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Similation of the Dynamic Characteristics of Launch Vehicle Stabilization During Longitudinal Oscillations

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Abstract: **-** Frequencies of natural longitudinal oscillations of liquid at the inlet to the service feed line were calculated for a spherical fuel tank installed in a spacecraft. The authors are also developed a structural scheme for the spacecraft orientation system and synthesized continuous regulators in the frequency and time domains.

Keywords: *- Mathematical modeling, service simulating test, stability, system, oscillations, amplitude oscillator, damping, fuel tank, management system, orientation, LV - launch vehicle, SGA - strain gauge amplifier, LPRE – liquid prolellant rocket engine, SC – spacecraft, EMF - electromotive force, FR - frequency responce, PR - phase response*

I. INTRODUCTION

When designing sophisticated pieces of thechnology such as rockets, space rocket blocks and spacecraft, it is necessary to analyse dynamic processes occurring in them and in their partially fuelled tanks in order to specify dynamic properties of the product in general, in its modules and assembly components.

When launch vehicles and spacecraft are yet unmade, it is possible to explore their operational reliability under actual usage conditions only by using the methods of mathematical modeling, service simulating test or physical simulation.

Even if simplified, calculation of dynamic properties and provision of perturbed motion stability of an aircraft with due account to its body toughness and movability of liquid fuel is a challenging task, when linearization of equations is possible. Numerous solutions of the task in nonlinear formulation, which may be allied to check figures, are of little use in rocket design. The best way to calculate dynamic characteristics of a rocket is physical simulation.

In the process of design of a launch vehicle and of a spacecraft system we have to solve the task of an optimal synthesis, i.e. we have to select a structure and parameters of the system, which would provide its optimal performance. This is described in details in [1-6]. Thus, in the process of design, solution of the synthesis task will be split into several successive steps and present an iterative process with the cycles, characteristic for each step: theory, calculations, experiment, and analysis [4].

Each powered portion of flight of the launch vehicle with LPRE may be with unstable longitudinal oscillations, when dynamic load on the launch vehicle grows rapidly.

The most unfavorable are low frequency (up to 50 Hz) spring-type pitch motions of the launch vehicle which are accompanied by longitudinal oscillations of liquid fuel in tanks and mains. Pressure pulsations in the tanks and mains cause pulsation in supply of fuel components into the engine, pressure ripple inside the combustion chamber and pressure disturbance inside the LPRE. This disturbance is transferred in its turn to the body of the launch vehicle, and forms a closed oscillation system, in which initial slight disturbance may turn into rapidly growing in amplitude oscillations in the system in general and in each of its components[1]. This makes us formulate the task as an engineering one, and seek a solution of the problem of fuel tank dynamics using structurally similar models during longitudinal oscillations.

Objectives: to calculate the frequency of natural longitudinal oscillations of the liquid at the inlet to the service feed line into the spherical fuel tank, to develop a structural scheme for the orbital stage orientation, and to synthesize continuous controllers in the frequency and time domains.

Tasks:

1. To calculate frequency of natural longitudinal oscillations of liquid in the spherical fuel tank.
2. To calculate reduced mass of liqid in the fuel tank for different natural oscillation frequencies.
3. To develop a structural scheme for the orientation system of an orbital spasecraft with a spherical fuel tank, which shall be basic for frequency and phase response (FR and PR) of the control system along one axis.
4. To perform a service simulating test of an orbital spacecraft with a spherical fuel tank and to synthesize continuous controllers in the frequency and time domains.

Research target: simulated model of a spherical fuel tank installed into a spacecraft.

Subject of research: dynamic properties and continuous controllers included into the control system of a spherical fuel tank mounted in a spacecraft.

II. SIMULATION OF DYNAMIC PROCESSES TAKING PLACE IN UNITS AND IN FUEL TANKS

The The experimental study of dynamic processes at rocket design and construction phase is traditionally performed using models of an aircraft or of its modules and units. The most precise dynamic properties may be obtained in experiments with application of structurally similar models, i.e. full-scale models which replicate corresponding objects not only in respect of their geometrical parameters, but also in their mass and rigidity characteristics [1].

Structurally similar models allow us to determine dynamic properties of objects fully and accurately, and are used, for example, to study the behavior of the launch vehicle under the influence of loads practically occurring during its flight, to determine characteristics of its stress-strain behaviour, and oscillation mode and frequencies of the body in general, or of its specific components.

Creation of structurally similar models is a labor-intensive process because the model must accurately reproduce the design of a real object. Therefore, in some cases, when the experiments do not require any simulation of spacecraft deformation and stress, it is permitted to use geometrically similar models. They provided no similarity either in properties and thickness of materials, or in stiffness of the spacecraft, but only similarity in geometric parameters: external (or internal) contours, shape and arrangement of structural elements and units. Geometrically similar models shall be typically used to study motion parameters of liquid components of fuel in the tanks of the launch vehicle or the spacecraft [1].

If we meet some supplementary conditions when selecting parameters for models of real objects, designing test benches, and developing experimental techniques and modes, the results of experiments with the models may be transferred to full-scale objects with a high degree of reliability [1].

III. METHODS FOR DETERMINATION OF THE DYNAMIC CHARACTERISTICS

The In many launches of launch vehicles equipped with LPRE (liquid propellant rocket engines) unstable in-flight longitudinal oscillations with a frequency up to 50 Hz were observed [3].

The body of the launch vehicle, feed lines, liquid-propellant engines make a closed oscillation loop, where disturbance of engine thrust may result in oscillations of body, and of fuel in tanks and in lines, etc., and ultimately in oscillatory thrust. Initial thrust oscillations may increase. Elastic shell of the tank filled with liquid will make a separate oscillatory system. Frequencies and modes of longitudinal oscillations are general parameters of rocket body oscillations. It is vitally important to learn how to calculate such characteristics of longitudinal oscillations as dynamic reactions in attachment points of fuel tanks and pressure pulsations on entering the service line [1].

It is important to establish, which combination of rocket design parameters and flight modes result in pressure pulsations, increase them and cause them to be passed to the engine and entail thrust oscillations.

IV. DESCRIPTION OF THE EXPERIMENTAL UNIT

In the present study, experiments are conducted with a hemispherical shell 8 (Fig. 1) made of aluminum-based material AM-16B (a model version). A section of pipe duct is affixed to the pole of the shell, and is provided with a pressure pulsation sensor 7 performing the function of a cap. In order to measure elastic vibrations of the walls, several tension sensors 4 are attached to the shell along the meridian.

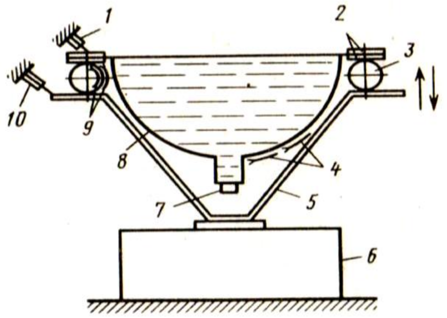


Fig. 1. Experimental hemispherical tank

The hemispherical shell is provided with a bead along its equator, which is clamped with two hard steel rings 2 for installation of shell components. Generally, there are 6 attachment points.

Axisymmetric shell vibrations shall be excited by a vibro-bench through frame 5 and the attachment points of the shell, which have a certain rigidity and enable to measure the force conveyed by the vibro-bench to the shell. They are made in the form of rings 3 with tension sensors 9 attached to both sides (external and internal).

To measure displacement of the base of the vibro-bench to which the tested shell is attached, we will use probes 1, 10 made of elastic plates with tension sensors attached on their both sides. One end of the plate shall be firmly fixed to the stationary base and the other one shall rest upon the tested model, or upon the table of the vibro-bench, if displacement is to be measured [9].

V. RESULTS OF THE STUDY

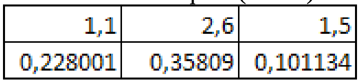
The service simulating test was done in Microsoft Excel та MATLAB/ Simulink environments.

For proper frequency values [6]: $\lambda_1 = 1{,}35$; $\lambda_2 = 3{,}33$; $\lambda_3 = 5{,}04$ we will calculate natural frequencies of longitudinal oscillations of the spherical tank from the formula [1]:

$$\omega_{0j} = \frac{1}{2\pi}\sqrt{\frac{\lambda_j E\delta}{\rho R^3}},$$

where λ_j are proper values: for the first natural frequency $\lambda_1 = 1{,}35$; for the second natural frequency $\lambda_2 = 3{,}33$; for the third natural frequency $\lambda_3 = 5{,}04$; E is a modulus of tank rigidity; δ is thickness of tank walls; ρ is liquid density; R is tank radius.

The natural frequencies of oscillations of the tank with liquid ($H_2O_{2_p}$) will be as follows:



1,1	2,6	1,5
0,228001	0,35809	0,101134

As can be seen from calculations and experiment [6], natural longitudinal oscillations of liquid in a tank filled by 60…100 % of its volume, depend very little from the tank charge level.

Free oscillation damping decrements for different values of natural frequencies shall be calculated from the formula [2]:

$$d = \frac{\Delta\omega\pi}{\omega_0},$$

where ω_0 is a natural frequency, which is used for determination of the oscillation decrement; $\Delta\omega$ is a breadth of resonance peak over its height. It is 0,7 of the peak height.

The calculations show that in a steady state condition in the absence of longitudinal accelerations, and small amplitudes of liquid oscillations, when we exclude temperature changes (adiabatic thermal insulation), the free oscillation decrement obtained as a result of computations, remains practically unchanged and tends to 1 [9].

VI. CONTROL SYSTEM SERVICE SIMULATING TEST FOR A LAUNCH VEHICLE WITH A SPHERICAL TANK

A diagram of the system of the spacecraft stabilization along one axis with a spherical fuel tank is shown in Fig. 2. The working fluid (fuel): (hydrogen peroxide) with a concentration of 92-96%. The thrusters work due to thermochemical decomposition of the working fluid in the chamber on a platinum (Pt) catalyst. The automatic control system shall dose the working fluid (fuel). The thrusters work in pairs, creating a moment (by using Step) in the reverse directions with the aim to damp accelerated motion inertia and stabilize relative to one of the axes. The orbital stage consists of a body with an installed thermally insulated fuel tank, payload in the head and orbital stage control system. The angular orientation sensor measures deviation in the angular position of the stage θ, and the angular velocity sensor measures angular deviation change rate $\frac{d\theta}{dt}$.

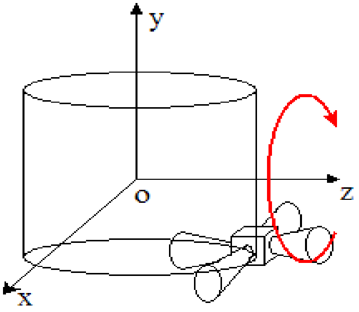


Fig. 2. Launch vehicle stabilization diagram

Control engines create a moment to correct angle position of the launch vehicle according to data furnished by sensors. Using the results of sensor analysis and by setting numerical values for all the physical parameters we obtained an operator function of a simplified model for orientation of the launch vehicle with a spherical tank relative to one axis (OZ), as a ratio of an object's position angle (θ) and controlling moment (m)[5]:

$$W_s(s) = \frac{\theta}{m} = \frac{s^2 + 0,1s + 7,5}{s^4 + 0,12s^3 + 9s^2}. \tag{1}$$

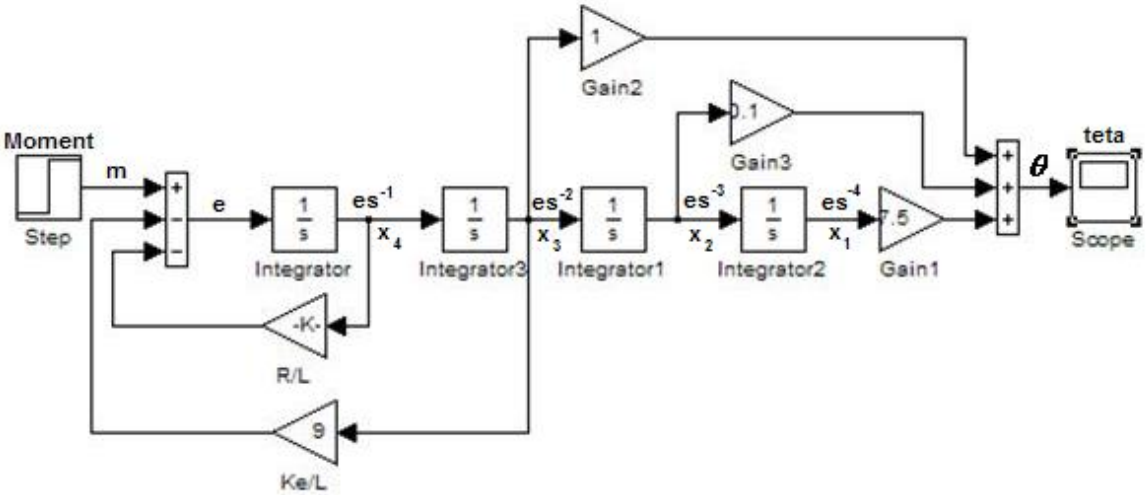


Рис. 3. Structural diagram of the stabilization system for a launch vehicle with a spherical fuel tank

The transfer function (1) may be represented as one block and tested. To do this, we must pass from the transfer function to a 3D state equation.

There are several ways to convert an operator function into 3D state equations [7]. Therefrom we applied the direct programming method.

The expression (1) becomes:

$$W_s(s) = \frac{\theta}{m} = \frac{s^{-2} + 0,1s^{-3} + 7,5s^{-4}}{1 + 0,12s^{-1} + 9s^{-2}}, \tag{2}$$

whereof $\theta = (s^{-2} + 0,1s^{-3} + 7,5s^{-4}) \cdot e$, where $e = \dfrac{m}{1 + 0,12s^{-1} + 9s^{-2}}$ (3)

The structural diagram, which has been made according to the equations (2-3) is shown in Fig. 3.

According to the above structural diagram, the 3D state equation shall be as follows:

$$\left.\begin{aligned} \dot{x}_1 &= x_2; \\ \dot{x}_2 &= x_3; \\ \dot{x}_3 &= x_4; \\ \dot{x}_4 &= -9x_3 - 0,12x_4 + m; \\ \theta &= 7,5x_1 + 0,1x_2 + x_3. \end{aligned}\right\} \tag{4}$$

or in vector form

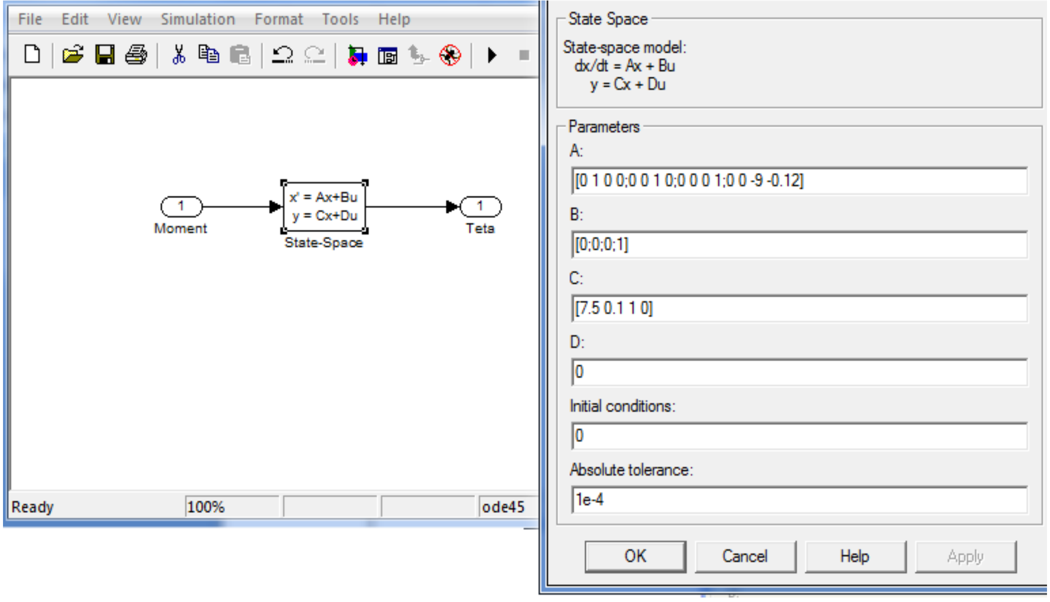
$$\left.\begin{aligned} \dot{X} &= AX + BM, \\ Y &= CX + D\Theta, \end{aligned}\right\} \tag{5}$$

$$X = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}, A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 9 & -0.12 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, M = \begin{bmatrix} 0 & 0 & 0 & m \end{bmatrix},$$

where $C = \begin{bmatrix} 7.5 & 0.1 & 1 & 0 \end{bmatrix}, D = 0.$

Fig. 4 shows a state variable model (Simulink block) and property window with values of above matrixes entered.

Amplitude-phase response (APR) and phase -frequency response (PFR) of the system, obtained using LTI-Viewer are given in Fig. 5.



State Space

State-space model:
dx/dt = Ax + Bu
y = Cx + Du

Parameters

A:
[0 1 0 0;0 0 1 0;0 0 0 1;0 0 -9 -0.12]

B:
[0;0;0;1]

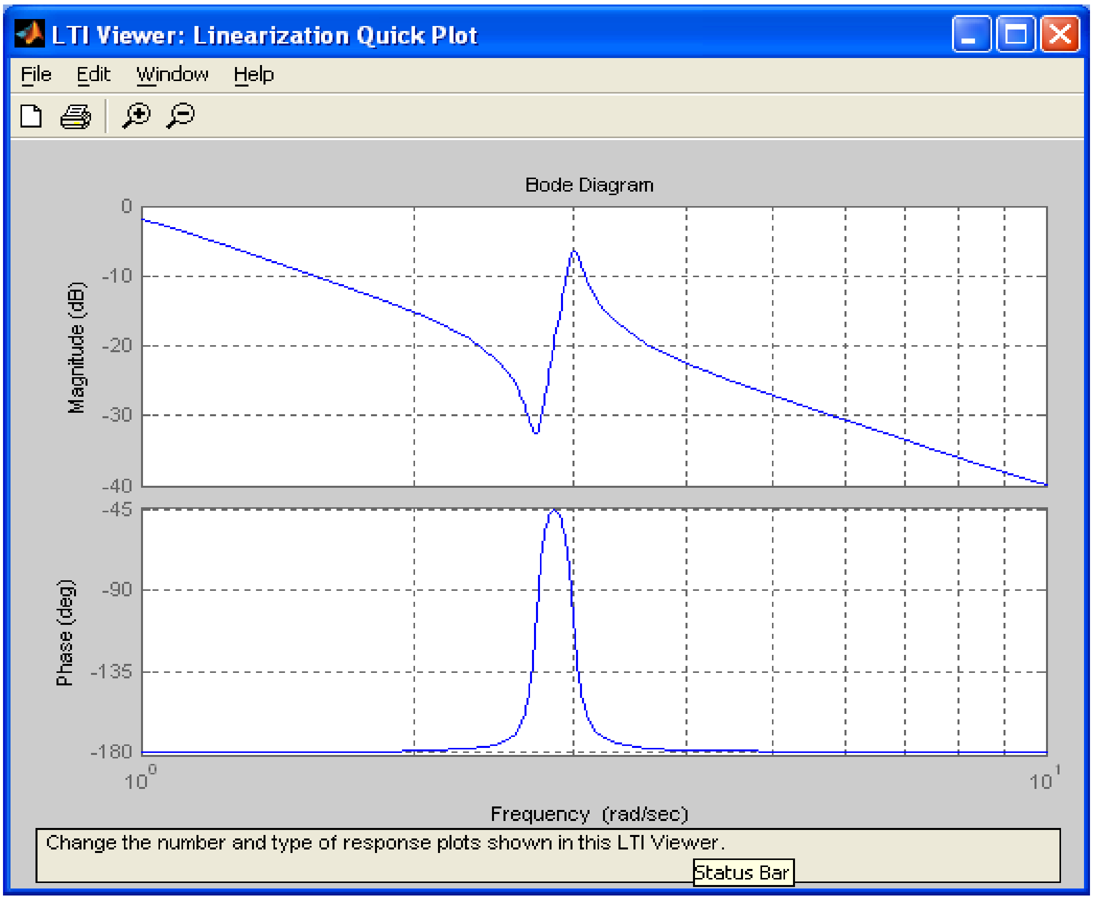
C:
[7.5 0.1 1 0]

D:
0

Initial conditions:
0

Absolute tolerance:
1e-4

Fig. 4. Simulink model of the system and property window



Change the number and type of response plots shown in this LTI Viewer.

Fig. 5. Bode diagram for frequency response of the stabilization system of the launch vehicle with a spherical fuel tank

According to Bode diagram, we have a stable steady condition for the given system in the range between 0 and -40 dB in amplitude, and -450... -1800 in phase. This means it is virtually impossible to provide "absolute" stability for the system, which consists of the orbital stage with a spherical fuel tank only along one axis.

VII. OBJECT'S CONTROLLER DESIGN WITH A REQUIRED TRANSFER FUNCTION

Of all the known methods of dynamic system configuration the most commonly encountered are the subordinate control systems. In such systems, an object is divided into a number of dynamic links, with a regulator synthesised for each link. A signal from the previous regulator shall be send to the input of a given regulator with a transfer function $W_p(s)$, which corresponds to the controlled variable, and a signal from output of $k-$ link in the system. The advantage of this structure is that it provides a possibility to simply achieve the desired dynamic characteristics of the entire system. In addition, this structure allows to constraint any of the coordinates in the system. For this purpose, it is enough to restrict oneself to setting a relevant coordinate.

The main advantage of the subordinate structure is a possibility to suppress disturbances in the controlled object, which may be caused both by external factors (temperature, supply voltage, load moment, etc.) and internal relations in multidimensional systems [7].

The object model are to be divided into links so that output values of the links are physical units, which from researcher's point of view are interesting for their influence upon regulation and control. Consequently, the number of regulators in the subordinate control system will be equal to the number of object links.

The task for the synthesis is to establish the structure and parameters of loop regulators. The synthesis itself shall be done using a so-called standard method as follows [7]:

1. The synthesis of the regulators shall be done in a sequential order starting with a regulator of the internal loop. Thereafter, interim loops regulators shall be synthesized, and the last one – the outer loop regulator.
2. Each loop regulator shall be done as a sequential correcting device providing desired properties for the given local control system.

The major function of the regulators is to provide a closed system with requisite dynamic characteristics, which are rather standard today. So, at each stage of the regulator synthesis, a researcher has to do with the structure shown in Fig. 6 [7].

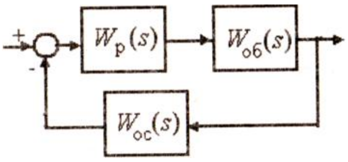


Fig. 6. General regulator structure

The transfer function in the structure shown in Fig. 6 may always be presented as a dynamic chain of the second order.

We may synthesize the regulator in the structure (Fig. 6) in two ways. In the first instance it shall compensate one (big) time constant of an object. Such regulators are designated as 1st type regulators [7].

In the second one it shall compensate two time constant of the object, and such regulators are designated as 2nd type regulators.

Let's consider synthesis of an object regulator with a transfer function $\frac{k_{об}}{(T_2 s+1)(T_1 s+1)}$ with parameters [6]: $K_{об} = 10; T_1 = 0{,}01$ c; $T_2 = 0{,}01$ c; $K_{oc} = 0{,}01$.

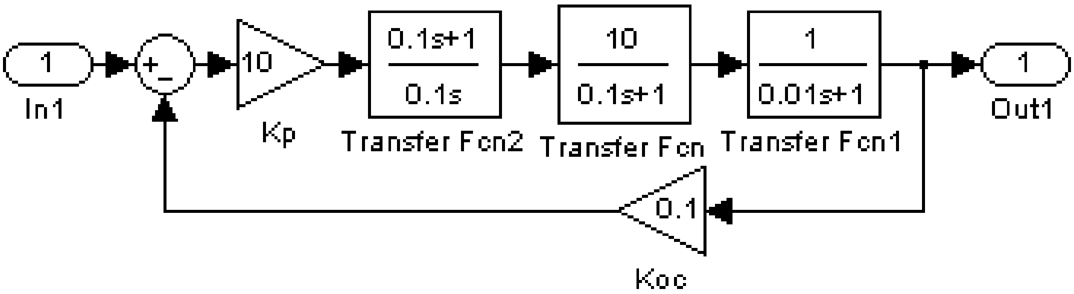


Рис. 7. Simulink model of a closed system for a launch vehicle with a spherical fuel tank

Let’s select the 1st type regulator with a transfer function $W_p(s) = \frac{k_p(T_1 s + 1)}{T_2 s}$.

In the closed system we assign a damping coefficient $\xi = 0{,}5$ (overshoot $\delta \approx 20\ \%$) and using the diagram (Fig. 3.38, [7]) we shall determine a relative gain of the regulator $\bar{k}_p = 4$. Thereafter, having calculated a critical regulator gain $k_{kp} = \frac{T_2}{4 T_1 k_{об} k_{ос}} = 2{,}5,$ we shall determine gain which provides required characteristics for the closed system $k_p = \bar{k}_p k_{kp} = 10$.

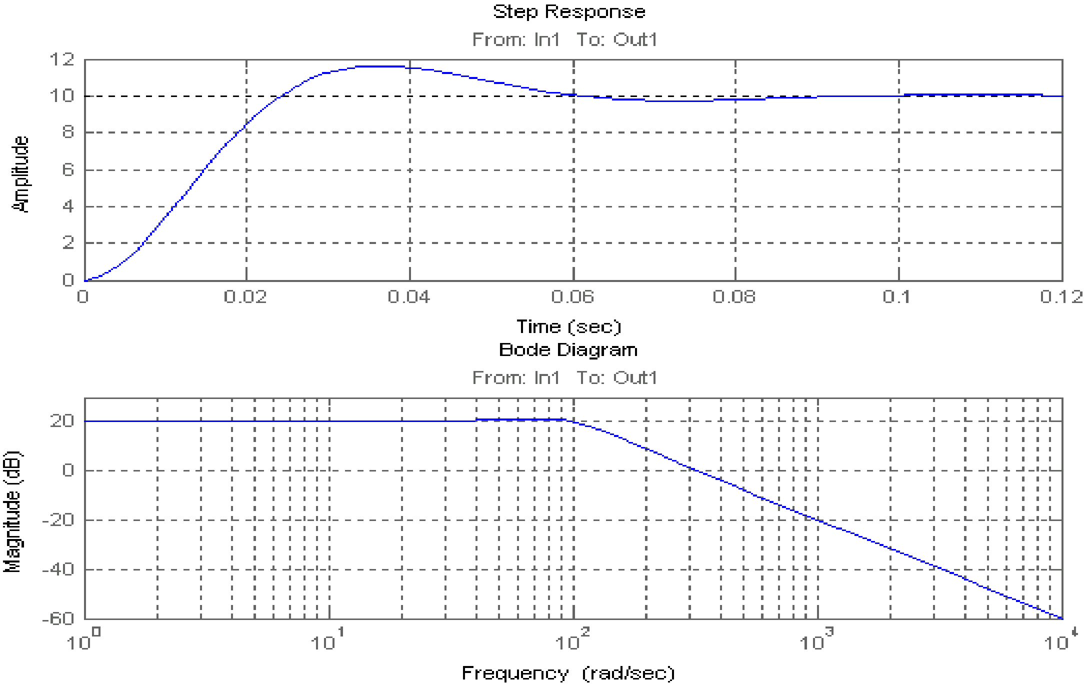


Fig. 8. Dynamic characteristics of the closed system in a spherical fuel tank during longitudinal oscillations

A model of a closed system is shown in Fig. 7, and dynamic characteristics of the model are shown in Fig. 8.
The simulation results demonstrate transition of the system in stable condition in amplitude in 0,04 s from beginning of regulation. In the frequency interval up to $\omega = 100$ rad/s the oscillation magnitude is constant, and in higher frequencies it shall linearly decrease, i.e. we observe stable persistence up to 10^4 rad/s.

VIII. SYNTHESIS OF REGULATOR IN A DIRECT CURRENT TRACING SYSTEM

For the specified object i.e. the spherical multicomponent fuel tank installed in the orbital stage, the closed structure contains speed and angular loops requiring synthesized regulators. For the speed loop we choose a regulator so that the open loop corresponds to the optimum in modulus [7]: $W_{1p} = \frac{k_{1p}}{(T_p s + 1)}$, then

$$W_{1роз}(s) = \frac{k_{1p} K_2 k_{1oc}}{s(T_p s + 1)} = \frac{1}{2T_p (T_p s + 1)}. \qquad (6)$$

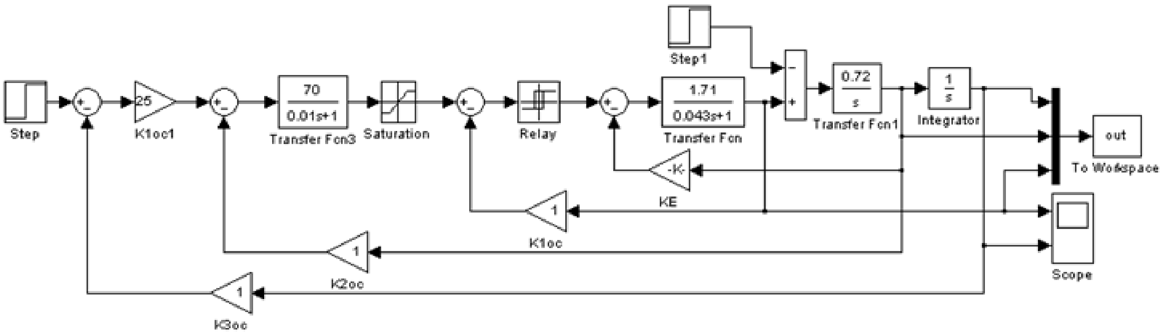


Fig. 9. Model of the tracing DC control system (dynamic processes in multicomponent fuel tank)

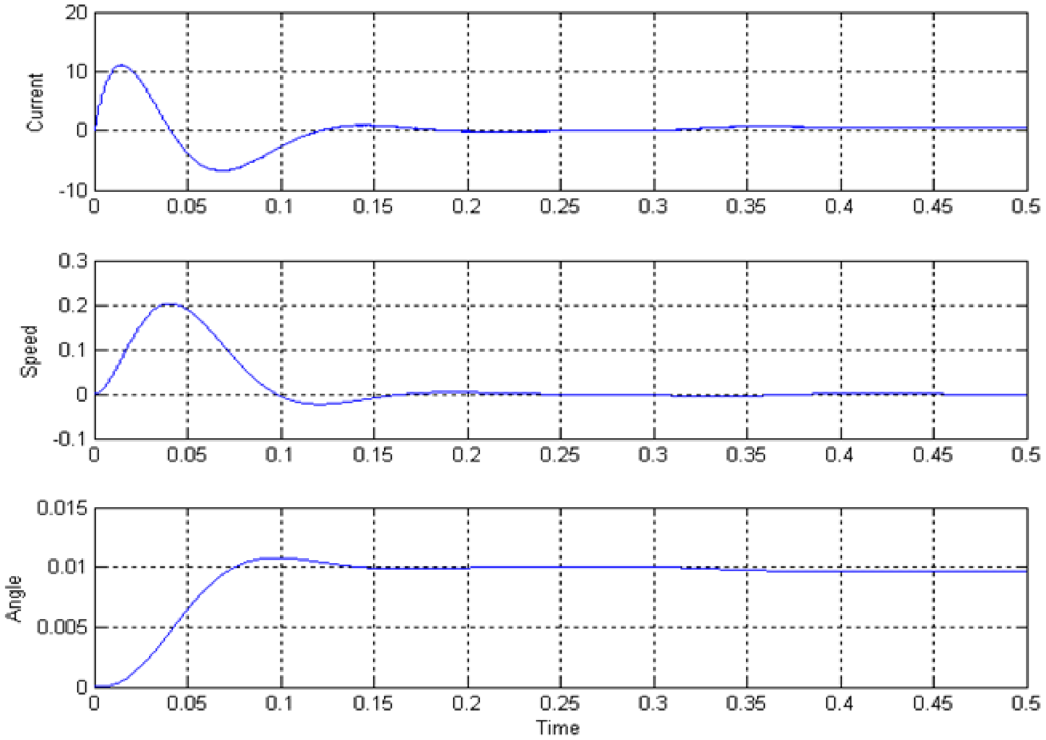


Fig. 10. Transition processes in the tracing DC system (dynamic processes in multicomponent fuel tank)

We set $T_p = 0{,}01$ c; $k_{1oc} = 0{,}01; K_2 = 71{,}4;$ determine $k_{1p} = \frac{1}{2T_p K_2 k_{1oc}} = 70.$

Similarly we synthesize the outer (angular) loop with $k_{2oc} = 1{,}0; k_{2p} = \frac{1}{4T_p k_{2oc}} = 25.$

A model of the tracing system is shown in Fig. 9. Transitional processes in the system are shown in Fig. 10. Consequently, the regulator has been synthesized. In 0.2 s from operation start the system becomes dynamically stable within the entire time interval [9].

IX. CONCLUSION

1. Natural frequencies for longitudinal fluid oscillations have been calculated for the spherical rocket fuel tank installed in the launch vehicle and fluid masses based on $(H_2O_2)_p$ have been provided.
2. The paper suggests a method for determination of fuel tank characteristics during longitudinal oscillations with application of structurally similar models.
3. Natural longitudinal oscillations of liquid in a spherical fuel tank at the inlet to the service feed line have been determined by mathematical modeling in MS Excel environment.
4. A block diagram for the spacecraft orientation system with a spherical fuel tank, which was used as a basis for development of frequency response and phase response for the control system along one axis, has been made in MATLAB/Simulink environment.

5. In accordance with the results of simulation modeling of the spacecraft with a spherical fuel tank, we synthesized continuous regulators in the time and frequency domains as arbitrarily complex dynamic elements of the second order.
6. In accordance with Bode diagram, we have stable condition for the given system in the amplitude range 0 to -40 dB and in the phase range -45^0 … $-180^{0,}$ excluding area with frequency 0 rad/s.
7. The simulation results demonstrate stability of the system in amplitude in 0, 04 s. In the frequency interval the characteristic is constant up to $\omega = 100$ rad/s, and further we observe stability up to 10^4 rad/s.
8. We have synthesized regulators with a specified transfer function in the tracing onboard DC system.

Thus, the tasks and objectives set in the work have been fulfilled with application of modern computer technologies. The research results are supported by the data from information sources and corresponding publications, and may be used to practically implement the project.

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