373. INFLUENCE OF OVERLOAD ON LOW-FREQUENCY INSTABILITY OF WORKING PROCESS IN THE COMBUSTION CHAMBER OF THE SOLID PROPELLANT ROCKET ENGINE

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(Received 2 April 2008; accepted 29 August 2008)

Abstract: In the paper the real oscillatory process is reproduced by statement of direct numerical experiment and the mechanism of occurrence and refill of low-frequency acoustic instability in the combustion chamber of the solid propellant rocket engine with the account of flight overload is investigated for the first time. The direct numerical modeling of low-frequency acoustic instability is carried out by means of Davydov's method (method of large particles), which is well-suited for the solutions of many problems of mechanics of the continuous media. The results of numerical modeling are presented here. The hydrodynamic highly nonlinear nature of low-frequency fluctuations connected to structure and character of current in the combustion chamber of the rocket engine on firm fuel are proved to be true.

Keywords:

Notation

$A-$ amplitude of fluctuations;
$a-$ sound speed;
$E-$ complete specific energy;
$f-$ frequency of pressure fluctuations (pulsations);
$G-$ drain-arrived complex;
$g-$ acceleration of free fall;
$J-$ specific internal energy;
$k-$ adiabatic parameter;
$L-$ length (characteristic size);
$p-$ pressure;
$q-$ function of thermal interphase interaction;
$r-$ coordinate along an axis 0R, radius;
$t-$ time;
$u-$ speed along an axis 0X;
$v-$ speed along an axis 0R;
$\mathbf{W}-$ a vector of speed;
$W-$ the module of a speed vector, speed of submission of products of combustion from a surface of burning;
$x-$ coordinate along an axis 0X;
$\alpha-$ a share of volume occupied by the 1st phase of a mix;
$\rho-$ density;
$\tau-$ function of force interphase interaction.

Acronyms

SPRE – solid propellant rocket engine.

Symbols

$g-$ gas;
$p-$ particles in combustion products, parameter dependent on pressure;
$r-$ along an axis 0R;
$w-$ a burning surface;
$x-$ along an axis 0X;
$tm-$ true meaning;
$1-$ the first phase of a heterogeneous mix;
$2-$ the second phase of a heterogeneous mix;
*- special meaning.

The problem of instability of working processes in rocket engines is one of the complex problems in vibroengineering. It is necessary to note that classical books and articles by K.M. Ragulskis [1-2 etc.] provide us the fundamental results in the field of vibroengineering.

The problem of operational instability in its various manifestations appeared with the beginning of the development and use of the first solid propellant rocket engines (SPRE) [3-5], engines operating on liquid fuel [4, 6] and other types of fuel [7]. At present, in connection with the development of new-generation high-performance solid-fuel engines, the problem has become even more significant.

Generally, the operational instability of a solid propellant engine can be of both acoustic and non-acoustic highly nonlinear nature [4, 5, 7, 8]. The acoustic instability considered in this study is associated with the generation of periodic, both low-frequency and high-frequency, pressure fluctuations in the engine combustion chamber. The low-frequency pressure fluctuations within the approximate frequency range of $f \approx 20 - 2000$ Hz manifest mainly in the longitudinal direction of the combustion chamber. Meanwhile, high-frequency pressure fluctuations at frequencies $f > 2000$ Hz manifest in the transverse and tangential directions of the combustion chamber.

The low-frequency acoustic instability of the solid propellant engine operation is the most hazardous. This type of instability is characterized by a considerable deviation of both the working pressure in the combustion chamber and the engine thrust from their mean values. This disturbs the normal operation of a nozzle, initiates the transfer of rigid periodic vibratory loads to the rocket system as a whole and is a source of intense unmasking noise, etc.

In [8-11] the actual oscillatory process was reproduced by direct numerical simulation and the mechanism of the generation and the maintenance of the acoustic instability in the solid-fuel engine combustion chamber was investigated. The reasons for the occurrence (excitation and maintenance) of the oscillatory process should be sought in the structure and nature of the flow of combustion products in the rocket engine combustion chamber (naturally, with regard for the interaction of the flow with the burning surface of the solid-fuel charge). Here, the fluctuations are of a hydrodynamic (gas-dynamic) highly nonlinear nature. The fluctuation frequency (the first, second, and other longitudinal modes) and, especially, amplitude are dependent on a number of factors. The principal factor is the presence of a considerable radial stratification of the combustion-product flow in the chamber with respect to the flow parameters, mainly velocity. At the nozzle inlet, the flow of such complicated structure interacts irregularly with the wall of the rear engine base and is partially reflected from it (both the flow itself and the flow-induced disturbances are reflected). In the base region near the lateral wall of the combustion chamber, either a reverse flow (with respect to the main flow) is formed or the flow is considerably decelerated. Thus, in the solid propellant engine combustion chamber, an unsteady, transient, low-frequency acoustic pulsating flow is generated and then periodically maintained due to the finite dimensions of the combustion chamber.

This study (look also [10, 11]) is devoted to the numerical investigation of the effect of the flight g-loading on the low-frequency acoustic operation instability of the solid-fuel engine combustion chamber. The operating conditions of rocket engine on a test rig and in flight are quite different. One of the main distinctive factors is the gravity-field effect. The flight g-loading, in particular, its large values in the final stage of rocket acceleration at almost complete burning-out of the fuel, has an appreciable and non-unique effect on the performance of the solid propellant engine and the rocket system as a whole. At large flight g-loading, an additional, even insignificant action of the rocket engine on the control system and on the payload can result in an emergency situation.

The approaches of the mechanics of continuous multiphase media are applied to the description of process of current in the combustion chamber and nozzle of SPRE [12 etc.]. Gas combustion products of firm fuel we will name as the first phase, while the firm burned-down particles (oxide of aluminium) - the second phase. The first and second phases will be considered as a heterogeneous mix with the temperatures and movement speeds. In such system each phase occupies a part of mix volume: $\alpha, (1-\alpha)$. Their movement is considered as movement of interpenetrating and cooperating environments.

In addition, for a simulated problem we will accept the following assumptions: (a) from the spatial point of view we will study process of current in 2D axi-symmetric statement; (b) we shall consider gas combustion products as the ideal completely-reacted gas; (c) the reburning of a firm phase (particles of aluminium) in the combustion chamber of the engine is not taken into account; (d) agglomeration and splitting of the burned-down firm phase (oxide of aluminium) during movement through the combustion chamber and nozzle is not taken into account as well; (e) the gravitational field of mass force works along the axis of the rocket engine (rocket flies vertically upwards); (f) influence of an atmosphere of air is neglected.

Taking into account aforementioned assumptions, a complete non-stationary system of the vortical differential equations of gas dynamics for heterogeneous flow in combustion chamber and nozzle of a solid propellant rocket engine will be written down as:

- the equations of indissolubility (preservation of mass)

$$\begin{aligned} &\frac{\partial \rho_1}{\partial t} + div(\rho_1 \mathbf{W}_1) = G_{gw}; \\ &\frac{\partial \rho_2}{\partial t} + div(\rho_2 \mathbf{W}_2) = G_{pw}; \end{aligned} \qquad (1)$$

- the equations of preservation of a pulse on coordinates axes

$$\frac{\partial(\rho_1 u_1)}{\partial t} + div(\rho_1 u_1 \mathbf{W}_1) + \alpha \cdot \frac{\partial p}{\partial x} = -\tau_x + W_x \cdot G_{gw};$$
$$\frac{\partial(\rho_1 v_1)}{\partial t} + div(\rho_1 v_1 \mathbf{W}_1) + \alpha \cdot \frac{\partial p}{\partial r} = -\tau_r + W_r \cdot G_{gw};$$
$$\frac{\partial(\rho_2 u_2)}{\partial t} + div(\rho_2 u_2 \mathbf{W}_2) + (1-\alpha) \cdot \frac{\partial p}{\partial x} = \tau_x + W_x \cdot G_{pw};$$
$$\frac{\partial(\rho_2 v_2)}{\partial t} + div(\rho_2 v_2 \mathbf{W}_2) + (1-\alpha) \cdot \frac{\partial p}{\partial r} = \tau_r + W_r \cdot G_{pw}; \quad (2)$$

- the equations of preservation of specific energy

$$\frac{\partial(\rho_2 J_2)}{\partial t} + div(\rho_2 J_2 \mathbf{W}_2) = q + J_{pw} \cdot G_{pw};$$
$$\frac{\partial(\rho_1 E_1)}{\partial t} + \frac{\partial(\rho_2 E_2)}{\partial t} + div(\rho_1 E_1 \mathbf{W}_1) + div(\rho_2 E_2 \mathbf{W}_2) + div(\alpha p \mathbf{W}_1) + div[(1-\alpha) p \mathbf{W}_2] = J_{gw} \cdot G_{gw} + J_{pw} \cdot G_{pw}, \quad (3)$$

- where for axi-symmetric case –

$$div(\varphi \mathbf{W}_i) = \frac{\partial(\varphi u_i)}{\partial x} + \frac{1}{r} \cdot \frac{\partial(r \varphi v_i)}{\partial r},$$
$$\varphi = [\rho_i, \rho_i u_i, \rho_i v_i, \rho_2 J_2, \rho_i E_i, \alpha p, (1-\alpha) p];$$
$$i = (1,2).$$

The system (1) - (3) is identical both for dimensional and dimensionless sizes. Further we will use the last, having taken as characteristic parameters, for example, parameters of braking for the given engine. Density ρ_i we will relate to ρ_*; speed (in projections on coordinate axes) u_i, v_i - to sound speed at parameters of braking a_*; pressure p - to $\rho_* \cdot a_*^2$; specific energy (both internal and complete) J_2, E_i - to a_*^2; linear sizes - to the characteristic size of the combustion chamber L; time t - to L / a_*.

For short circuit of system of the differential equations (1) - (3) will use equation of a condition as:

$$p = (k-1) \cdot \rho_1^{tm} \cdot \left(E_1 - \frac{W_1^2}{2} \right). \quad (4)$$

The direct numerical modeling of low-frequency acoustic instability in SPRE with the account of flight overload was carried out by means of Davydov's method (method of large particles) [13, 14 etc.], which is well recommended for the decision of many nonlinear problems of mechanics of continuous media [15 etc.]. In accounts we used obvious parametrical (two parameters) completely conservative certainly - margin circuit of a method. The uniform orthogonal settlement grid was applied ensuring uniformity of computing space [10]. On irregular (not conterminous with a settlement grid) borders of settlement area the device of fractional cells was used [16]. The arrival from a burning surface of a solid propellant charge was carried out by "injecting" in settlement cells vectorially-located on a burning surface combustion products with the previously certain characteristics dependent on structure of firm fuel and parameters of a flow near burning surface.

Let's consider some calculation results.

In Fig. 1 the basic layout circuit of free volume of the researched SPRE combustion chamber is presented. Here A - forward bottom, AB - burning surface, BC - wall of the combustion chamber, C - back bottom.

Next we present results of numerical analysis without flight overload. Fig. 2 (the position 1) illustrated temporal change (during the several periods of fluctuations) of pressure of combustion products in the rocket engine chamber. The current value of pressure here is given as a deviation from the average value for the period of fluctuations and is referred to as fluctuations amplitude. The pressure is fixed in the forward bottom area of the engine (see Fig. 1, position A). Frequency of fluctuations of pressure - $f = 77$ Hz. Process of fluctuations is steady.

Similar oscillatory process in SPRE is observed in the case of action of flight overload, but the intensity of fluctuations varies. Fig. 2 (the position 2) provides temporal change (during the several periods of fluctuations) of pressure of combustion products in the chamber of the rocket engine at fixed flight overload, which is equal to $P = 20 \cdot g$. The current value of pressure is also given as a deviation from the average value for the period of fluctuations and is referred to as fluctuations amplitude with the flight overload. The pressure also is fixed in the forward bottom area of the engine (see Fig. 1, position A). Frequency of pressure fluctuations is $f = 77{,}5$ Hz. Process of fluctuations is steady.

Fig. 3 (the position 1) illustrates change of pressure fluctuations amplitude in the combustion chamber of the rocket engine as a function of magnitude of flight overload. The current pressure fluctuations amplitude is referred here to as amplitude of pressure fluctuations without flight overload.

Fig. 3 (the position 2) provides average change (for the period of fluctuations) of pressure in the combustion chamber of the rocket engine as a function of flight overload. The current value of average pressure is also referred to as average pressure value without flight overload.

At increase of flight overload the amplitude of pressure fluctuations in the combustion chamber of SPRE decreases practically according to the linear law (Fig. 3 positions 1). So, for example, the flight overload equal to $P = 20 \cdot g$ (see a Fig. 3 and in addition Fig. 2) reduces amplitude of pressure fluctuations by 1.4 times, while the fluctuations frequency is nearly constant. The average pressure in the combustion chamber of the rocket engine decreases as well but this change is insignificant (Fig. 3 position 2).

However some decrease of pressure fluctuations amplitude in the combustion chamber and, hence, draft fluctuations amplitudes of the engine in this case practically does not promote improvement of SPRE work conditions. The conditions of a rocket flight with significant overloads and low-frequency pulsing operations mode of the rocket engine even with small amplitude of pressure and draft fluctuations are critical, that proves to be true in practice. Such modes of SPRE operations are necessary to carefully analyze on ground before realization of expensive flight tests.

The results of the performed simulations will be well coordinated with the data of flight tests of several rocket systems, including rocket system with the solid propellant engine examined in this paper. Thus conclusions made in addition prove to be true [8, 9] concerning hydrodynamic (gas-dynamic) highly nonlinear nature of low-frequency acoustic pressure fluctuations connected with structure and character of current in the combustion chamber of SPRE. In this case formed at low-frequency acoustic instability secondary (opposite in relation to the basic flow) current in the combustion chamber of SPRE from the back bottom (see Fig. 1, position C) along the wall of the combustion chamber (position BC) and burning surface (position AB) to the forward bottom of the engine (the position A) under action of an flight overload is slowed down. Fig. 4 presents the distribution of speed of longitudinal movement of gas combustion products along the wall of the chamber and burning surface of a solid propellant charge at the various moments of time (is submitted within the framework of the period of fluctuations) without flight overload (w/o) and with flight overload $P = 20 \cdot g$ (o). The period of investigated low-frequency fluctuations makes here approximately ~ *13* ms, therefore curves appropriate *2,5* ms and *15* ms practically coincide. At flight overload the receipt of weight of combustion products in forward bottom area of the engine decreases, which in turn reduces amplitude of pressure fluctuations in the combustion chamber of SPRE and, hence, reduces amplitude of the rocket engine draft fluctuations.

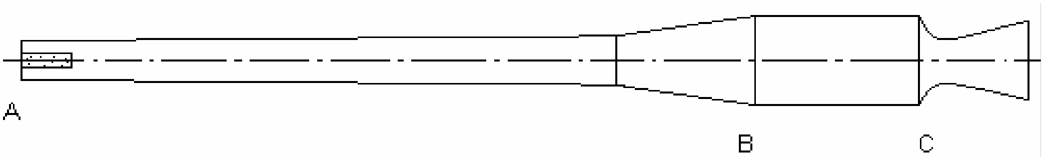

Fig. 1. Basic layout circuit of free volume of the combustion chamber of investigated SPRE

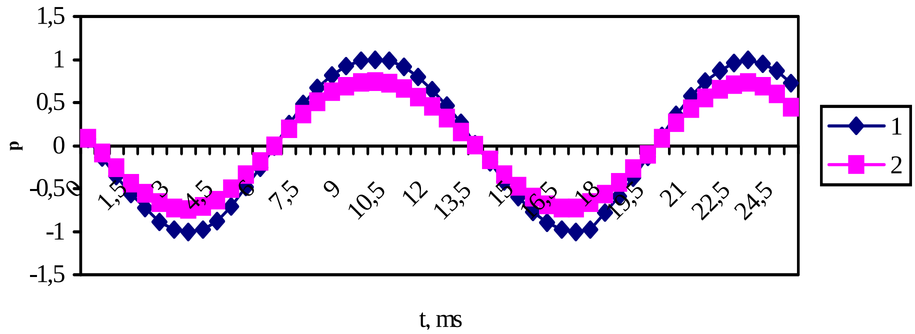

Fig. 2. Temporal change combustion products pressure in the rocket engine chamber without the flight overload (position 1) and with the flight overload (position 2)

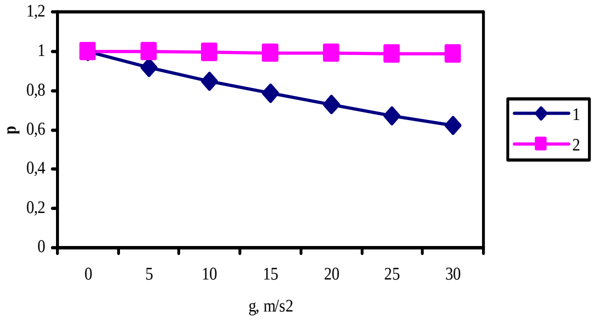

Fig. 3. Change of pressure fluctuations amplitude (position 1) and change of average pressure (position 2) in the combustion chamber of the rocket engine as a function of magnitude of flight overload

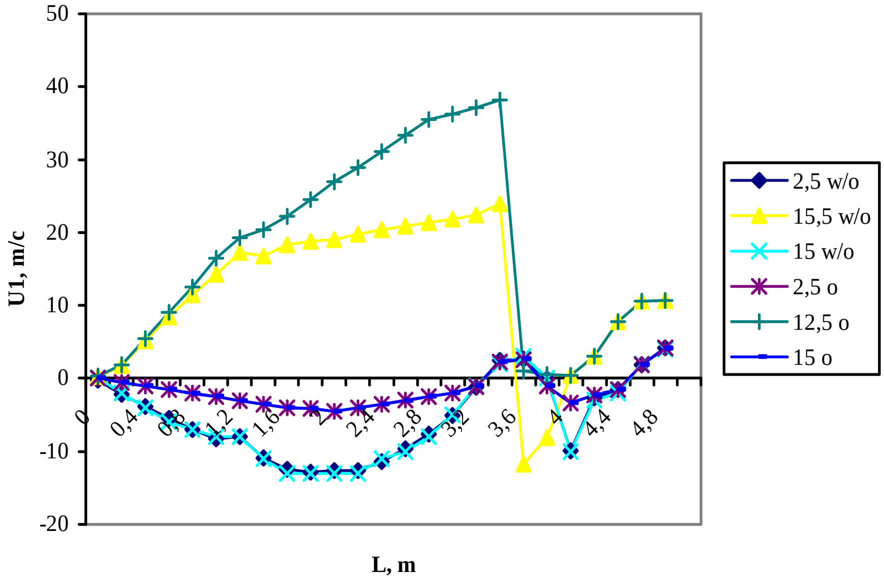

Fig. 4. Distribution of speed of longitudinal movement of gas combustion products along the wall of the chamber and burning surface of a solid propellant charge at the various moments of time (within the framework of the period of fluctuations) without the flight overload (w/o) and with the flight overload $P = 20 \cdot g$ (o)

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