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DETERMINATION OF THE PROPELLANT SLOSH PARAMETERS FOR ROCKET PROPULSION SYSTEM OF THE SPACE STAGE WITH COMPLEX SPATIAL TANKS CONFIGURATION

The computational modeling of sloshing for propulsion system of the rocket launcher space stage with complex configuration is carried out. Using finite element method and the tools of computer aided engineering (CAE) systems the spatial oscillations parameters of liquid free surface are determined. The slosh modeling results were used in the analysis longitudinal (POGO) stability of three-staged liquid launcher and in the evaluation of serviceability of propellant continuousness providing systems.

sloshing, propulsion system, space stage of rocket launcher, longitudinal stability, structural vibrations, finite element method, CAE systems

Introduction

Engineering practice shows the periodic motions of free surface of a liquid propellant (named as sloshing) in launch vehicle tanks can be dangerous for normal operation of liquid propellant continuousness providing systems in rocket propulsion system and for realization of stability conditions of the vehicle movement [1 – 3]. Amount the works (for example, see [4, 5]) were devoted to the problem of determination of hydrodynamical characteristics of oscillating liquid in the containers that considerate as a body of revolution. However the modern space stages of the liquid launch vehicles have structural features that complicate a computational modeling of liquid propellant slosh using traditional methods [4, 5]. The inconstant tank wall thicknesses, stage complex spatial configuration [1] with an immersing of one tank into another, various load-bearing elements are such design features.

A performance of analysis of dynamic behavior of liquid propellant in the propulsion system tanks by the computer techniques (CAE systems) [6, 7] based on finite element method will allow to take into account the space stage tanks design features and will optimize stage designing.

1. Statement of problem

It is necessary to perform a computational modeling of spatial vibrations of launcher space stage with the complex tanker module (the design concept is shown in fig. 1) by the finite element method and to determinate liquid propellant and the stage structure vibration parameters (the modes frequencies, shapes, and effective mass, slosh amplitudes) enable for a study of launch vehicle longitudinal stability and for determination of the efficiency of propellant continuousness providing systems. For decision this problem space stage of launch vehicle was considered as the closed dynamic «propulsion system – stage structure – liquid propellant» system under an action of oscillatory component of propulsion forces $\mathbf{F}$. It was described by a system of differential equations:

$$[\mathbf{M}]\frac{d^2}{dt^2}(u)+[\mathbf{C}]\frac{d}{dt}(u)+[\mathbf{K}]u=\mathbf{F}\,, \qquad (1)$$

where $[\mathbf{M}]$ is $n\times n$ mass matrix; t is current time; u is $n\times n$ displacement vector; $[\mathbf{C}]$ is $n\times n$ damping matrix of space stage elements prescribed to recommendations [4]; $[\mathbf{K}]$ is $n\times n$ stiffness matrix; $\mathbf{F}$ is oscillatory component of propulsion forces.

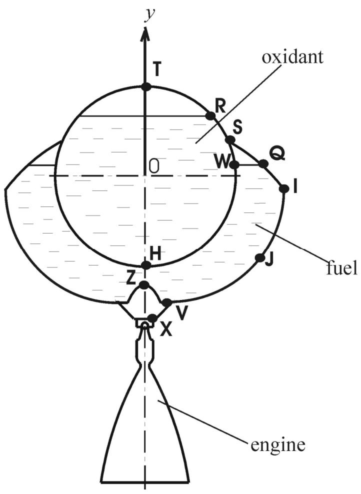

Fig. 1. Schematic diagram of structure and liquid propellant interaction in the space stage with complex spatial configuration of the tanks of propulsion system

The joint deformation conditions of conjugated surfaces of liquid and solid mediums (taking into consideration a sliding of liquid by the tank walls) and the boundary conditions of rigid fixing of structure top part are posed in the finite element model of the system spatial vibrations.

2. Results of modeling of sloshing in the propulsion system with the complex spatial configuration of the tanks

Using developed in CAD system geometrical models of volumes and surfaces, the launch vehicle space stage model was compounded at Ansys packet [7] and the stage schematization was executed by a set of finite elements. The finite elements of «elastic shell» were used for modeling of fuel tanks, oxidizer tanks, instrumentation module, mid-flight engine bed, mid-flight engine. Liquid propellant in the space stage modules was modeled by finite elements of «fluid 3D»; the pressurization system cylinders and start system cylinders, the oxidizer and fuel tanks of the special jet system were modeled by the finite elements of «concentrated mass». The finite elements model of the space stage with complex spatial configuration of the tanks of propulsion system is shown in fig. 2.

Results of computation of free longitudinal vibrations parameters of the space stage indicated a presence only two frequencies of 14,97 and 32,3 Hz (the corresponding effective masses are 16,4% and 6,8% of stage mass) in the frequency range of possible launch vehicle longitudinal instability. The mathematical modeling of the «propulsion system – launch vehicle structure» dynamic system and the analysis of the longitudinal stability of three-staged liquid launch vehicle were carried out on the basis of these results.

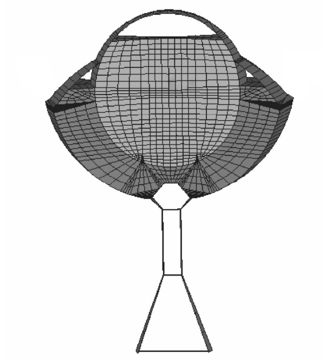

Fig. 2. The finite elements model of the space stage with complex spatial configuration of the tanks of propulsion system (the variant of maximum filling level of tanks)

An evaluation of the parameters of propellant slosh sequent of a cruise rocket engine thrust oscillations is very important for solving of a problem of definition of serviceability factor of intra-tank propellant continuousness providing systems [3]. The frequencies and amplitudes of free surface oscillations of liquid propellant as result of external periodic effects (vibrations of rocket engine structure) were studied using developed stage finite element model. The system frequency responses were computed as the ratio of propellant free surface complex amplitude to the complex amplitude of the rocket engine structure longitudinal vibration. As follows from the analysis of the computed frequency responses of the propellant free surface displacement, the engine structure vibrations at the frequency range of 0,9 – 1,7 Hz results in propulsion system resonant phenomena which are expressed as an increase in amplitudes of oxidizer and fuel free surfaces longitudinal vibration in the space stage tanks.

The maximal values of modules of ratio of the propellant free surface displacement complex amplitude to engine structure complex amplitudes were established. In particular, for liquid oscillation damping level (equal to 2% of critical) it wasn't exceeded the following values: for the oxidizer free surface is 32 at the vibration frequency closed to 1,0 Hz; for the fuel free surface is 50 at the vibration frequency closed to 1,2 Hz (see fig. 3); for the oxidizer free surface 25 at the vibration frequency closed to 1,6 Hz.

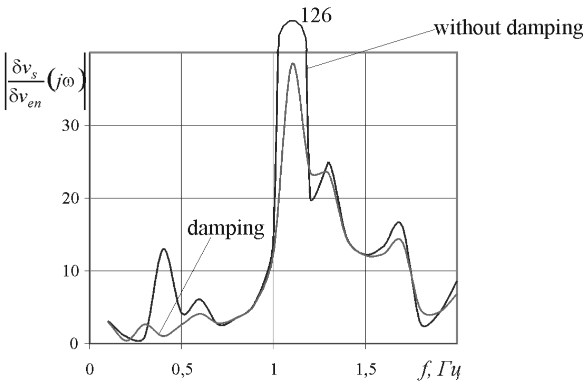

Fig. 3. Sloshing frequency responses as amplitude ratio of fuel free surface longitudinal displacement v_s to rocket engine structure longitudinal displacement v_{en} (with damping and without damping effect)

The shape of free surface oxidant tank of the space stage at the frequency of 1,2 Hz is shown in fig. 4.

Using above mentioned maximal values modules of the frequency responds the amplitudes of the free surface oscillations at the dangerous frequencies were computed. For different critical levels of propellant at tanks the serviceability factors of propellant continuousness providing intra-tank systems were determinate.

Conclusions

The computational modeling of sloshing for propulsion system of the rocket launcher space stage with complex configuration is carried out. Use of the finite element method and the software environment of CAD/CAE systems for computational modeling of «structure – liquid» system spatial oscillations allows to conduct the analysis of complex tank structures with determination of liquid propellant slosh parameters, the vibration parameters at the various cross-sections of space stage structure and dynamic characteristics of space stage as an object of control.

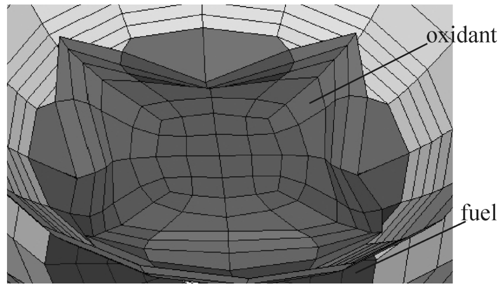

Fig. 4. The computational grid illustrated the sloshing shape of liquid oxidant at the frequency of 1,2 Hz

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