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MATHEMATICAL MODELING OF START-UP TRANSIENTS AT CLUSTERED PROPULSION SYSTEM WITH POGO-SUPPRESSORS FOR CYCLON-4M LAUNCH VEHICLE

Liquid-propellant rocket propulsion systems of the first stages of launch vehicles of medium, heavy, and super-heavy class usually include POGO-suppressors, which are one of the most widely used methods to eliminate launch vehicle longitudinal structural vibrations (POGO phenomena). However, until now, the theoretical studies and analysis of the effect of the POGO-suppressors' installation in the feedlines of main liquid rocket engines on transient processes in systems during rocket engine starting have not been carried out due to the complexity of such analysis and the lack, first of all, reliable nonlinear models of cavitation phenomena in rocket engine pumps.

A mathematical model for the start-up of a clustered rocket propulsion of the Cyclone-4M launch vehicle has been developed that takes into account the low-frequency dynamics of the POGO-suppressors and the asynchronous start-up timeline sequences of the rocket engines. The first stage of the launch vehicle propulsion system includes four RD-870 rocket engines. A nonlinear mathematical

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model of low-frequency dynamic processes of the POGO-suppressor with bellows separation of liquid and gaseous media is presented. A significant effect of cavitation in the pumps of engines and the POGO-suppressor installation to the LOX feedline on the propulsion system dynamic gains is shown.

Based on the developed mathematical model of the clustered rocket propulsion start-up, the studies of the Cyclone-4M main engines' start-up transients were carried out. The asynchronous start-up timeline sequences of the rocket engine and the places of installation of the POGO-suppressors in the LOX feedline branches to the RD-870 rocket engine — near the general feedline collector as standard placement or directly at the entrance to the engines — were investigated. The analysis of start-up transients in the oxidizer feed system of the considered propulsion (the time dependences of the flowrate and pressure at the engine inlet) showed the following.

Firstly, while the synchronous start-up of the engines, the installation of the POGO-suppressors near the feedline collector makes it possible to eliminate all engine inlet overpressures that exist in the rocket propulsion system in case of the absence of the POGO-suppressors.

Secondly, the RD-870 engine asynchronous start-up operation affects negatively the time dependences of the propellant flowrate and pressure at the engine inlet if the POGO-suppressors are located near the feedline collector. So, in the propulsion system's start-up timeline interval 0.95...1.35 s, for some computational variants of the initial moments of the engine operation start, an abnormally large drop in the LOX flow rate and the overpressures at the engine inlet is observed. The asynchronous start-up of the RD-870 engines with the installation of the POGO-suppressors at the engine inlet does not significantly change the start-up transients compared to the synchronous starting of the engines.

Thirdly, thus, it is shown that the installation of the POGO-suppressors both at the engine inlet and at the RD-870 branches near the collector has a significant positive effect on the quality of start-up transient processes for the main engines of the 1st stage of the Cyclone-4M launch vehicle. Placing the POGO-suppressors at the engine inlets is not standard and is considered without reference to the propulsion system layout. Nevertheless, the POGO-suppressors installed at the inlet to the engines are an effective means of preventing overshoots and dips in the parameters of the liquid-propellant rocket engine, including the conditions of asynchronous starting of the liquid rocket engines in the clustered propulsion system.

The results obtained can be used in mathematical modeling of the start-up of the first stage propulsion system either for multistage sustainer rockets used in parallel with booster rockets or for the clustered multi-engine rocket propulsion system containing POGO-suppressors.

***Keywords**: liquid-propellant rocket engine, low-frequency dynamic processes, start-up, pump cavitation, clustered feed system, asynchronous engine start-up, POGO-suppressor.*

INTRODUCTION

Start-up is probably the most difficult dynamic operation mode of the liquid rocket engine (LRE) [3, 18]. During a short start-up time of LRE, the hydraulic paths are filled by propellants, ignited in a gas generator and a combustion chamber, the turbopump assembly rotor speed and propellant flow rates change from initial zero to nominal values, etc.

The theoretical study of transient processes during LRE start-up is important for predicting and eliminating problem situations during startup, as well as for optimizing the engine start-up (event timeline sequence).

At present, mathematical models of dynamic processes for many units and systems of liquid rocket engine have been developed, for example, in papers [3, 10]. It makes it possible to obtain preliminary theoretical forecasts of transient processes of a number of parameters for liquid rocket engine start-ups.

A semi-empirical model of filling the LRE hydraulic lines by cryogenic propellants is presented in [18]. The model takes into account the partial evaporation of liquid oxygen and its two-phase flow in the path in the initial part of the engine start-up period.

The kinetics of ignition and propellant burnup in the LRE gas generator and the combustion chamber at the initial start-up period of the liquid rocket engine were investigated in [10, 18].

Theoretical approaches to mathematical modeling of cavitation phenomena in liquid rocket engine pumps in a wide range of operating parameters (including engine start-up) have been developed in a number of works [4, 15—17] focused on pumping systems nonlinear dynamics. A methodical approach for mathematical modeling of low-frequency dynamics of a liquid rocket engine is presented in the paper [5].

An account of the non-simultaneity of the entry into operation of a separate liquid rocket engine in a multi-engine propulsion system and an influence of this factor on the transient processes of hydrodynamic parameters at start-up of a multi-engine propulsion system is shown [14].

The first stage propulsion system of modern launch vehicles of medium, heavy, and super-heavy class usually includes POGO-suppressors. POGO-suppressor installation is one of the common ways to eliminate longitudinal (POGO) vibrations of liquid launch vehicles. The mechanism of longitudinal vibrations is due to the convergence of natural frequencies of launch vehicles structure with natural frequencies of propulsion system feedlines [9, 11, 13, 22]. Medium and especially heavy and super-heavy launch vehicles are prone to loss of longitudinal stability as a result of launch vehicle big mass, consequently, the structural low oscillation frequencies.

The possibility of such launch vehicles' longitudinal instability is very high. It can be explained by the fact of changes in the natural oscillation frequencies of launch vehicles' structure and changes in the natural frequencies of propellant oscillations in the propulsion system during rocket stage operation are in the same range. The installation of the POGO-suppressor in the feed system of the propulsion system leads to a decrease in the first natural frequency of liquid oscillations in the propulsion system. This allows the oscillation frequencies of the launch vehicle structure and the liquid in the feed system of the propulsion system to be separated to safe values leading to launch vehicle POGO stability.

However, to date, the theoretical studies and analysis of the POGO-suppressor installation in the feed lines of main liquid rocket engines' effect on transient processes in systems during liquid rocket engines' start-up have not been carried out.

Difficulties in conducting such an analysis and the absence, first of all, reliable nonlinear models of cavitation phenomena in pumps, in the overwhelming majority of cases, lead to the next fact. Only experimental parameters of the performance of some individual engines were obtained during fire bench testing of specific liquid rocket engines.

The launch vehicles of the Mayak and the Cyclone-4M families designed in Ukraine take into account the POGO suppressors [2] installed in the feed of the propulsion system. This makes it actual to analyze the impact of POGO-suppressors in the LRE feed lines on transients in the propulsion system.

The main objective of this work is the mathematical modeling and research of transient processes of launching the clustered propulsion system of the first stage of the Cyclone-4M launch vehicle, taking into account the installation of POGO-suppressors on the propulsion system and liquid rocket engines' asynchronous start-ups.

1. The studied propulsion system of the 1st stage of Cyclone-4m launch vehicle. The Cyclone-4M launch vehicle is a two-stage monoblock medium-class launch vehicle [20]. The structure of the first stage is based on the use of well-developed systems and units of the Zenith launch vehicles. The first stage is equipped with a propulsion system using liquid oxygen and kerosene fuel components and includes four RD-870 engine blocks.

Liquid rocket engine RD-870 is made with a turbo-pump system for propellant feeding according to the staged combustion scheme. The engine thrust on Earth is 794.5 kN (vacuum thrust is 888.5 kN), the engine specific thrust impulse on the Earth is 301 s (in the vacuum the specific thrust impulse is 340 s), the mass of the RD-870 engine is 1353 kg [20]. A simplified flow schematic of the RD-870 liquid rocket engine is shown in Fig. 1.

The feeding of the rocket RD-870 engines with a LOX from the tank is carried out through a general main pipe (with a length of about 7 m), which is connected to the collector. Fig. 2 contains the propulsion system layout with only 2 branches to the RD-870 engines shown for simplicity.

Branch pipelines from the collector to each engine contain installed POGO-suppressors. The length of the pipeline from the collector to the engine inlet is 3 m, and from the engine inlet to the oxidizer low-pressure pump inlet is about 2 m. Hereinafter, for presenting the materials of the paper, the engine inlet means the location directly at the low-pressure pump inlet.

The branch pipelines from the collector to the engine inlet have a rather long length. That is why they can have a significant effect on the low-frequency dynamics of the propulsion system, especially for research cases of the different engines' starting operation (engines' asynchronous start-ups) [14].

To provide the Cyclone-4M launch vehicle POGO stability, the POGO-suppressors are installed accordingly with the design of the I stage propulsion system.

The POGO-suppressors are designed according to the scheme with bellows separation of gas and liquid

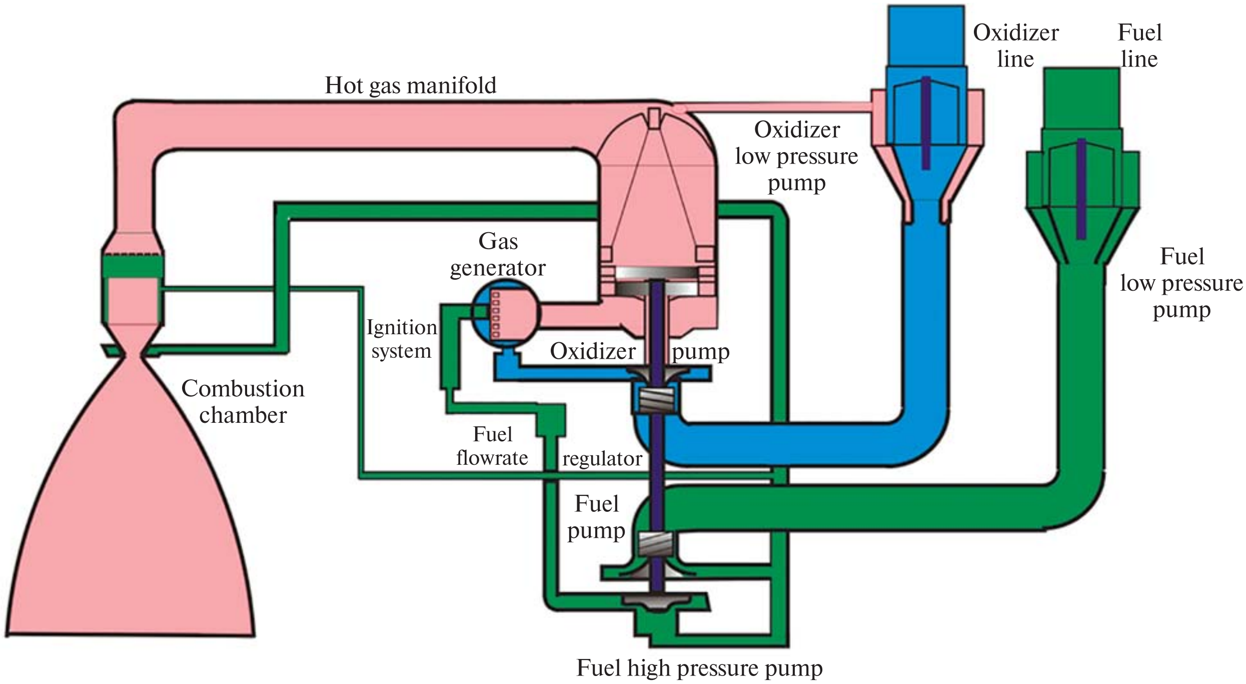

Fig. 1. Simplified flow schematic of the LRE under research

media. The standard location of the POGO-suppressors is in the branches of the LOX feed system to the main RD-870 liquid rocket engines (near the collector, as shown in Fig. 2). The same scheme shows POGO-suppressors (indicated by a dotted line) in case they are installed directly at the engine inlet. The parameters of the standard version of POGO-suppressors were selected from the condition of providing the POGO stability of the Cyclone-4M launch vehicle during its flight for the first stage propulsion operation period [13].

2. Developed mathematical model of start-up of clustered (multi-engine) propulsion system of the Cyclone-4M launch vehicle. The mathematical model of start-up of the first stage propulsion system of the Cyclone-4M launch vehicle is extremely cumbersome. The full model includes more than 350 nonlinear ordinary differential and algebraic equations and cannot be presented in this volume of the paper.

The main approaches to mathematical modeling of the low-frequency dynamics of systems of this liquid rocket engine are presented in [14]. This model describes the dynamic processes in the propulsion system, including the opening of the oxidizer and fuel valves, filling the hydraulic paths by propellant, spinning up the rotors of the main and low-pressure turbopump assembly, the ignition of the propellant in the gas generator, etc.

Let us briefly dwell on the mathematical models of some low-frequency dynamic processes in units and subsystems of propulsion system. They are either characteristic of engines with generator gas afterburning or are important in the mathematical modeling of start-up of clustered propulsion system**.**

For rocket engines with staged combustion, it is important to take into account the time delays caused by non-isothermality of processes in the elements of the liquid rocket engine gas path (the residence time of the combustion products in the gas paths) and the time delays caused by the delay in the conversion of liquid propellants into gaseous ones [7].

In the mathematical model of liquid rocket engine start-up, an approximate replacement of the equations $y(t) = x(t-\tau)$ of the time delay element with ordinary differential equations is used. This replacement is based on the approximation of the transfer function of the delay element $W_e(p\tau) = \exp(-p\tau)$ by fractional rational functions of $p\tau$ (where p is a complex variable of the Laplace transform at zero initial conditions; τ is time delay). To approximate the transfer functions of the delay elements in the equations of the gas generator and the gas pipe dynamics, two fractional rational functions were used: the function

$$R_{n(T02)}(p\tau) = [T_{0,2}(p\tau/2)]^2 =$$
$$=1/(1+p\tau/2+0.125p^2\tau^2)^2 \approx W_e(p\tau)$$

is obtained by replacing the delay element with a chain of two oscillating elements with half the delays [21], and the function

$$W_e(p\tau) \approx P_{1,2}(p\tau) =$$
$$(1-p\tau/3)/(1+2p\tau/3+p^2\tau^2/6)$$

by using the Padé method [7].

In the RD-870 engines with oxidizer-rich staged combustion, gaseous oxygen is discharged after the low-pressure oxidizer pump turbine into the liquid oxygen flow at the inlet to the main oxidizer pump.

The condensation process of gaseous oxygen can lead to low-frequency instability [21] of the propulsion feed system of the LRE. In the mathematical model of propulsion system start-up, for taking into account the injection of gaseous oxygen into the liquid oxygen flow, generalized results of experimental investigations of the condensation process of superheated oxygen vapor in the liquid oxygen flow were used [6, 12].

Cavitation phenomena in LRE pumps play one of the leading roles in the propulsion system dynamics' studies [4, 15—17]. They can qualitatively change the dynamic characteristics of the LRE. For engine start-up, they lead to a cavitation disruption of the engine pumps.

The experimental-computational hydrodynamic model of cavitation oscillations for taking into account the cavitation phenomena in the pumps was used [16]. This model generalized the results of experimental investigations of 18 inducer-centrifugal pumps in the cavitation self-oscillation mode. This model is adapted for a wide range of input pressures [4] (from pump stall pressure to pressures corresponding to the beginning of the emergence of pump cavitation mode).

The LOX feed of the propulsion system of the first stage of the Cyclone-4M launch vehicle includes long branched pipelines.

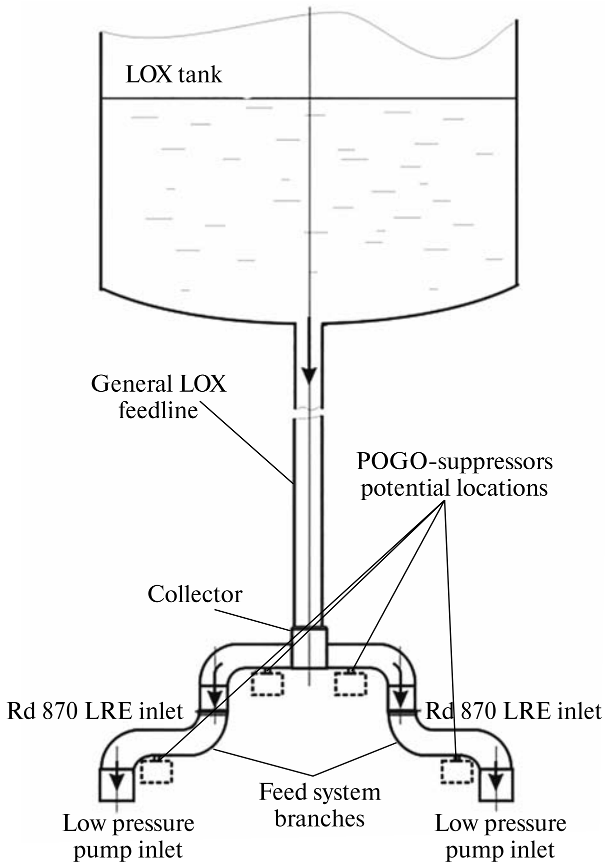

Fig. 2. The simplified layout of the oxidizer feed system

The methodological approach [5] for the mathematical modeling of the low-frequency dynamics of such feed systems was used. This approach provides for the sequential solution of the following problems. The first problem is the development of a linear mathematical model of hydraulic path dynamics considered as a system with distributed parameters and determination of its frequency characteristics. The second problem is an approximate replacement of this system with a system with lumped parameters, i.e., by developing of finite hydrodynamic elements' model. This system is carried out based on matching the frequency characteristics of these two systems. The third problem is the construction of a nonlinear mathematical model of low-frequency dynamics of the propulsion hydraulic lines. This final model is used to compute the start-up of a propulsion system.

A specific feature of the developed model is taking into account the asynchronous start-up operation of

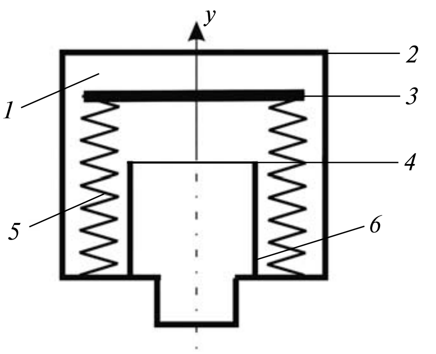

Fig. 3. The calculation schematic of the POGO suppressors with bellows separation of liquid and gaseous media

engines RD870 of the propulsion system (first stage) of the Cyclone-4M launch vehicle following the approach described in [14] and developed on the basis of the Sobol sequence [19]. The asynchronous join into operation of engines at propulsion system start-up was modeled by varying the value of the displacements of the initial command in the engine start-up sequence of the second, third, and fourth engines relative to the first engine start-up sequence in cluster. For computing start-ups, it was assumed that these offset values are evenly distributed between the maximum and minimum (zero) offset to perform the minimum number of calculations.

3. Mathematical model of POGO-suppressor low-frequency dynamics for study the start-up transients of the Cyclone-4M launch vehicle propulsion system. The POGO suppressors are located in the branches on the RD870 liquid rocket engine near the collector in the first stage propulsion system of the Cyclone-4M launch vehicle. The calculation schematic of the POGO-suppressors dynamics with bellows separation of liquid and gaseous media is shown in Fig. 3, where the following designations are introduced: *1* is a gas cavity; *2*, *3*, *4* are upper, middle, and lower positions of the bellows cover; *5* is bellows; *6* is a damper support ring.

The mathematical model of dynamic processes in the POGO suppressor describes the one-dimensional motion of the fluid and movable structural elements of the suppressor along its longitudinal axis and includes the equation of motion of the bellows cover, the equation of fluid motion in the suppressor, and the equation of continuity in the gas cavity of the suppressor:

$$m\frac{d^2y}{dt^2} + F_{fr}(y) + k(y - y_{nom}) = F_{ef}(p_c - p_g), \quad (1)$$

$$p_{col} = p_c + a_D \cdot |G_D| \cdot G_D + J_D\frac{dG_D}{dt} + h\gamma_o \cos\alpha \frac{d^2y}{dt^2}, \quad (2)$$

$$C_D\frac{dp_g}{dt} = G_D, \quad (3)$$

where m is the equivalent mass of the suppressor bellows cover; y, y_{nom} are the current coordinate of the bellows cover and the coordinate with no bellows deformation; t is the current time; $F_{fr}(y)$ is nonlinear dependence of the friction force on the coordinate y; k is the total longitudinal stiffness of the bellows and gas; F_{ef} is the effective area of the suppressor bellows; $p_{\tilde{n}}$ is fluid pressure on the bellows cover; p_g is pressure in the gas cavity of the suppressor; p_{col} is fluid pressure at the junction of the suppressor and the oxidizer feedline; a_D, J_D — coefficients of hydraulic and inertial resistance of the fluid in the suppressor; $G_D = \gamma_O F_{ef}\frac{dy}{dt}$ is fluid flow through the suppressor; h is the height of the liquid column in the suppressor; γ_O is specific gravity of liquid oxygen; α is the angle between the longitudinal axis of the suppressor and the longitudinal axis of the launch vehicle; $C_D = \frac{\gamma_O V_g}{\kappa p_g}$ is the compliance of the suppressor gas cavity; $V_g = V_g^{\max} - y \cdot F_{ef}$ is the current value of the volume of the gas cavity; $V_g^{\max}$ is the maximum value of the volume of the gas cavity; κ is the gas adiabatic exponent.

Zero coordinate of the bellows cover $y = 0$ corresponds to the lower position of the bellows cover. The action of forces from the gas and liquid is balanced for $y = y_{nom}$. The bellows is in an unloaded state in this case.

The axial stiffness of the bellows k_S is an important variable that affects the overall compliance of the suppressor. It was calculated by two methods: on the basis of a one-dimensional model of the suppressor [1] and based on its finite element model using the ANSYS Mechanical software [8]. These methods gave similar results.

Fig. 4 shows the dynamic gain (*a* — module, *b* — argument) of the oxidizer feed line of the I stage Cyclone-4M propulsion system at nominal LOX pressures and temperatures at the engine inlet (curves *1* is without cavitation; curves *2* is taking into account cavitation in pumps; curves *3* is obtained with cavitation and POGO suppressor near the collector).

From the analysis of Fig. 4 follows that taking into account cavitation in pumps leads to a decrease in the natural frequencies of liquid propellant oscillations in the oxidizer feed system of the propulsion system: for the I mode of oscillations — from 16.0 Hz to 6.0 Hz, and for II mode — from 48.0 Hz to 38.8 Hz.

For simultaneous consideration of both pump cavitation and the POGO-suppressor installation near the collector, the natural frequencies of liquid propellant (LOX) oscillations in the feed system of the propulsion system in the range up to 50 Hz are 3.2 Hz, 34.6 Hz, and 39.6 Hz.

Thus, the installation of a POGO-suppressor in the propulsion system leads to a significant decrease in the first natural oscillation frequency in the feed system of the propulsion system. It allows the separating of frequencies of the natural longitudinal oscillations of the launch vehicle structure and the liquid in the LOX feed system of the propulsion system and ensures the launch vehicle POGO stability [11, 13].

4. Results of mathematical modeling of start-up of clustered propulsion system of the Cyclone-4M launch vehicle. The study of transients during the start-up of the clustered propulsion system of the Cyclone-4M launch vehicle was carried out on the basis of the developed start-up nonlinear mathematical model.

The results of these studies show that the installation of the POGO-suppressor has generally a positive effect on the quality of the transient process in the feed system of the propulsion system. That is why the overshoots and dips of propulsion system parameters during its start-up are largely leveled by the flexibility of the gas cavities in suppressors. The main results of the transient processes' study for the case of the synchronous start-up of all rocket engines are shown in Fig. 5...8. The following designations are used here: *1* is without POGO suppressor; *2* is with POGO-suppressor near the collector (standard location); *3* is with POGO suppressor at engines inlet.

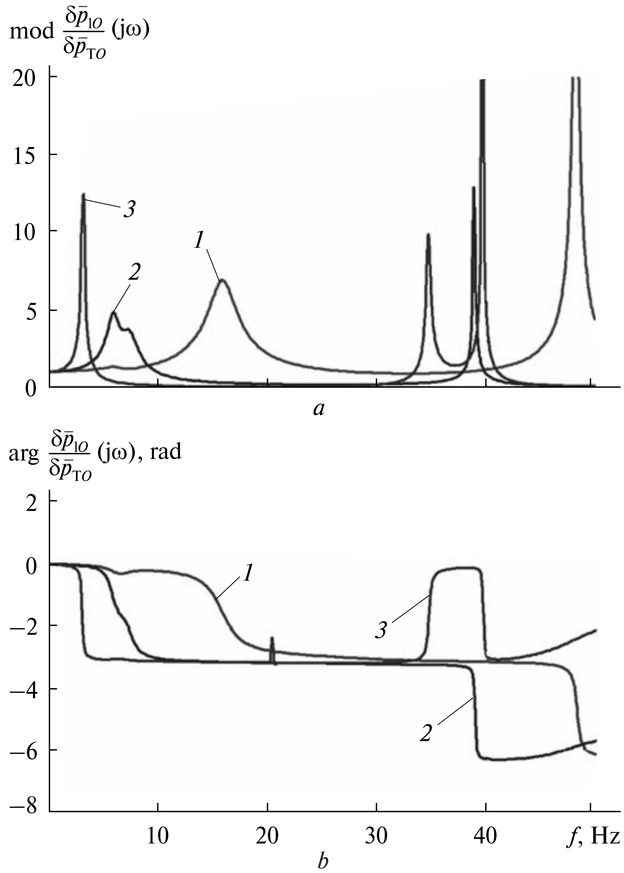

Fig. 4. Pressure dynamic gains (*a* is a module, *b* is an argument) of the LOX feedline of the LRE of the Cyclone-4M LV (1st stage) at nominal LOX pressures and temperatures at the engine inlet (curves *1* is without cavitation; curves *2* is taking into account cavitation in the pumps; curves *3* is with cavitation and the POGO-suppressors near the collector)

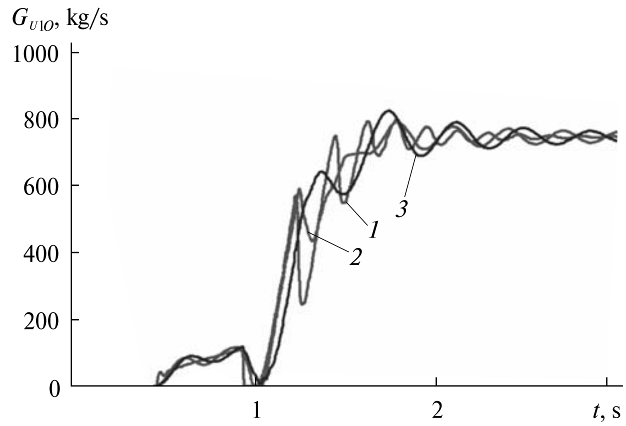

Fig. 5. The start-up transients of LOX flowrate at general feedline

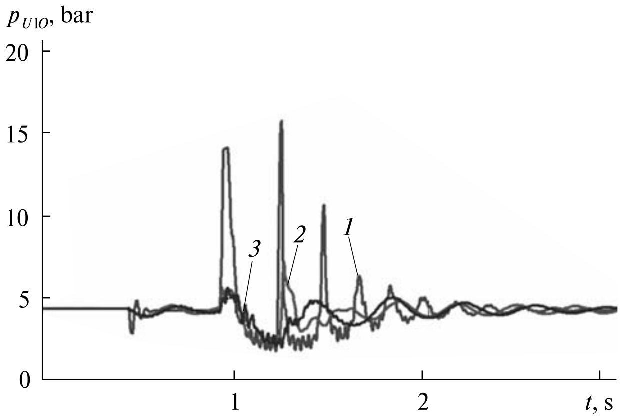

Fig. 6. The start-up transients of LOX pressure at the collector

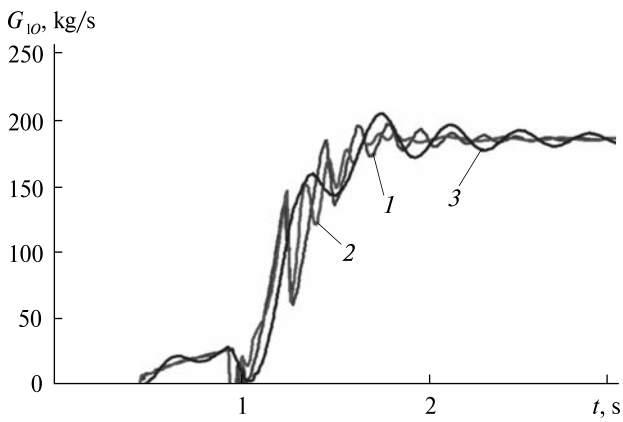

Fig. 7. The start-up transients of LOX flowrate at the engine inlet

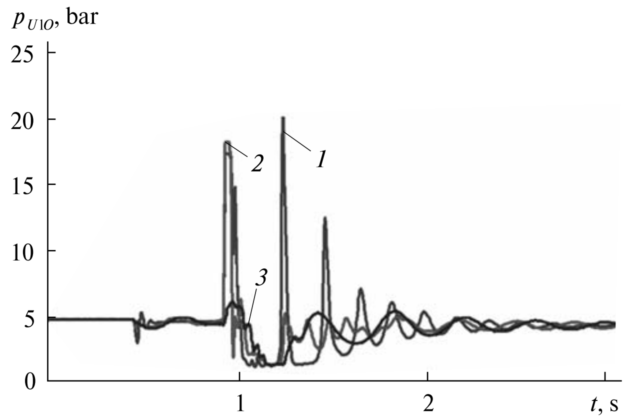

Fig. 8. The start-up transients of LOX pressure at the engine inlet

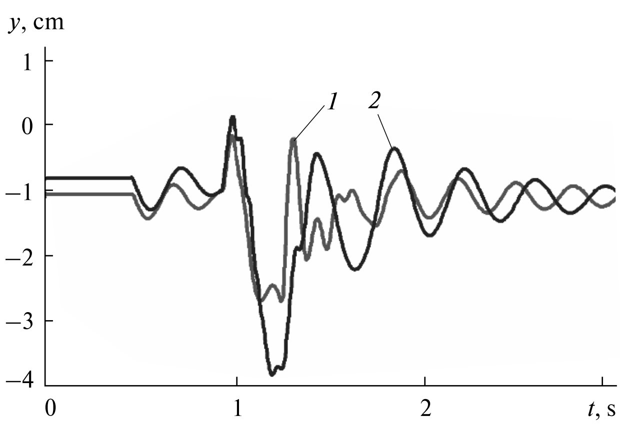

Fig. 9. The transients of suppressor coordinate of the position of the bellows cover *y* during the start-up

Fig. 5 and Fig. 6 shows that the installation of the POGO-suppressor near the collector makes it possible to reduce the flow rate dip in the main pipeline G_{U1O} in the time interval 1.23...1.27 s by more than 2 times (from 313 kg/s to 150 kg/s) and significantly reduce fluid pressure overshoots in the collector from 14.0 bar ($t = 0.96$ s), 15.4 bar ($t = 1.24$ s), and 10.5 bar ($t = 1.46$ s) to a level of no more than 7.1 bar. The POGO-suppressor installation at the liquid rocket engine inlet allows the eliminating of the flow rate drop in the main pipeline G_{U1O} and the reduction of the fluid pressure overflow in the collector p_{U1O} to a level of no more than 5.6 bar.

By contrast, for transient processes of flow rate G_{1O} and pressure p_{1O} at the inlet to the liquid rocket engine, the next fact is investigated. Fig. 7 and Fig. 8 show the installation of the POGO-suppressor near the collector practically does not change the value of the flowrate drop of about 82 kg/s in the time interval 1.23...1.27 s and also does not eliminate the pressure surge of 17.2 bar (at the moment of start-up time $t = 0.96$ s). Installing a POGO suppressor at the inlet to engines allows us to avoid a drop in flow G_{1O} and significantly reduce all overshoots p_{1O} to a level not exceeding 6.0 bar.

Fig. 9...11 show the transients (time dependences) of main parameters of a POGO-suppressor for the start-up of the Cyclone-4M launch vehicle propulsion system (coordinate of the position of the bellows cover y, the pressure p_G in the gas cavity of

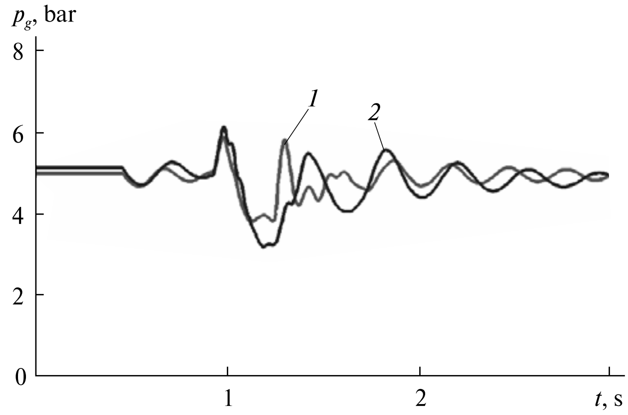

Fig. 10. The transients of suppressor gas pressure p_g during the start-up

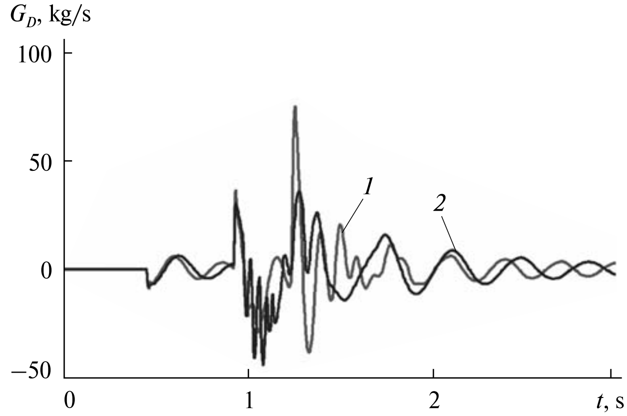

Fig. 11. The transients of the suppressor G_D flowrate start-up

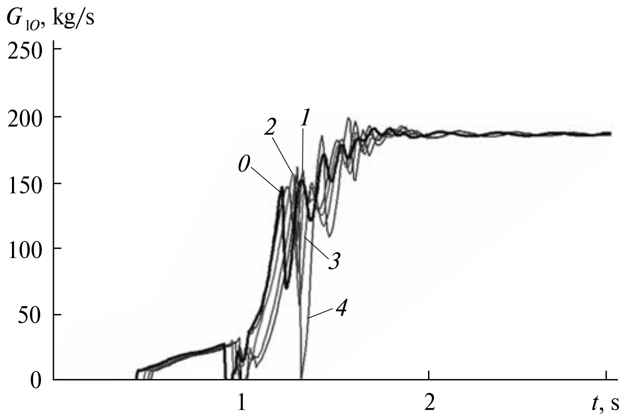

Fig. 12. The transients of fluid flowrates at the LRE inlets for the case of asynchronous propulsion system start-ups

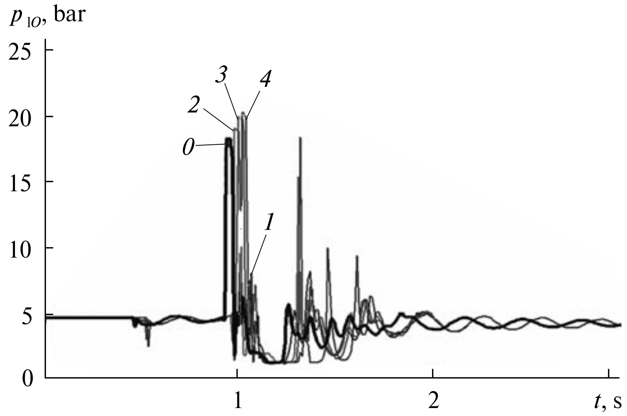

Fig. 13. The transients of fluid pressure at the LRE inlets for the case of asynchronous propulsion system start-ups

the suppressor, and the flow rate of the liquid through the suppressor G_D) for the case of the synchronous start-up of LRE and the installation of a POGO-suppressor near the collector (curves *1*) and at the engine inlet (curves *2*).

An analysis of these figures shows that although the bellows cover does not sit against the stop, its stroke can reach several centimeters. The maximum liquid flowrate G_D into the POGO-suppressor (75 kg/s) can briefly reach a third of the nominal oxidizer flowrate through the engine.

Based on the results of mathematical modeling of the start-up of the propulsion system of the Cyclone-4M launch vehicle, the analysis of the effect of the four RD-870 engines asynchronous operation was carried out.

For the case of a POGO-suppressor placing near the collector, it is shown (see Fig. 12 and 13) that possible displacements of the start moments of engines (curves *1*, *2*, *3*, *4* correspond to the numbers of engines) lead to a deterioration in the quality of transient processes in flow rate G_{1O} and pressure p_{1O} at the inlet to the engines (compared to the option when all engines are started synchronously — curves *0*).

So, in the time interval 0.95...1.35 s, for some variants of the displacement of start moments of engines' start-up, an abnormally large drop in the oxidant flow rate at the inlet to the engines G_{1O} and pres-

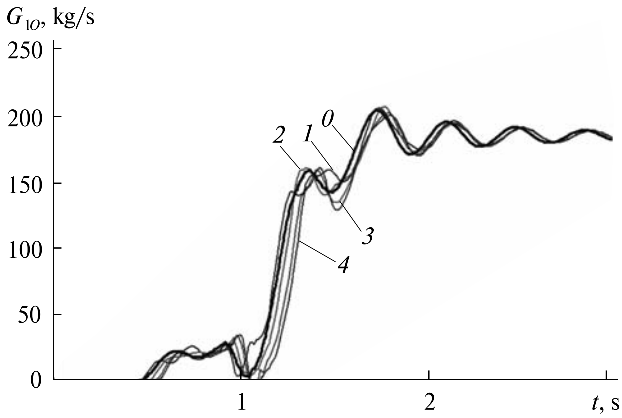

Fig. 14. Transients of LOX flowrate at the inlet to the liquid-propellant engine with asynchronous starting of the engines (the suppressors at the inlets to the LRE)

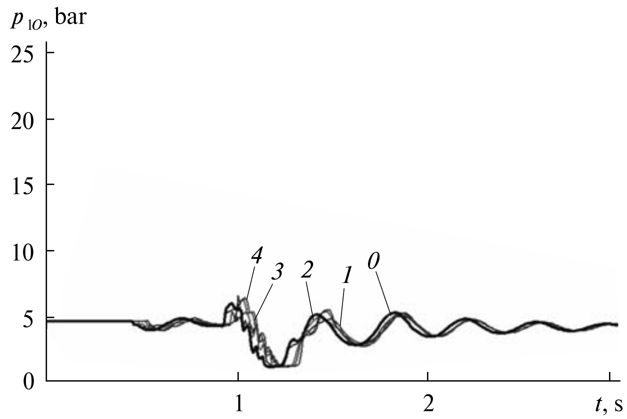

Fig. 15. Transients of LOX pressure at the inlet to the liquid-propellant engine with asynchronous starting of the engines (the suppressors at the inlets to the LRE)

sure overshoots p_{1O} are observed. For example, for the values of the displacement times of engine start-up: the second by 0.0375 s, the third by 0.0625 s, and the fourth by 0.0750 s relative to the first, the oxidizer flow rate at the inlet to the engines G_{1O} of the fourth engine is 1.7 kg/s (for the case of the synchronous engines' start-up — 70.8 kg/s).

The maximum value of the pressure at the engines' inlet p_{1O} of the fourth engine reaches 20.0 bar (while in the case of the synchronous engines' start-up, this value is 18.1 bar). Note that in the absence of a POGO-suppressor, the maximum pressure at the engines' inlet can reach 33.6 bar.

As a result of mathematical modeling of the start-up of the propulsion system of the Cyclone-4M launch vehicle (with a shift in the start time of engine start-ups' sequence), it is shown that the installation of POGO-suppressor at the engine inlet leads to a more significant improvement in the quality of transient processes in terms of flow rate G_{1O} and pressure p_{1O} at engine inlet (see Fig. 14 and 15, where *y*-axis scales and designations are similar as in Fig. 12 and Fig. 13). The calculated dependences of the flow rate at the engine inlet G_{1O} on time for the propulsion system start-up do not have significant gaps. The maximum pressure at the engine inlet p_{1O} for the entire start-up time does not exceed 6.7 bar. It is 3 times less than in the case of installation POGO-suppressor near the collector (20.0 bar).

It seems that a significant difference in transient processes for placing POGO suppressor near the collector and at the engine inlet is due to the following factors. Disturbances in the oxidizer feed system during the start-up of the propulsion system of the Cyclone-4M launch vehicle (caused first by the opening of the oxidizer valves, then by the ignition of the propellants in the gas generator and the subsequent increase in pressure in the gas generator) spread from the engine inlet upstream.

The placement of the POGO-suppressor at the engine inlet contributes to the effective localization of these disturbances. The location of the POGO-suppressor near the collector leads to their considerable distance (5 meters) from the sources of disturbances in the pipelines from the collector to the engines. This POGO-suppressor, located at the other end of the pipeline, cannot effectively eliminate disturbances as the POGO-suppressor at the engine inlets.

Thus, it is shown that installation of POGO-suppressor both at the engine inlet and in the branches on the RD870 rocket engine near the collector has a significant positive effect on the quality of transient processes for the start-up of the propulsion system of the Cyclone-4M launch vehicle. Placing the POGO-suppressors at the engine inlets is not standard. Here, the POGO-suppressor placing is considered without reference to the layout of the rocket propulsion system in order to increase the efficiency of damping transients during the rocket engines' start-ups. At least two problems are successfully solved with the help of the POGO-suppressor at the engine inlets. The first problem is ensuring the liquid launch vehicle POGO stability. The second problem is improving the quality of transient processes for the start-up of the propulsion system, including under conditions of asynchronous liquid rocket engine start-up as a part of the clustered propulsion system.

CONCLUSIONS

A mathematical model has been developed for the start-up of a clustered propulsion system of the Cyclone-4M launch vehicle, including four main RD-870 rocket engines. This model takes into account POGO-suppressors and the asynchronous start-up of the liquid rocket engine. A nonlinear mathematical model of low-frequency dynamic processes in POGO suppressor with bellows separation of liquid and gas media is presented. A significant effect of cavitation in the engine pumps and POGO-suppressors on frequency characteristics of the oxidizer feed system of the propulsion system is shown.

On the basis of the developed mathematical model of the start-up of the propulsion system, start-up transients were studied for the clustered propulsion system of the Cyclone-4M launch vehicle. These studies take into account the asynchronous entry into operation of the liquid rocket engine and the installation of POGO-suppressors as in the branches on the RD-870 rocket engine near the collector (standard placement) and at the engine inlets (as alternative option).

The analysis of transient processes in the oxidizer feed system of the propulsion system under consideration, the dependences of the flow rate and pressure at the engine inlet on time showed the following.

1. For the case of the synchronous engine start-up, the installation of POGO-suppressors near the collector allows eliminating all pressure overshoots at the engine inlet (except for one of 17.2 bar). These pressure overshoots exist in the propulsion system in the absence of POGO-suppressors. For installation suppressors at the engine inlet, the pressure overshoots at the engine inlet are limited to 6.0 bar, i.e., that is, the pressure overshoots are practically absent.

2. The asynchronous entry into operation of the RD870 rocket engines negatively affects the time dependences of the flowrate and pressure at the engine inlets for suppressors locating near the collector. So, in the start-up time interval 0.95...1.35 s, for some variants of the displacement of the start moments of the engines' start-up sequences, the abnormally large drops in the LOX flowrates and pressure overshoots at the engines' inlet are observed. The asynchronous start-up of the RD-870 engines for POGO-suppressors installation at the engine inlets does not significantly change the propulsion system start-up transients.

3. Thus, it has been shown that the installation of POGO-suppressors both at the engines' inlet and in the branches on the RD-870 rocket engine (near the collector) has a significant positive effect on start-up transients for the propulsion system of the Cyclone-4M launch vehicle. Placing the POGO-suppressors at the engine inlets is not standard and is considered without reference to the propulsion system layout. Nevertheless, the suppressors installed at the engine inlets are effective issues of eliminating overshoots and dips in the parameters of the propulsion system, as well as under conditions of the asynchronous start-up of a liquid rocket engine as a part of the multi-engine propulsion system.

The results obtained can be used in mathematical modeling of the start-up of the first stage propulsion system either for multistage sustainer rockets used in parallel with booster rockets or for the clustered multi-engine rocket propulsion system containing POGO-suppressors.

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МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ЗАПУСКУ БАГАТОДВИГУННОЇ РІДИННОЇ РАКЕТНОЇ УСТАНОВКИ І СТУПЕНЯ РАКЕТИ-НОСІЯ «ЦИКЛОН-4М» З ДЕМПФЕРАМИ ПОЗДОВЖНІХ КОЛИВАНЬ

Маршові рідинні ракетні двигунні установки (РРДУ) перших ступенів космічних ракет-носіїв (РН) середнього, важкого і надважкого класу зазвичай включають демпфери повздовжніх коливань, які є одним з поширених способів усунення поздовжніх коливань рідинних РН (POGO-коливань). Однак до теперішнього часу теоретичні дослідження і аналіз впливу встановлення демпферів поздовжніх коливань у живлячих магістралях маршових рідинних ракетних двигунів (РРД) на перехідні процеси в системах при запусках РРД не проводилися через складність здійснення такого аналізу, і перш за все — через відсутність достовірних нелінійних моделей кавітаційних явищ в насосах.

Розроблено математичну модель запуску багатодвигунної РРДУ I ступеня ракети-носія «Циклон-4М», що включає чотири маршових РРД РД-870, з урахуванням встановлення демпферів поздовжніх коливань і неодночасного запуску РРД. Представлено нелінійну математичну модель низькочастотних динамічних процесів у демпферах поздовжніх коливань з сильфонним розподілом рідкого і газового середовищ. Показано суттєвий вплив кавітації в насосах двигунів і демпферів поздовжніх коливань на частотні характеристики системи живлення окислювачем РРДУ. На основі розробленої математичної моделі запуску РРДУ досліджено динамічні процеси при запуску багатодвигунної РРДУ I ступеня РН «Циклон-4М» з урахуванням неодночасного запуску окремих РРД і встановлення демпферів поздовжніх коливань як у відгалуженнях на РРД РД-870 біля колектора (штатне розміщення), так і на вході у двигуни. Аналіз перехідних процесів у системі живлення окислювачем розглянутої РРДУ, залежностей витрати і тиску на вході у двигун від часу виявив такі особливості. По-перше, встановлення демпферів поздовжніх коливань біля колектора дозволяє при одночасному запуску двигунів усунути на вході у двигун майже всі закидання тиску, які мали місце для РРДУ, не оснащеної демпферами поздовжніх коливань. При встановленні демпферів на вході у двигуни закидання тиску на вході у двигун практично відсутні. По-друге, неодночасність вступу в роботу РРД РД-870 негативно відбивається на залежностях від часу витрати і тиску на вході у двигун при розташуванні демпферів біля колектора. Так, в інтервалі часу 0.95...1.35 с для деяких варіантів зміщення моментів початку запуску двигунів спостерігається аномально велике падіння витрати окислювача на вході у двигуни і закидання тиску на вході у двигуни. Неодночасність запуску двигунів РД-870 при встановленні демпферів на вході у двигуни істотно не змінює перехідні процеси при запуску РРДУ в порівнянні з одночасним запуском двигунів. По-третє, показано, що встановлення демпферів поздовжніх коливань як на вході у двигуни, так і у відгалуженнях на РРД РД-870 біля колектора, має суттєвий позитивний вплив на якість перехідних процесів при запуску РРДУ I ступеня РН «Циклон-4М». Розміщення демпферів поздовжніх коливань на вході у двигуни не є штатним і розглядається без прив’язки до компонування РРДУ. Разом з тим демпфери, встановлені на вході у двигуни, є дієвим засобом усунення закидання і провалів параметрів РРДУ, зокрема в умовах неодночасного запуску РРД у складі багатодвигунної установки.

Отримані результати можна використовувати при математичному моделюванні запуску маршової РРДУ ракети-носія пакетної схеми або багатодвигунної РРДУ, що містять демпфери повздовжніх коливань.

Ключові слова: рідинний ракетний двигун, низькочастотні динамічні процеси, запуск, кавітація в насосах, система живлення, неодночасність запуску, демпфер поздовжніх коливань.