankshaft rotation speed decreases, the operating point on the curve (Figure 10b) will shift towards decreasing the error of the quasy-stationary method, with the exception, possibly, of only the lowest rotation frequencies. A similar picture is observed in piston compressors, where the operating point, corresponding to the operating speed, is usually located in the same part of the diagram (Figure 10b).

7 Conclusion

A simple quasi-stationary model of the intake reed valve of an engine with periodic workflow, designed to close 0-dimensional thermodynamic models of the full cycle, and an alternative dynamic model for mathematical modelling of the valve reed motion, are considered.

Based on the data obtained, a comparative analysis of the accuracy and reliability of the quasi-stationary and dynamic models of the reed valve was carried out. It has been established that the quasi-stationary model makes it possible to find the air flow rate through the reed valve with an accuracy of 5-6% for a pressure drop varying according to a sinusoidal law, if the frequency and/or the Strouhal number do not exceed the range of permissible values. The permissible limits for changes in the frequency of forced oscillations, corresponding to the Strouhal number of 0.20-0.30, in which the quasi-stationary model has a minimal error compared to the dynamic model, are found.

The data obtained confirms that, with proper consideration of the existing limitations, the quasi-stationary model gives results close to those provided by more complex dynamic models, including those with a higher dimension. This indicates the possibility of using a quasi-stationary model for elements such as reed valves as an approximate alternative to more complex dynamic models, which is especially important when creating and preliminary debugging of 0-dimensional thermodynamic models of engines with periodic workflow.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A *Nomenclature*

Symbol	Definition
L	length, m
F	area, m^2
V	volume, m^3
l	length, m
b	width, m
δ	thickness, m
$\bar{E}$	modulus of elasticity, Pa (N/m^2)
I_x	moment of inertia, m^4
$\bar{v}$	air velocity, m/s
M	Mach number
γ	heat capacity ratio
R	gas constant, J/kg.K
$\bar{p}$	pressure, Pa
$\bar{T}$	temperature, K
$\bar{\rho}$	density of gas (air), kg/m^3
$\bar{t}$	time, s
$\Delta \bar{t}$	step in time, s
$\bar{x}$	longitudinal coordinate, m
$\bar{y}$	vertical coordinate (lift), m
$\bar{u}$	speed of movement of the valve petal, m/s
$\bar{a}$	speed of sound, m/s
ξ	coefficient of hydraulic resistance
μ	flow coefficient
f	process frequency, s^{-1}
Sh	Strouhal number
$\bar{m}$	mass, kg
$\bar{Q}$	amount of heat, W

The overbar over gas parameters indicates the dimensional values.