MODELING, SIMULATION AND DESIGN OF THE STABILIZATION SYSTEM FOR COMPLEX FLEXIBLE AEROSPACE VEHICLES

A.I. Panferov, A.V. Nebylov, S.A. Brodsky
International Institute for Advanced Aerospace Technologies of
State University of Aerospace Instrumentation
67, Bolshaya Morskaya, St.-Petersburg, 190000, Russia
e-mail: nebylov@aanet.ru

1. ABSTRACT

Possible approaches to the mathematical description of the dynamic properties of aerospace vehicles in the processes of flight in atmosphere are observed. This description includes different mathematical models such as: models of the construction flexibility, sloshing of the fuel and oxidant, rigid body flight in the variable gravitational field with variable distributed mass of the vehicle, integral and distributed aerodynamic in the big diapason velocities, aeroflexibility, models of different types of the rocket engines and so on. In the basis of these mathematical models the library of the program units were designed. This library was included in the special program, which allows automating the processes of simulation of arbitrary axisymmetrical aerospace constructions. The program allows calculating the general mathematical models in different forms, to simplify these models and to use for design the systems of stabilization.

2. INTRODUCTION

Possible approaches to the mathematical description of different types of flexible vehicles are observed. Mass and aerodynamic characteristics are changing considerably during the flight of aerospace vehicles. From the point of view of control theory such vehicles are the typical non-linear and non-steady plants. The aim of designer is to create the light construction. For these reason such objects are deformed in flight, and their elastic properties appear. Elastic longitudinal and lateral oscillations of the complex form arise, which frequencies are changing during the flight. Elastic oscillations are usually described by differential partial equations or ordinary differential equations of the great dimension. Deformation of a body results in appearance of the local attack angles and slide angles. As a result of it, the local forces and moments of forces arise. These forces and moments are synchronized with the changes of local angles of attack and slide. The local forces and moments are the reasons of amplification or attenuation of elastic oscillations. This phenomena is known as aeroflexibility. At excessive development of elastic oscillations the structural failure may take place. Paying attention to these effects has a great importance at control of space stations and space probes, airplanes and other mobile objects liable to the considerable dynamic loads [1].

Besides the flexibility and aeroflexibility, it is necessary to take into account in the mathematical models of aerospace vehicles the following factors:

1. Dependence of all parameters on time, velocity and altitude of flight, drift of CG, and so on.
2. Distributed and integral aerodynamic forces.
3. Oscillation of liquid in tanks (Sloshing).
4. Inertia of engines.
5. Errors of measuring instruments.
6. Environment stochastic forces and moment of forces.

Mathematical descriptions of all these factors are complex and are based on different physical models. For research of elastic systems the special programs exist, for example, ANSYS, NASTRAN, Coventor, Femlab, Structural Dynamics Toolbox for use with MATLAB, etc. In these programs the finite element method is used, which has been well recommended at calculation concerning the simple designs. For dynamic processes investigation and also for simulation of elastic oscillations of the flying vehicles, which consist of hundreds and thousand units of complex form, such approach is unsuitable. For calculation of distributed and integral aerodynamic forces can be used the program Fluent. The program Matlab allows to design of control or stabilization system. It is required to use all models simultaneous for analysis of interconnections and detection of possible resonances. For with reason, the resulting mathematical model is very complex. There are no known programs to analyze and simulate such complex systems which include subsystems, which base on different physical principles.

Authors propose new approach and special program to input construction of aerospace vehicles, to calculate mathematical model, to correct this model on the basis of separate experiments, to simplify separated models for any factors. The program allows using whatever experimental data about properties of the vehicle, presented in the most various formats. Hand-operated input and correction of separate values, and also the automated lead of large arrays of the information is provided. At absence or inaccessibility of a part of experimental data in the program, the models based on various theories or on generalization of experimental data of vehicles are used. The software for simulation of flexible essentially non-steady vehicle motion, synthesis of control systems for such a vehicle, research of dynamic properties by different methods in time and frequency domains, is developed and described in this paper. The basis of the program is the structure which allows analyzing the dynamic responses, simulation and visual information representation of the complex dynamic systems [3], [4].

In the present paper all stages of aerospace vehicles design are discussed, including the following problems:

- input of initial constructive data of vehicle,
- determination of controllability and observability for the full and simplified model of a vehicle for real control inputs and arbitrary choice of measured signals,
- choice of flight program and control law,
- automatic linearization relative to arbitrary trajectory,
- automate processes of mathematical models simplification for flexible vehicles and separate physical phenomena (oscillations of a liquid in cavities, time lag of engines, local aerodynamic loadings, etc.) and to control these simplifications,
- execute a system synthesis of control for elastic object in frequency area with the given margin of stability on amplitude and a phase,
- control system synthesis for a vehicle with use of method of Kalman filtration and methods of optimal control,
- simulation of vehicle motion with nonlinear model and control law different complexity,
- investigation effect of local aerodynamic loadings on elastic vibrations of a vehicle,
- determination eigenfrequencies of a liquid oscillations in tanks and computation of the local forces which are affect on a vehicle body because of these oscillations,
- choice of sensors and actuators characteristics,
- computation charts of relations for any variables of state vector, both from a time, and from other variables of state vector,

– any frequency characteristics plots construction,
– choice of flight program and control law,
– determination of the elastic vibrations of a body and oscillation of liquid in tanks modes and to illustrate these oscillations as animations,
– study of control system sensitivity to vehicle parameters change.

2. METHODS OF THE PROBLEM SOLUTION

A flexible aerospace vehicle will be considered in the paper as an example, but the suggested method could be applied to any kind of flexible plant. Increasing requirements to the manoeuvrability of flying vehicles at a minimum weight of structure results in development of flexible properties, which are significant for motion control. Taking into account all these effects that are essentially important at control of space stations and probes, airplanes and other mobile objects having the considerable dynamic loads because of functioning of engines and resistance of the air environment. Presence of flexibility determines the capability of appearance of oscillations in control system at different resonant frequencies. Many cases when flexibility of controlled plant was a reason of control system instability are known, resulted in development of oscillations and finally in a structural failure. Creation of effective regulators is precluded with complexity of obtaining the certain information about flexible properties of object, the significant relation of natural frequencies to the varying weight, velocity and drag. Last two parameters largely depend on a flight path, which is frequently beforehand unknown. Complexity of obtaining the information about the local aerodynamic loads on a surface of object complicates the control system design [5].

Many types of vehicles considerably change weight and aerodynamic characteristics during a flight. From the point of view of control theory such vehicles are the typical non-linear and non-steady plants. The aim of vehicles designers is to create maximum light constructions. It results in straining of such objects in flight; flexible properties of their bodies are manifested. The elastic longitudinal and lateral oscillations of the composite shape are arising, their frequencies change during the flight. Flexible vibrations are usually described by differential partial equations or ordinary differential equations of high order. Deformations of a body result in appearance of local angles of attack and slips. As a result of it the local forces and the moments of forces appear, which are synchronized with changes of local angles of attack and slips. The local forces and moments cause amplification or attenuation of flexible vibrations. At excessive development of flexible vibrations the structural failure occurs. Oscillations of fuel and oxidant in tanks result in origination of forces and the moments of forces concerning all three axes of the vehicle. Natural frequencies and oscillation frequencies of liquid depend on the shape of tanks and their location at the vehicle, a degree of filling of tanks by a liquid. Development of liquid oscillations in tanks depends on motion of object and in turn influences motion of object, in particular on flexible component oscillations. For this reason it is necessary to include the model of liquid oscillations in a structure of the generalized model of vehicle motion. Technical complexity and sophistication of state-of-the-art vehicles results in the necessity of division the processes of vehicle designing on some stages [6], [7].

At the first design stage the vehicle is considered as a rigid body of variable mass. At this stage the problems of vehicle rational aerodynamic configuration and required efficiency of actuators for control system are solved. Possible methods and approaches of motion stabilization for vehicles with a rigid body are considered. Usually at such design stage the methods of aerodynamics, flight dynamics, automatic control, and also specialized and universal programs, such as MATLAB, are used. If the vehicle is unstable at this stage the synthesis of the elementary control system ensuring a steady motion along a desirable path is fulfilled. During the simulation the state vector is saved in file as a reference path. Information about reference path is used for automatic linearization on the next stages of investigations complex models and control systems. It is supposed, that peculiar properties of elastic object unaccounted at this design stage do not result in large deviations from a reference path and the possibility of using the linear model is saved.

At a next design stage flexibility of vehicles and oscillation of liquids in tanks are taken into account. Local forces and the moments of forces as functions of time and coordinates along a centerline of a vehicle are computed. Analytical and semigraphical methods of calculation at this design stage yield only approximated outcomes. The indicated reasons determine the necessity of development of the specialized program for simulation the motion of flexible objects of the composite form, the analysis of their dynamic properties and design of control systems.

In the present paper other approach to modelling and control system design for flexible objects is observed. It is known, that the flexible object is described by partial differential equations. The control theory of such objects is complex, bulky and presently is analytically insufficiently designed. There are numerical methods of calculation of the arbitrary quantity of harmonics of flexible vibrations and replacements of partial equations by ordinary differential equations of high dimension. For automation of analytical derivation of such mathematical model of flexible aerospace vehicle, for control law synthesis, for the analysis and simulation of controlled flight, and also for representation of outcomes of modeling in the two-dimensional and three-dimensional space, the authors have developed the specialized software package.

3. MATHEMATICAL MODELS OF PHYSICAL PHENOMENA HAVING PLACE AT FLIGHT

Solid Dynamics

The rigid part of mathematical model of vehicle is allocated into the separate block, in which the system of differential non-linear equations of vehicle spatial motion is integrated. These equations in vector form in body-axes can be written as

$$\frac{d\mathbf{V}}{dt} = \frac{\mathbf{F}}{m} - \Omega \times \mathbf{V}, \tag{1}$$

$$\frac{d\Omega}{dt} = \mathbf{I}^{-1}\left(\mathbf{M} - \Omega \times \left(\mathbf{I} \cdot \Omega\right)\right) \tag{2}$$

These equations express the motions of a rigid body relatively to an inertial reference frame. Here $\mathbf{V}$ is velocity vector at the center of gravity (CG), Ω is angular velocity vector about the c.g, $\mathbf{F}$ is total external force vector, $\mathbf{M}$ is total external moment vector, $\mathbf{I}$ is inertia tensor of the rigid body.

Outputs of this subsystem are parameters of vehicle motion as a rigid body.

Flexibility

Equation of elastic line flexible displacements from the longitudinal neutral axis looks like

$$\Delta \mathbf{M} \ddot{\mathbf{q}} + \Delta \Xi \dot{\mathbf{q}} + \mathbf{q} = \Delta \mathbf{f}, \tag{3}$$

where $\mathbf{q}(t)$ is deflection of elastic line from the longitudinal axis; Δ is symmetrical stiffness matrix; $\mathbf{M}$ is diagonal mass matrix; Ξ is symmetrical structural damping matrix; $\mathbf{f}$ is distributed load.

This equation describes only the flexible displacements of object points in the body-fixed coordinates. The distributed loads resulting to longitudinal moving of object and its rotation are filtered by a matrix of rigidity, do not result in deformation and are taken into account only in the equations of object motion as a solid body. Damping and elastic forces do not affect the moving vehicle as a rigid body, because the condition of dynamic balance is satisfied.

Full equation of flexible displacement in generalized coordinate z is set as:

$$\mathbf{G\,V\,\ddot{z}} + \mathbf{G\,D\,V\,\dot{z}} + \mathbf{V\,z} = \sqrt{\mathbf{M}}\Delta\mathbf{f}\ , \tag{4}$$

where $\mathbf{z}(t)$ is vector of generalized coordinates (modes of flexible oscillations); $\mathbf{G}$ is $\mathbf{G} = \sqrt{\mathbf{M}}\,\Delta\sqrt{\mathbf{M}}$; $\mathbf{D}$ is $\mathbf{D} = (\sqrt{\mathbf{M}})^{-1}\,\Xi\,(\sqrt{\mathbf{M}})^{-1}$; Λ is diagonal matrix of eigenvalues of symmetric matrix $\mathbf{G}$; $\mathbf{V}$ is orthogonal matrix of eigenvectors: $\mathbf{V}' = \mathbf{V}^{-1}$. Eigenvalues equal to zero correspond to motion of solid body.

The eigenfrequency of *i*-mode of free bending oscillation is defined as:

$$\omega_i = \lambda_i^{-1/2} \tag{5}$$

The relation between displacements of elastic line $\mathbf{q}(t)$ and generalized coordinates $\mathbf{z}(t)$ looks like

$$\mathbf{q}(t) = \sum_i \mathbf{h}^{<i>}\, z_i(t)\ , \tag{6}$$

where $\mathbf{H}$ is matrix of shapes $\mathbf{h}^{<i>}$ of free bending oscillations $\mathbf{H} = (\sqrt{\mathbf{M}})^{-1}\mathbf{V}$.

For the flexible discrete system having the definite number of point mass particles the number of eigenfrequencies accords to the number of particles and can be defined by the equation (6) dimension. Shapes and eigenfrequencies for this system can be found as the exact solutions. For the continuous object, when the tolerance of forms and eigenfrequencies evaluation is given, the sampling frequency sets the number of bending eigenfrequencies.

It is advisable to limit the number of modes when simulating the distributed flexible object dynamics by dominant harmonics. Reduced equation of flexible displacement in generalized coordinate z is:

$$\mathbf{G\,V}_{\{K\}}\mathbf{\ddot{z}} + \mathbf{G\,D\,V}_{\{K\}}\mathbf{\dot{z}} + \mathbf{V}_{\{K\}}\mathbf{z} = \sqrt{\mathbf{M}}\Delta\mathbf{f}\ , \tag{7}$$

where K is dominant modes numbers: $K = \{\, i_1, i_2, \cdots i_k \,\},\ k < n$; $\mathbf{V}_{\{K\}}$ is matrix that consists of K columns of matrix $\mathbf{V}$.

The equation (7) in the matrix form describes the singular system of differential equations that cannot be expressed by the highest order derivative. The transformation

$$\mathbf{\ddot{z}} = \left(\mathbf{G\,V}_{\{K\}}\right)^{+}\left\{-\,\mathbf{G\,D\,V}_{\{K\}}\mathbf{\dot{z}} - \mathbf{V}_{\{K\}}\mathbf{z} + \sqrt{\mathbf{M}}\,\Delta\,\mathbf{f}\right\} \tag{8}$$

is used for its numeric integration.
The elastic line displacements can be divided into two components $\mathbf{q} = \hat{\mathbf{q}} + \tilde{\mathbf{q}}$, as:

$$\hat{\mathbf{q}} \in L\left((\sqrt{\mathbf{M}})^{-1}\mathbf{V}_{\{K\}}\right),$$

$$\tilde{\mathbf{q}} \perp L\left((\sqrt{\mathbf{M}})^{-1}\mathbf{V}_{\{K\}}\right). \tag{9}$$

In the equation (9) the elastic line displacements $\hat{\mathbf{q}}$ and its derivatives $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ are taken into account.

The distributed and concentrated forces appear because of formation and a break-down of a vortex on the vehicle surface.

Local aerodynamic effects substantially depend on the velocity and altitude of flight, the form of a mobile object, angular orientation and flexible deformations of a body. Even at a constant velocity of flow on the vehicle surface the vortices are generated. It results in the composite and time-varying distribution pattern of local loads on a surface of object. At high speeds of flight in the separate parts of vehicle there are local spikes of pressure. For their modelling it is important to define zones of the appendix of large local loads and their time history. Usually these zones are arranged close to transitions from conical to cylindrical surface forms or to places of joints of surfaces more the composite form. At designing of vehicle the aim to avoid such connections is usually set, but it is not possible to remove them completely. Here models for the description of the most typical local loads from vortices are resulted.

Large local loads arise near to junctions of separate structural parts. Usually it is places of transition from a conic surface to cylindrical, places of a docking of cylinders of miscellaneous diameter. Vortex flows will be produced a little bit below streamwise places of details docking, intensity of vortexes and frequency of their separation largely depends on conditions of flight. More particularly these models are described in [5], [6].

Aerodynamics and local loads

Distributed and integral aerodynamics forces are calculated in this program block. Parameters of vehicle motion as rigid body and bending oscillations for each flight moment are taken into account. Distributed coefficients are evaluated for each point along the longitudinal axis of vehicle. Distributed aerodynamic coefficients $C_n(x)$ and allocated values C_{n_i} are linked with integral coefficients C_n, $C_m(x_{cg})$, $C_{mq}(x_{cg})$ at arbitrary disposition of center gravitation x_{cg}, by the equations:

$$C_n = \sum_i C_{n_i} = \int_0^l c_n(x)dx\,, \tag{11}$$

$$C_m(x_{cg}) = \sum_i C_{n_i}(x_i - x_{cg}) = \int_0^l c_n(x)(x - x_{cg})dx\,, \tag{12}$$

$$C_{mq}(x_{cg}) = \sum_i C_{n_i}(x_i - x_{cg})^2 = \int_0^l c_n(x)(x - x_{cg})^2 dx. \tag{13}$$

Local angle of attack a_i^* at a point with coordinate x_i on the line of vehicle longitudinal axis with account of flexible oscillations is

$$a_i^* = a + \frac{x_{cg} - x_i}{V_i}\dot{\vartheta} - \frac{\dot{q}_i}{V_i} + \frac{\partial q_i}{\partial x_i}\,, \tag{14}$$

where $\frac{\partial q_i}{\partial x_i}$ is slope of elastic line in current time; $\dot{q}_i$ is velocity of shape of elastic line. Here V_i is local air velocity; a is angle of attack of solid body; ρ is air density. In order to evaluate the atmospheric perturbations it is necessary to know the airspeed.

The force f_i, distributed along longitudinal axis of vehicle and integral drag force F_x are evaluated by the block as:

$$f_i = \rho\frac{V_i^2}{2}C_{n_i}a_i^*\,, \qquad F_x = \frac{\rho \cdot V^2}{2}C_d\, a \tag{15}$$

Aerodynamic effects of jet exhaust stream turn are also taken into account.

Sloshing effects

Presence of the cavities filled with a liquid (fuel and an oxidizer) inside object results in appearance of additional forces and the moments of the forces influencing vehicle motion. Studying of oscillations of a liquid in tanks is one of the problems of classical hydrodynamics where for the description of motion of a liquid are used either Lagrange variables, or variables of the Euler. Lagrange variables determine motion of the fixed liquid particle, they depend on time and coordinates of this particle in the initial moment of time. Studying of motion of a liquid by means of these variables consists in the analysis of changes, which undergo various vectorial and scalar values (for example, speed, pressure etc.), describing motion of some fixed particle of a liquid depending on time. Variables of the Euler characterize a motion condition of particles of the liquid located in the different moments of time t in a given point of the space with coordinates x, y, z. In other words, various vectorial and scalar elemental motions are considered as a function of a point of the space and time, that is as the functions, four arguments: x, y, z, t.

At studying oscillations of a liquid the following assumptions were accepted:

1. A liquid in a cylindrical tank is ideal and incompressible.
2. Movements and speeds of all particles of a liquid and walls of a tank are small values in the sense that products and squares of them can be neglected.
3. Motion of a liquid in coordinate system Oxyz has potential of speeds. Believing initial motion of a liquid vortex-free and a field of mass forces potential, on the basis of Lagrange theorem a conclusion can be made.
4. The total acceleration vector of a field of mass forces *g* in any the time of motion makes a small angle with this axis.

As equations of oscillations of a free surface are similar to equations of a mathematical pendulum oscillations at the analysis of vehicles dynamics, naturally, there is a question of replacement of a varying liquid with a system of mathematical pendulums. The solution of this problem is adduced in the work.

The problem is formulated as follows. It is necessary to find a mechanical system which would has the same dynamic properties at motion that the liquid in part filling a cavity of a circular cylindrical tank has. A required mechanical system has to be presented as a rigid body (rod) with n mathematical pendulum. Points of mathematical pendulum bracket are located on a single straight line, which is the line of the main central axes of a rigid body with the weights of pendulum fixed on this axis. This straight line will be counted as a centerline of a rod, and a position of weights of pendulum on this axis unperturbed.

Let us designate through n the number of a harmonics; l_n length of the equivalent pendulum; r0 radius of a tank; Ln* distance from a CG up to an oscillating liquid; h - a filling depth of a tank, mn* weight n-th a pendulum, L distance from CG up to a surface of a liquid in a tank, x_{CG} coordinate of vehicle CG, x_{botton} coordinate of a bottom of a tank.

The length of pendulums, their weight and arrangement concerning center of rotation CG are determined by the following expressions:

$$l_n = \frac{r_0}{\zeta_n th(\zeta_n \frac{h}{r_0})}, \qquad L_n^* = L_n = L\left[1 - \frac{2r_0}{\zeta_n L} th\left(\zeta_n \frac{h}{2r_0}\right)\right], \qquad m_n^* = m_n = \pi r_0^3 \rho \frac{2th\left(\zeta_n \frac{h}{r_0}\right)}{\zeta_n\left(\zeta_n^2 - 1\right)},$$

$$z_n^* = \lambda_n, \qquad L = x_{CG} - x_{bottom} + h, \qquad \omega_n^2 = \frac{g^*}{l_n}, \qquad g^* = \ddot{x}_0 + g \cdot \sin(\upsilon_0),$$

ζ_1 = 1.841, ζ_1 = 5.331, ζ_1 = 8.564, ζ_1 =11.71, ...

Each tone of oscillations of a liquid is simulated by a mathematical pendulum of certain length. The weight of a pendulum is equal to adduced weight of the oscillating liquid. The weight of a pendulum decreases with increase of number n of the tone of oscillations. Distance Ln* from center of rotation CG of a vehicle up to weight of a pendulum corresponds to distance Ln from CG up to center of adduced weight of the oscillating liquid.

4. STRUCTURE OF CONTROL SYSTEM

The block diagram of control system for a flexible vehicle is shown in Fig. 1. At the design stage the state-space model reduction for stabilization and guidance systems is used.

The complexity of the models used at describing the aeroelastic effects via the equations of motion discussed previously makes design of stabilization and guidance systems an extremely difficult problem.

To start this process it is necessary to linearize the system dynamics near the nominal trajectory. Reduction of the linear model is then performed and the desired manner in which the reduced-order linear model approximates the full-order model. At the stage of control system synthesis it is important to represent accurately the system frequency response in the frequency range where of the loop transfer function is close to occur one. There are frequencies both above and below the critical frequency range which may not need to be well modeled. The frequency range of interest is very important for applying model simplification.

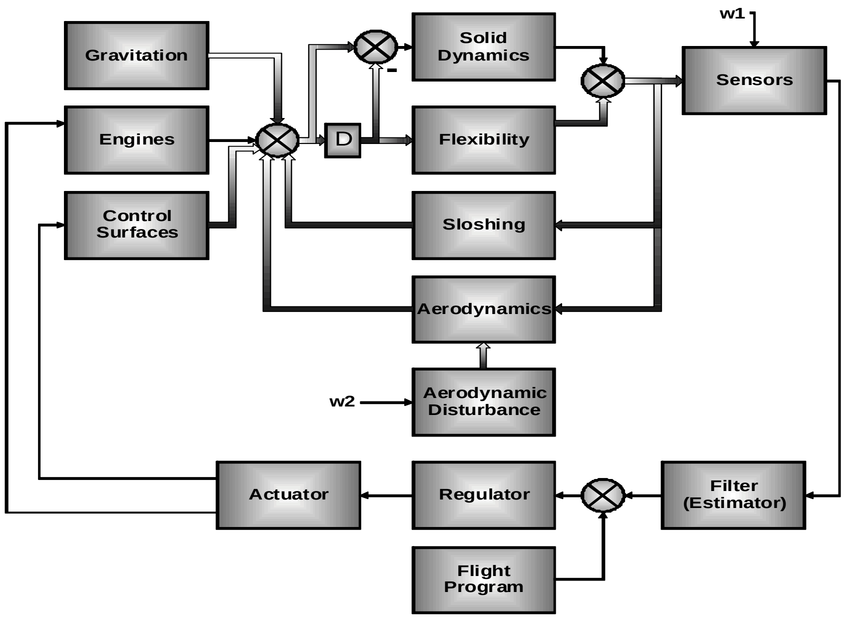

Fig.1. The simplified block diagram of control system

There are many methods by which the linear elastic vehicle models can be simplified. Several of these methods are used in the software package. The purpose of this simplifications is to design the robust controller. Truncation deletes some of the modes or states truncation from the full-order model. Residualization accounts only the effects of some modes or states whose dynamics is not crucial. Balanced reduction minimizes frequency response error and has the certain advantages associated with obtaining desired accuracy. Symbolic simplification addresses the impact of various physical parameters on the system responses and ignores those ones that have a little influence. Some advantages and disadvantages for each of these methods exist. After design the robust controller for simplified model, the analysis of real accuracy with complete is executed.

5. THE EXAMPLE OF DESIGNING THE GUIDANCE SYSTEMS

The nonlinear flight dynamics equations can be used for design maneuvers of a vehicle. The state representing of a desired maneuver is given as the problem of amounts to determining the engine thrust and the control surface forces permitting the realization of this maneuver. If the flight dynamics problem represents a time-dependent maneuver, such as the transition from one steady state to another, then the zero-order state and forces depend on time and the extended aeroelasticity state equations are time-varying, which precludes the standard stability analysis. However, the state equations still permit control design and response simulation. Dependence of the vehicle dynamical characteristics on time presents in Fig. 2. In this figure some open loop Bode diagrams for different stages of motion of the flexible vehicle with control system are shown.

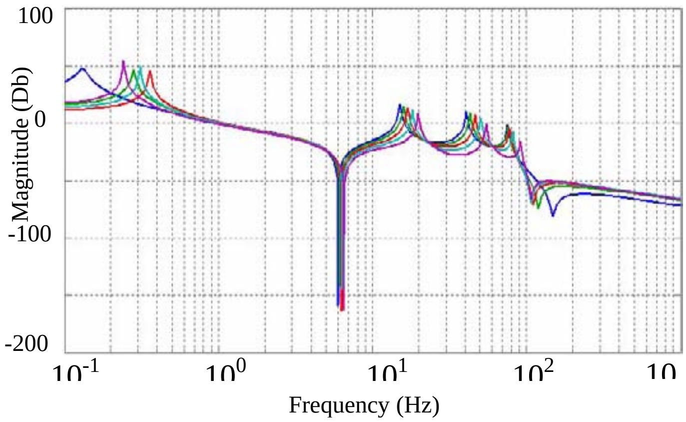

Fig.2. Open loop Bode diagrams for different points of time

The corresponding extended aeroelasticity problems are derived and used to design the feedback controls guaranteeing the vanishing of the rigid body perturbations and the elastic vibration, and hence the stability of the maneuver. The control design consists of a linear quadratic regulator in conjunction with a stochastic observer.

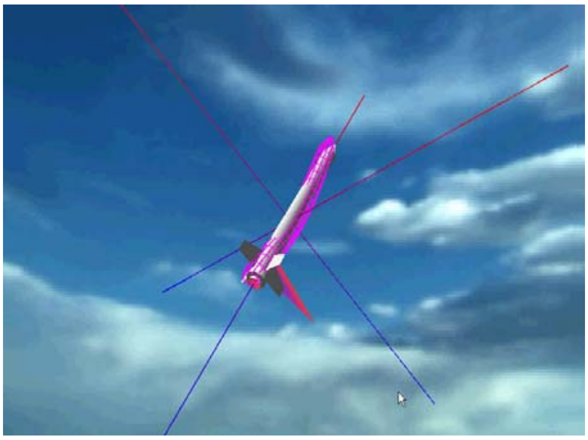

Fig. 3. Animation of flexible vehicle flight

All algorithms are realized in the program package. A fragment of animation of flexible oscillations in the vehicle flight is shown in Fig. 3.

6. CONCLUSIONS

The software for modeling of flexible vehicle motion, synthesis of control systems for such vehicle, research of dynamic properties by different methods in time and frequency domains, are developed and described in the paper.

The developed program allows solving the following problems:

- input of initial constructive data of vehicle,
- determination of controllability and observability for the full and simplified model of a vehicle,
- choice of flight program and control law,
- automatic linearization for arbitrary trajectory,
- robust control system synthesis,
- determination of bending modes and sloshing characteristics,
- choice of sensors and actuators characteristics,
- bode plots construction,
- choice of flight program and control law at simplified nonlinear model,
- determination of the elastic vibrations of a body and oscillation modes of liquid in tanks,
- study of control system sensitivity to vehicle parameters change,
- stability margins ranking.

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