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Forecasting of the Spacecraft Dynamic Loading Under the Rocket Engine Thrust Oscillations of the Launch Vehicle

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Abstract. During the rocket launch into working orbits, the rocket structure and its spacecraft are subjected to extreme dynamic impacts. During this period, the rocket structure and the spacecraft may be subjected to vibroacoustic loads, which can lead to malfunctions of the devices and the strength of the light, thin-walled spacecraft. Testing the spacecraft's self-oscillations and predicting the spacecraft's reaction to dynamic loads from the launch vehicle (LV) is a complex task, the relevance of which is manifested in the significant saving of material and technical resources invested in spacecraft development. An approach has been developed to predict the dynamic loads of spacecraft launched into working orbits using LVs (of various layout schemes). The approach makes it possible to estimate the values of dynamic loads (spectral densities of vibration accelerations) of the spacecraft under the propulsion system thrust oscillations acting on the LV structure in the active part of the liquid LV flight. The approach includes mathematical modeling of spatial oscillations of the launch vehicle structure by its structural and layout scheme and preliminary experimental determination of the power spectral density of the rocket engine structure.

Keywords. Spacecraft vibration acceleration; Liquid rocket propulsion system; Mathematical modeling; spectral density; Thrust oscillations of the rocket engine.

1. Introduction

The rocket structure and its spacecraft (SC) are subjected to extreme dynamic impacts [1-3] during the period of launching into working orbits. The rocket structure and the spacecraft can be affected by vibroacoustic loads (from propulsion system thrust oscillations and aerodynamic influences), which can lead to malfunctions of the instruments and the strength of the light, thin-walled spacecraft structures. Abrupt changes in the stress-strain state of the structure of the launch vehicle and spacecraft (pyroshocks) that occur during the separation of the space stage of the launch vehicle can also lead to additional problems in the strength of the spacecraft structure. Vibration accelerations of spacecraft structures launched into orbit during the launch vehicle (LV) design are regulated by several guiding documents (standards), particularly in [4-5].

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For specific launch vehicles, these quantities are given, for example, in [6-10].

This article aims to develop an approach to predicting the spacecraft dynamic loads launched into orbits by launch vehicles (of different layout schematics) under oscillations in the rocket engine's thrust in the LV flight's active leg.

2. Determination of the Oscillation Spectral Density of the LRE Thrust and Vibration Accelerations of the LRE Structure based on the Results of the LRE Fire Tests

Thrust oscillations and operational vibration accelerations of the LRE structure, recorded during the LV flight and fire tests of its propulsion system [11-12], are studied during the design and development of the propulsion system in the framework of the tasks of determining the operability of the LRE systems and the vibration strength of the LRE design, taking into account the action of a combination of internal and external factors affecting the engine operation. Vibration loads acting on the engine structure (during their fire tests) at the points of attachment of the liquid-propellant rocket engine to the LV structure, during launch and in the flight of the launch vehicle, are divided into loads caused by low-frequency processes, as well as high-frequency oscillations in the rocket engine systems [13-14].

It should be noted that the root-mean-square thrust value used in the statistical analysis of the LRE test parameters makes it possible to calculate the value of the amplitude spectrum A_i of LRE thrust *R(t)* oscillations with the oscillation frequency f_i. investigated dynamic process, i.e., the measured value *R(t)* LRE thrust (after converting to a discrete form the dynamic component of the thrust value $R(f_i)$, recalculated through the combustion chamber pressure $p(t)$ at time *t* with the number of measurements *i*=1, ... N). The spectral densities $S_{LPE}(f_i)$ of powerful LRE thrust oscillations (the deviation of the measured engine thrust value *R(t)* from the current stationary value $\overline{R}(t)$ at time *t**) are valued based on the following relations known from the theory of processing periodic signals (for example, [15-16]):

$$A_i = \sqrt{2D_i} \tag{1}$$

$$D_i = \int_{f_i-0,5\Delta f_w}^{f_i+0,5\Delta f_w} S_{LPE}(f_i)\,df \tag{2}$$

where the dispersion D_i of the periodic value of thrust *R(t),* $S_{LPE}(f_i)$ is the PSD spectral density of the measured value *R(t)* of LRE thrust oscillations at time *t**, determined in the frequency scanning range $f_1 < f_i < f_{N/2}$, Δf_w is the width of the integration window, depending on the studied LRE thrust oscillation frequency f_i.

Given the preceding, in the problem being solved of predicting the spacecraft vibration loading, it is advisable to rely on the maximum PSD values of the vibration acceleration of the propulsion system attachment point, the value of which can be normalized, for example, using the nominal engine thrust value $\overline{R}$ (i.e., P_{LPE} ($S_{LPE}(f)/\overline{R}$)) during the investigated fire LRE tests. Thus, the experimental values of the spectral density of thrust oscillations and (or) vibration accelerations of its structural elements obtained during the LRE fire tests can be used to predict the values of the vibration accelerations of the spacecraft if this LRE is used on the designed launch vehicle. The dynamic interaction between the LV structure and LRE, which significantly affects the vibration loads of the spacecraft during its orbital launch [17]. The construction of computation schemes of natural oscillations of these launch vehicles is based on their design and layout schemes. The schematization of the design and idealization of the oscillatory movements of the LV elastic structure allows us to consider it as a weakly damped linear ‘LV structure with a spacecraft-liquid propellant in tanks ’oscillatory system with a finite number of degrees of freedom and viscous friction, which reproduces the dynamic characteristics of the LV structure at the frequency range from 1 Hz up to 100 Hz with sufficient accuracy for practice. The mathematical model of the ‘SC - LV structure - propulsion’ closed dynamic system can be described by the equations of dynamics of the main links of this system, namely, the launch vehicle structure, the first stage sustainer rocket engines, and their feed lines.

Longitudinal natural oscillations of the liquid-propellant LV structure were described based on energy dissipation as oscillations of the linear ‘LV structure with SC–liquid propellant in the tanks of the LV first and second stages’ dynamic system with “frozen” coefficients. The energy dissipation in the dynamic system was taken into account based on the viscous friction model [18-20]. The mathematical model of this system, built using the finite element method, was represented in matrix form by a homogeneous differential equation:

$$M\ddot{X}(t) + C\dot{X}(t) + KX(t) = 0 \tag{3}$$

where X is the vector of nodal displacements of the ‘LV structure with SC – liquid propellant in the tanks of the LV first and second stages’ system, having the length n_1; $\dot{X}(t) = dX(t)/dt; \ddot{X}(t) = d^2X(t)/dt^2$; n_1 is the number of degrees of freedom of the system of differential equations; M, C, K is the matrix of masses, damping coefficients and stiffness respectively, having the order n_1.

In the case of the so-called ‘core and strap-on boosters’ LV structure layout, the supporting structures of the core and strap-on boosters in the mathematical model of longitudinal oscillations of the launch vehicle were represented in the form of elastic thin-walled rods of the variable cross-section.

The formation of the computation scheme of free oscillations of the central and side blocks of the promising launch vehicle of the package layout was carried out based on its structural layout scheme. The bearing structures of the core and strap-on boosters in the model were presented as elastic thin-walled rods of variable cross-section. The main oscillatory movements of the launch vehicle subsystems (natural vibrations of liquid fuel masses (taking into account the elasticity of the bottoms and walls of tanks), natural vibrations of the ‘adapter – spacecraft’ subsystem, slosh - vibrations of the free surface of liquid fuel) were simulated by mechanical oscillators using [13, 19, 21].

One-dimensional mechanical oscillators oscillating in the direction of the LV longitudinal axis modeled the elastic longitudinal vibrations of sustainer rocket engines with the fundamental frequency of the "elastic frame - LREs" subsystem.

Similarly, mathematical modeling of spatial oscillations of the two-stage and single-stage launch vehicle was performed. In particular, the finite element model of the oscillation structure of the two-staged launch vehicle of the ‘tandem’ scheme with a spacecraft included 72 elements of the ‘elastic beam’ type, ten elements of the 'concentrated mass' type, ten elements of the 'spring' type, and the calculated the grid consisted of 83 nodes.

The parameters of forced vibrations of the launch vehicle structure of the above layout schemes were calculated based on system (3) using the methods of complex amplitudes and finite element analysis tools of the SAE systems [21-22].

In the mathematical model of the forced dynamics of the 'first-stage liquid-propellant rocket engine – LV structure' system, the oscillations of the launch vehicle structure were described as oscillations of the dissipative system under the action of disturbing forces $F(t)$ from the liquid-propellant rocket engine that is, by an inhomogeneous matrix equation [19]:

$$M_v \ddot{X}(t) + C_v \dot{X}(t) + K_v X(t) = F(t) \tag{4}$$

Where $F(t)$ is a vector of length n, whose components are the disturbing forces acting on the launch vehicle structure from the side of the LRE (primarily, engine thrust oscillations and pressure oscillations at the inlet to the LRE pumps), M_v, C_v, K_v are respectively the matrix of LV masses, damping coefficients and stiffness (order n).

The mathematical model of the low-frequency dynamics of the first-stage propulsion system under the action of external disturbances was built based on modern concepts of dynamic processes in rocket liquid propellant engine subsystems. The model is described in detail in [14]. The linearized system of differential equations (in deviations), which represents the low-frequency dynamics of the engine taking into account the dynamics of cavitating inducer and centrifugal pumps [23], consists of a large number of equations and is usually [17] presented in a general form:

$$\sum_{i=1}^{n} \left[a_{\kappa i} \delta\dot{x}_i + b_{\kappa i} \delta x_i + c_{\kappa i} \delta x_i \left(t - \tau_{\kappa i}\right) \right] = d_\kappa \delta y_\kappa \quad \kappa = 1 \div n \tag{5}$$

where $\delta x_i, \delta y_\kappa$ are deviations of the regime parameters of the engine and external disturbances; $a_{\kappa i}, b_{\kappa i}, c_{\kappa i}$ are coefficients of the system, depending on the design and operating parameters of the engine; $\tau_{\kappa i}$ is delay in the equations of low-frequency dynamics of the gas paths of the liquid-propellant rocket engine.

Oscillations in propellant pressure on the bottoms of the tanks of the LV central and side blocks, caused by vibrations of the elastic structure, were considered external disturbances acting on the liquid-propellant rocket engine during the active leg of the flight.

It is known [1] that, according to the data of LRE fire bench tests, oscillations in engine thrust are observed even when there are no dynamic pressures of the propellants caused by the influence of dynamic processes in the feedlines and rocket structures. Oscillations in engine thrust during its fire tests are usually [13] due to the dynamics of working methods in the subsystems of the propulsion system. In particular, cavitation oscillations in the LRE feedline system, LRE regulatory oscillations, and combustion chamber dynamic processes.

In the active phase of the flight, the spacecraft, as a constituent element of the 'LV structure - SC –propulsion' closed dynamic system, experiences a dynamic effect from the LRE, which is transmitted to the adapter of the SC through the structure of the liquid-propellant rocket. To describe this dynamic effect, let us introduce the concept of the dynamic gain $W_{str}(j\omega)$ of the launch vehicle structure as the ratio $\frac{Z_{sc}(j\omega)}{Z_{lre}(j\omega)}$ of the displacement of the spacecraft structure $Z_{sc}(j\omega)$ to the rocket engine structure displacement of $Z_{lre}(j\omega)$ during its forced harmonic perturbation (ω is the system circular oscillation frequency). Then this ratio (dynamic gain $W_{str}(j\omega)$ can be expressed as the product of the frequency gain of m finite elements from the point of application of the engine thrust to the structure to the spacecraft installation site in the upper part of the LV structure (by the LV structural layout):

$$W_{str}(j\omega) = \frac{Z_{sc}(j\omega)}{Z_{lre}(j\omega)} = \prod_{i=1,m}^{m} W_i(j\omega)\cdot , \tag{6}$$

where $W_i(j\omega)$ is the frequency response (dynamic gain) of *i* separate finite element of the rocket structure, located in series along the longitudinal axis of the launch vehicle.

To estimate the stationary oscillations of the LRE structure, it can be described using the spectral density function of the vibration acceleration of the structure $S_{stre}(\omega)$ or by the dispersion:

$$\sigma_{stre}^2 = \int_{-\infty}^{\infty} S_{stre}(\omega)\, d\omega \tag{7}$$

Pulsations (dynamic components) of the rocket engine thrust, as dynamic effects on the LV structure, can be amplified or suppressed in certain frequency ranges of the LV structure oscillations. In addition, the propulsion system itself during the put of the spacecraft is affected by feedback from dynamic processes in the LV structure (including from the spacecraft), which, depending on the phase relationships between the dynamic links of the system, can also excite oscillations, for example, leading to POGO instability liquid-propellant rocket [20], to the instability of the considered 'SC - rocket structure – propulsion' dynamic system due to the LRE instability.

Let's assume that the thrust oscillations of the rocket engine are stationary. Using equation (6), we can express the relationship between the spectral density of vibration acceleration of the engine structure (combustion chamber) and the spectral density of the spacecraft attachment site structure as follows:

$$S_{sc}(\omega) = \left|W_{str}(j\omega)\right|^2 S_{stre}(\omega) \tag{8}$$

Based on equation (1), it is further possible to obtain the values of the vibration acceleration $A_{sc}(\omega)$ of the spacecraft depending on the oscillation frequencies of the liquid-propellant launcher in flight during the LRE operation, which will make it possible to judge the dynamic loading of the spacecraft.

3. Analysis of the Results of the Application of the Proposed Approach to the Prediction of vibration Accelerations of the SC Structure for LV of Various Layouts

As an example, figure 1 shows a typical dependence of the spectral density of vibration acceleration of a liquid-propellant rocket engine structure, reduced to its thrust value (i.e., $\bar{S}_{stre} = S_{stre}(\omega)/R_{LPE}$) and built based on an analysis of data from firing tests of a liquid-propellant rocket engine [24], the thrust of which here was measured in kN.

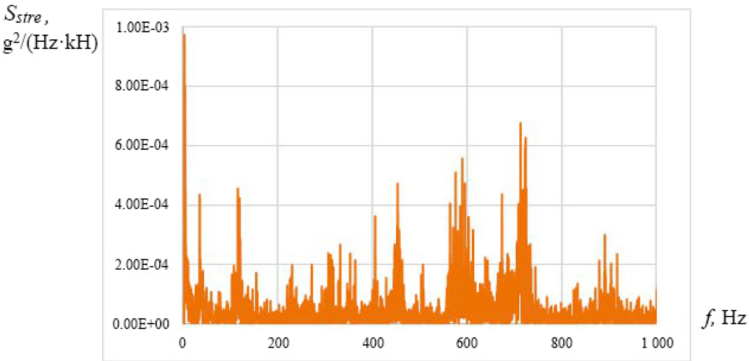

Figure 1. The reduced spectral density $\bar{S}_{stre}$ of the vibration acceleration of the engine structure for the frequency range from 1 Hz to 1000 Hz

To take into account the value of the LRE thrust in the problem of predicting the vibration accelerations of the spacecraft structure, formula (8) can be transformed into the following form:

$$S_{sc}(\omega) = |W_{str}(j\omega)|^2 \cdot \bar{S}_{stre} \cdot R_{LPE} \tag{9}$$

Figure 2 shows the dependences of the dynamic gain of the LV structure with the spacecraft $W_{str}(j\omega)$, calculated based on equations (4) - (5) for those researched launch vehicles. These dependencies are calculated for the studied liquid-propellant launch vehicles at the value of their relative LV flight time $\bar{t} = t/t_{fin} = 0.015$ (t_{fin} is the final operating time of the first-stage engines of the launch vehicle) at which the tanks of the launch vehicle are still almost completely filled with liquid propellants.

As follows from the results of the analysis of these dependencies, at the initial flight time, a single-stage LV (with a tandem layout) has the greatest dynamic effect ($W_{str}(j\omega)$) on the upper part of the LV structure at the frequency range of from 5 Hz to 7 Hz. At the same time, the modulus $W_{str}(j\omega)$ of the dynamic gain of the launch vehicle structure, calculated for a heavy LV with 'core and strap-on boosters' layout, as a result of the greatest value of the damping of the launch vehicle structure at low (up to 100 Hz) frequencies), is characterized by the smallest values of the $W_{str}(j\omega)$ coefficient.

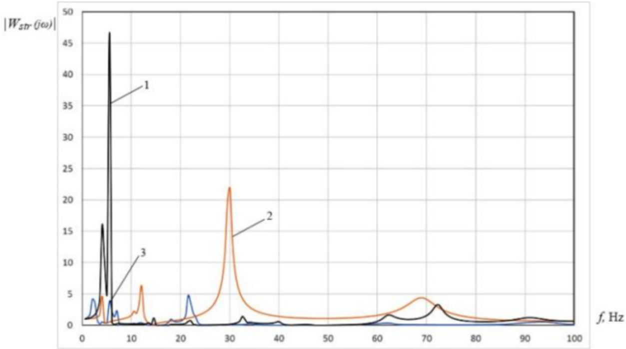

Figure 2. Dependences of the dynamic gain $W_{str}(j\omega)$ of the rocket structure with the spacecraft (1 is single-staged LV with tandem layout, two is two-staged LV with tandem layout, 3 is LV with 'core and strap-on boosters' layout)

Figure 3 shows the dependences of the spectral power densities of the spacecraft vibration acceleration calculated using the formula (7), constructed using the presented approach when they are launched into an orbit by different vehicles (1 is single-staged LV with tandem layout, two is two-staged LV with tandem layout, 3 is LV with 'core and strap-on boosters' layout).

From the analysis of dependencies shown in figure 3, as well as comparing them with the data in figure 1, it follows that, under the prediction made, the possibility of exceeding the maximum permissible values of vibration overloads is realized only in the case of launching a spacecraft into orbit by a single-stage launch vehicle (dependence 1). To ensure the safety of the spacecraft in flight (when designing for this case of the launch vehicle), it may be necessary to develop one of the vibration protection systems (for example, in design in [25]) installed at the spacecraft adapter.

According to the results of calculations, the values of the spectral density of vibration accelerations of the spacecraft structure (dependencies 2 and 3) turned out to be significantly lower (from 1.5 times up to 2 times) for the spacecraft environment conditions of two-staged liquid-propellant launch vehicles with a tandem layout and three-staged launch vehicles with core and strap-on boosters layout, than the limiting values of spacecraft vibration accelerations [9] by launched into working orbits using the American Falcon launch vehicle.

Thus, the feasibility of the proposed approach to forecasting the dynamic loading of spacecraft has been demonstrated using the example of a computational analysis of the spectral densities of spacecraft for launch vehicles with various design and layout schemes.

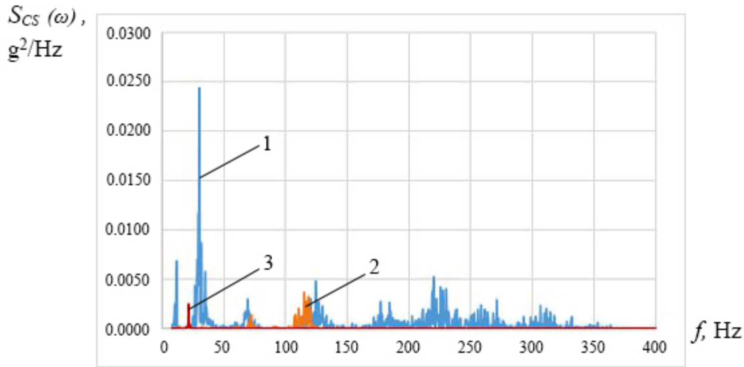

Figure 3. The calculated spectral power densities S_{cs} of vibration accelerations of the spacecraft structure for various launch vehicles (1 is single-staged LV of tandem layout, 2 is two-staged LV of tandem layout, 3 is LV of 'core and strap-on boosters' layout)

4. Contributions

An approach has been developed to forecasting the dynamic loading of spacecraft launched into orbits using various layouts of liquid-propellant rockets. The approach makes it possible to estimate the values of dynamic loads (spectral power densities of vibration accelerations) of the spacecraft structure during liquid propellant engine thrust oscillations, acting on the launch vehicle structure in the active leg of the flight of a liquid-propellant launch vehicle.

The approach includes mathematical modeling of spatial oscillations of the launch vehicle structure by its structural and layout scheme and preliminary experimental evaluations of the power spectral density of the rocket engine structure.

Using this approach, already at the initial stage of launch vehicle design, using the LRE vibroacoustic characteristics (known based on the results of LRE fire tests), it is possible to predict the parameters of the vibration loading of the spacecraft at different times of the LRE operation of the LV first stage, taking into account the LV layout and its design features.

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