GYROSCOPIC FORCES INFLUENCE ON AEROELASTICITY CHARACTERISTICS OF AN AIRPLANE WITH ENGINES ON PYLONS UNDER THE WING

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Abstract: The paper is devoted to development of a new method for aeroelasticity analysis with taking into account gyroscopic forces. The developed mathematical model is applicable for computation of dynamic aeroelasticity characteristics (eigenfrequencies and vibration forms, flutter, dynamic response in the frequency and time domain) in dependents on angular momentum of rotating rotor including case of elastic attachment of an engine on a pylon under the wing. The example of destabilizing influence of gyroscopic forces on flutter and aeroservoelasticity characteristics of an airplane with engines on pylons under the wing is described and analyzed.

1 INTRODUCTION

The engine rotor of the airplane, the screw of the helicopter is the gyroscope that has the considerable kinetic moment. Additional interaction appears at its vibrations between degrees of freedom the elastic structure and it can change the modal characteristics, appear the additional aerodynamic forces, and, as consequence, change the flutter characteristics.

There is considerable number of papers and articles about influence of gyroscopic forces, where the main attention is noted to so call “whirl flutter” (gyroscopic flutter of propellers and lifting rotors). As a rule, the stabilizing role of gyroscopic forces in "regular" lifting surface flutter analysis has been pointed out.

Research are accomplished in paper [6] on improvement of aeroelastic characteristics aircraft with the high aspect ratio wings by means the dispersion of elastic vibrations of wings in the damper inside aircraft by means of automatically controlled external and internal forces, including by means of gyroscopic effect. The tendency of increase the speed symmetric bending-torsion the wing flutter is noted at use of gyroscopic effect of the electric motor with damper for damping of precession vibrations at execution by it pitch vibrations.

In paper [7] influence on the wing flutter of gyroscopic forces from the engine rotor on a pylon under the wing without taking into account elasticity pylon is considered. The stabilizing role of gyroscopic forces in "regular" lifting surface flutter analysis has been pointed out.

The new approach has been developed for taking into account gyroscopic forces in aeroelasticity analysis with the use of polynomial Ritz method in the current paper. The Ritz method is widely used in computation of airplane aeroelasticity characteristics including case of elastic attachment of an engine on a pylon under the wing. The paper describes the computational algorithm in polynomial coordinates, and the generation of the equations of motion in modal coordinates with adding an antisymmetric matrix of gyroscopic forces to a damping matrix. The mathematical model obtained is applicable for computation of dynamic aeroelasticity characteristics (eigenfrequencies and vibration forms, flutter, dynamic response in the frequency and time domain) in dependents on angular momentum of rotating rotors.

2 ALGORITHM OF CALCULATION OF THE GENERALISED GYROSCOPIC FORCES IN POLYNOMIAL RITZ METHOD

The gyroscopic moment of forces acting on a structure at angular motion with the attached rotating aggregate is

$$M = -\Omega \times L, \tag{1}$$

where Ω is angular speed of point on the structure to which the rotating aggregate ("forced precession") is attached and L is kinetic moment of rotating aggregate.
Expression (1) is necessary for transforming to the generalized coordinates of polynomial method, and then to transform to modal coordinates, and to receive the additional generalized forces in the form:

$$Q_{gyr} = D_{0\,gyr}\,\dot{q} \tag{2}$$

where Q_{gyr} is a vector of the generalized forces in modal coordinates; $\dot{q}$ is a vector of speeds of modal generalized coordinates and $D_{0\,gyr}$ is the square matrix which determines gyroscopic forces.
Let's consider at first the right part of expression (1). In local system of coordinates of an elastic surface (ES) expression in a component of a vector the kinetic moment in case of arbitrary orientation looks like:

$$L = \begin{pmatrix} L_x \\ L_y \\ L_z \end{pmatrix} = I\omega_0 \begin{pmatrix} \cos\psi\, \sin\varphi \\ \sin\psi \\ \cos\psi\, \cos\varphi \end{pmatrix} \tag{3}$$

where I - the moment of inertia the rotating aggregate; ω_0 - is angular speed; ψ - a corner of orientation of the kinetic moment concerning a plane of an elastic surface; φ - a corner of a projection of the kinetic moment in a plane of an elastic surface.

Let's write expression for angular speed in polynomial coordinates. Let's remind structure of a vector of the generalized coordinates u. The vector consists of the blocks corresponding to elastic surfaces: u = col ($u^{(1)}$, $u^{(2)}$, … $u^{(m)}$), where superscript means number ES. Each block $u^{(j)}$ can include from 1 to 4 groups of the variables corresponding to normal deformations ES, to deflections rigid ailerons on this ES, motion in planes along local axis Ox and Oz.

Let's enter designations for convenience of the further discussion:

- For motion on a normal to ES $\quad w_y = \sum_n u_n(t) x^{p_n} z^{q_n}$
- For motion in the planes ES along axis Ox $\quad w_x = \sum_m v_m(t)\, z^{r_m}$
- For motion in the planes ES along axis Oz $\quad w_z$

Components of angular speed can be expressed in speeds of the generalized coordinates thus:

$$\begin{aligned}
\Omega_x &= \frac{\partial \dot{w}_y}{\partial z} = \sum_n q_n x^{p_n} z^{q_n - 1} \dot{u}_n \\
\Omega_y &= \frac{\partial \dot{w}_x}{\partial z} = \sum_m r_m z^{r_m - 1} \dot{v}_m \\
\Omega_z &= \frac{\partial \dot{w}_y}{\partial x} = \sum_n p_n x^{p_n - 1} z^{q_n} \dot{u}_n
\end{aligned} \qquad (4)$$

The given expressions can be presented in a matrix form as:

$$\Omega = \Phi \dot{u} \qquad (5)$$

Let's multiply from the left a vector of physical moment M on the transposed matrix of transition for transformation of a vector M to a vector generalized forces:

$$Q = \Phi^T M \qquad (6)$$

Let's receive link between speeds of the generalized coordinates and the generalized gyroscopic forces comparing expressions (3) - (6):

$$Q = D\dot{u},$$

where $D = \Phi^T (\Phi \times L)$. Vector product in brackets is calculated for each column of a matrix.

Further, transforming to modal coordinates *q*:

$$u = U q,$$

where *U* is a modal matrix, let's receive required expression of type (2) with a matrix:

$$D_{gyr} = U^T \Phi^T (\Phi \times L) \ U \qquad (7)$$

Let's enter following designations:

$f_k = x^{p_k} z^{q_k}$, k=1,.,n, $\quad g_k = z^{r_k}$, k=1,.,m

Here n - quantity degrees of freedom describing moving on a normal to an elastic surface, and m - in a plane of an elastic surface along axis Ox.
The matrix Φ made of corresponding coefficients of decomposition (4), has the next form:

$$\Phi = \begin{pmatrix}
\frac{\partial f_1}{\partial z} & \cdots & \frac{\partial f_n}{\partial z} & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 \\
0 & \cdots & 0 & 0 & \cdots & 0 & \frac{\partial g_1}{\partial z} & \cdots & \frac{\partial g_m}{\partial z} & 0 \\
\frac{\partial f_1}{\partial x} & \cdots & \frac{\partial f_n}{\partial x} & 0 & \cdots & 0 & 0 & \cdots & 0 & 0
\end{pmatrix}$$

Calculating vector product $(\Phi \times L)$ for each column of a matrix, we will receive for the general case the expression for a matrix of gyroscopic forces:

$$D_{\mathrm{gyr}} = \Phi^T \begin{pmatrix} -\frac{\partial f_1}{\partial x} L_y & \cdots & -\frac{\partial f_n}{\partial x} L_y & 0 & \cdots & 0 & \frac{\partial g_1}{\partial z} L_z & \cdots & \frac{\partial g_m}{\partial z} L_z & 0 \\ -\frac{\partial f_1}{\partial z} L_z + \frac{\partial f_1}{\partial x} L_x & \cdots & -\frac{\partial f_n}{\partial z} L_z + \frac{\partial f_n}{\partial x} L_x & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ \frac{\partial f_1}{\partial z} L_y & \cdots & \frac{\partial f_n}{\partial z} L_y & 0 & \cdots & 0 & -\frac{\partial g_1}{\partial z} L_x & \cdots & \frac{\partial g_m}{\partial z} L_x & 0 \end{pmatrix}$$

The received square matrix can present in the block form:

$$D_{gyr} = \left(\begin{array}{c|c|c|c} D_{11} & 0 & D_{13} & 0 \\ \hline 0 & 0 & 0 & 0 \\ \hline D_{31} & 0 & D_{33} & 0 \\ \hline 0 & 0 & 0 & 0 \end{array} \right)$$

D_{11} consists of elements $d_{ij} = \frac{\partial f_i}{\partial x}\frac{\partial f_j}{\partial z} L_y - \frac{\partial f_i}{\partial z}\frac{\partial f_j}{\partial x} L_y$ for $i \neq j$, where i =1...n, j=1...n

It can be seen that $d_{ij} = 0$ for $i = j$.

D_{13} consists of elements $d_{ij} = \frac{\partial f_i}{\partial z}\frac{\partial g_j}{\partial z} L_z - \frac{\partial f_i}{\partial x}\frac{\partial g_j}{\partial z} L_x$, where i =1...n, j=1+n+r... N-1

D_{31} consists of elements $d_{ij} = -(\frac{\partial f_j}{\partial z}\frac{\partial g_i}{\partial z} L_z - \frac{\partial f_j}{\partial x}\frac{\partial g_i}{\partial z} L_x)$, where j =1...n, i=1+n+r... N-1

Obvious that the block D_{33}=0.

Thus, the matrix of gyroscopic forces is antisymmetric. Formation of such matrix is programmed in system KC-M and it used for calculation of elastic vibrations frequencies out-flow, frequency and flutter characteristics

3 TEST EXAMPLE WITH THE SIMPLIFIED SCHEME OF AN ENGINE ROTOR

Test example of an elastically restrained engine rotor with two angular degrees of freedom was considered to verify the results obtained by Ritz method with taking into account of the gyroscopic forces. Parameters of a rotor and attaching rigidity are chosen close to the same parameters of the natural engine and pylon. The responses on angular motions from harmonious forces have been calculated by analytical formulas and by the program KC-M at different values of the kinetic moment for such a case. The results coincidence shows on the correct work of the program KC-M with taking into account of gyroscopic forces.

Also eigenfrequencies of model of an engine rotor are calculated. The received dependences of eigenfrequency from the kinetic moment are shown on Figure 1.
Frequency of pitch engine vibrations decreases from 5.1 Hz to 4 Hz with increase the kinetic moment, frequency of yaw vibrations increases from 8 Hz to 10.2 Hz.

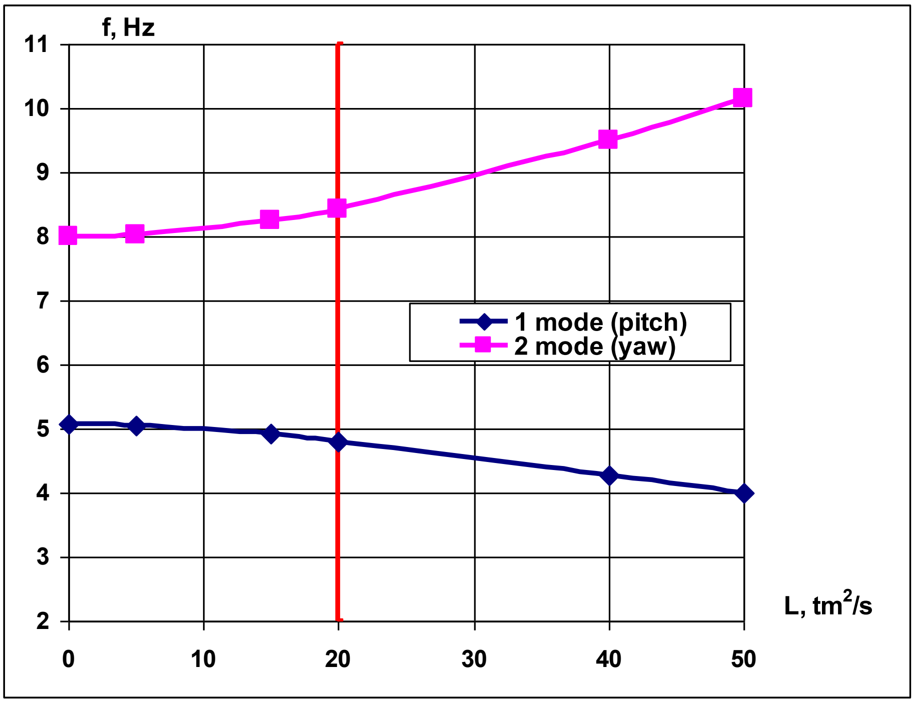

Figure 1: Dependence of vibrations frequencies on the engine kinetic moment

4 GYROSCOPIC FORCES INFLUENCE ON ELASTIC VIBRATION FREQUENCIES OF THE REGIONAL AIRPLANE

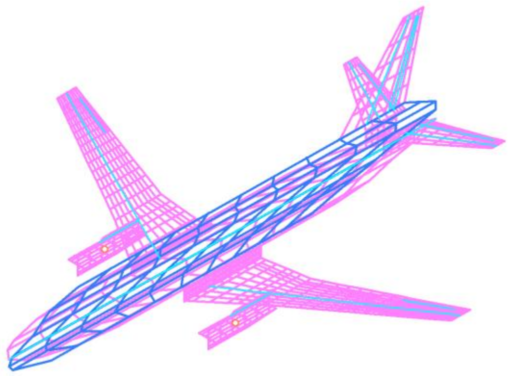

Figure 2: Analysis model regional the airplane

The model of the regional airplane (Figure 2) was used for performance of the further researches. Calculation of elastic vibrations frequencies of the plane with engines on pylons under a wing for rotations of the engine from 0 to 20000 r.p.m was carried out.

On Figure 3 it is shown that frequencies of pitch engine vibrations (5.1 Hz for symmetric and 6.7 Hz for antisymmetric) decrease approximately by 0.2 Hz with increase the kinetic moment. The frequencies of yaw vibrations increase approximately by 0.4 Hz with increase the kinetic moment. Thus, results are qualitative coincided with results of a test problem. Quantitative difference is caused by that engine vibrations in the analysis model of the airplane are not pure vibrations of pitch and yaw, and include deformations of other parts of the construction.

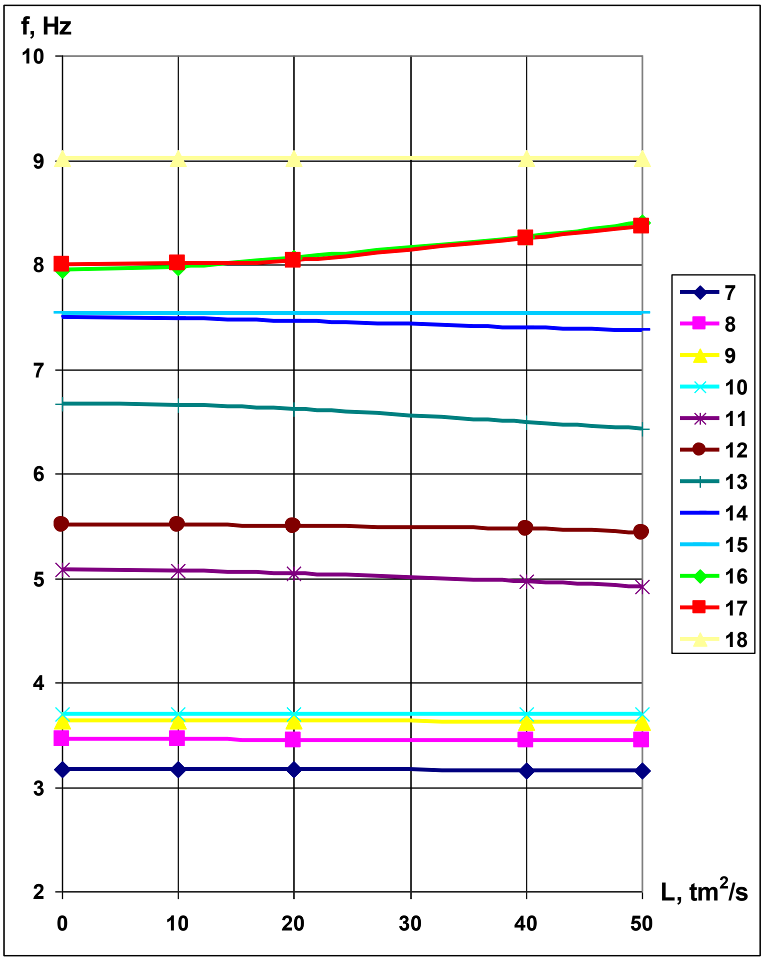

Figure 3: Dependence of elastic vibrations frequencies on the engine kinetic moment

5 INFLUENCE OF GYROSCOPIC FORCES ON FLUTTER

Calculation on flutter for regional airplane is accomplished for various rotations of the engine. Calculations are carried out for Mach number M=0.77. A set of reduced frequencies Sh=0.001, 0.5, 1.2, 1.5, 2, 3 are chosen for determination of non-stationary aerodynamic forces. The speed range considered in analysis is from 0 to 425 m/s.

The kinetic moment dimension on figures for all computation cases is tm^2/s. The maximum reduced rotations of the engine 7800 r.p.m corresponds kinetic moment L=20 tm^2/s.

Critical flutter speed at L=0 appears at interaction of the tenth and eleventh modes of eigen vibrations (bending vibrations of a wing and pitch engine vibrations) by frequency f = 5 Hz and V_{FL} = 248 m/s. Flutter arises by frequency f = 8.3 Hz and V_{FL} = 414 m/s (bending-torsional vibrations of a tip part of a wing) at higher speeds. Calculations have shown that the flutter speed decreases approximately by 1-2 % (Figure 4,6) when the kinetic moment increases. Parametrical analysis on flutter was accomplished also for the increased range values L. The flutter speed decreases approximately by 10 % (Figure 5,6) then increases a little and at L≥173 tm^2/s disappears when the kinetic moment increases.

Such effect is caused by redistribution of an engine vibration energy between the pitch and yaw motion due to action of gyroscopic forces. Besides, in this case the interaction between the engine vibrations and bending-torsion wing deformations, which determines flutter characteristics, is changed too.

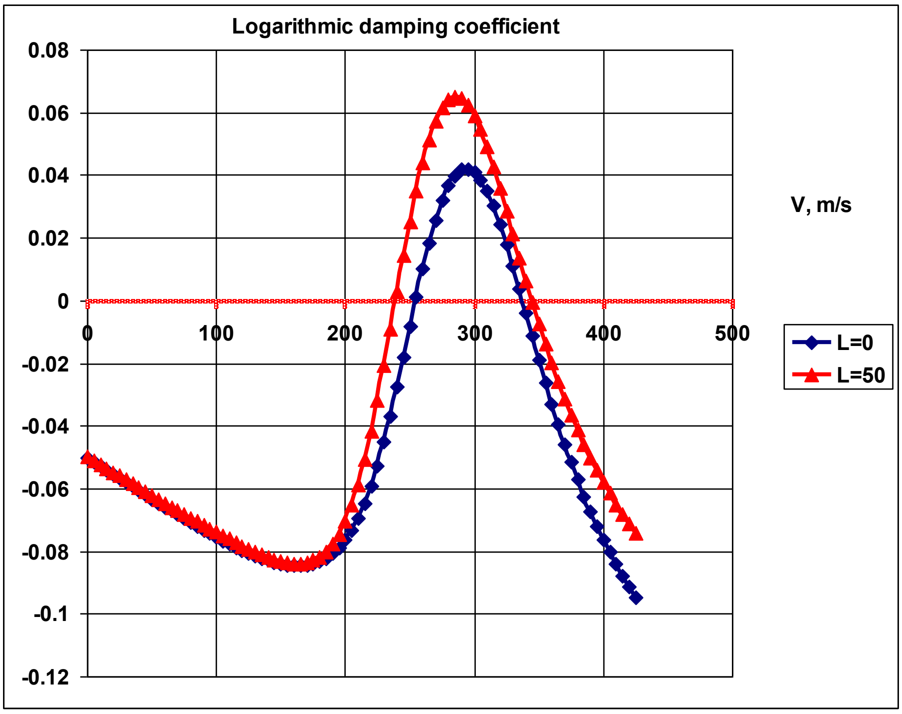

Figure 4: Dependence of flutter mode damping coefficient on the flow speed

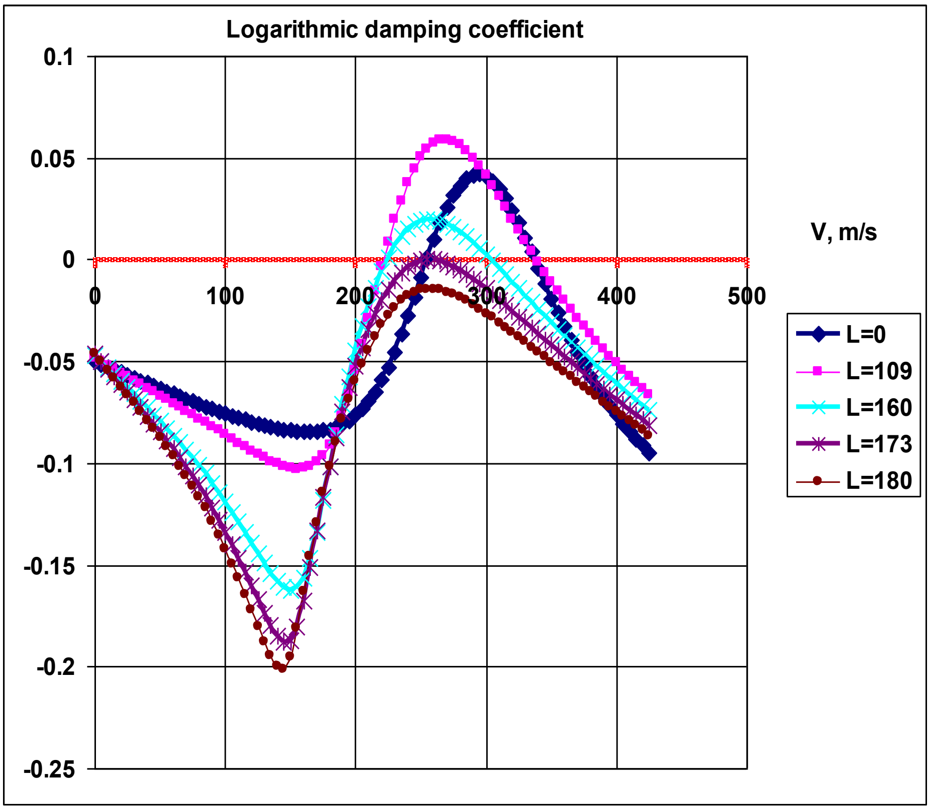

Figure 5: Dependence of flutter mode damping coefficient on the flow speed

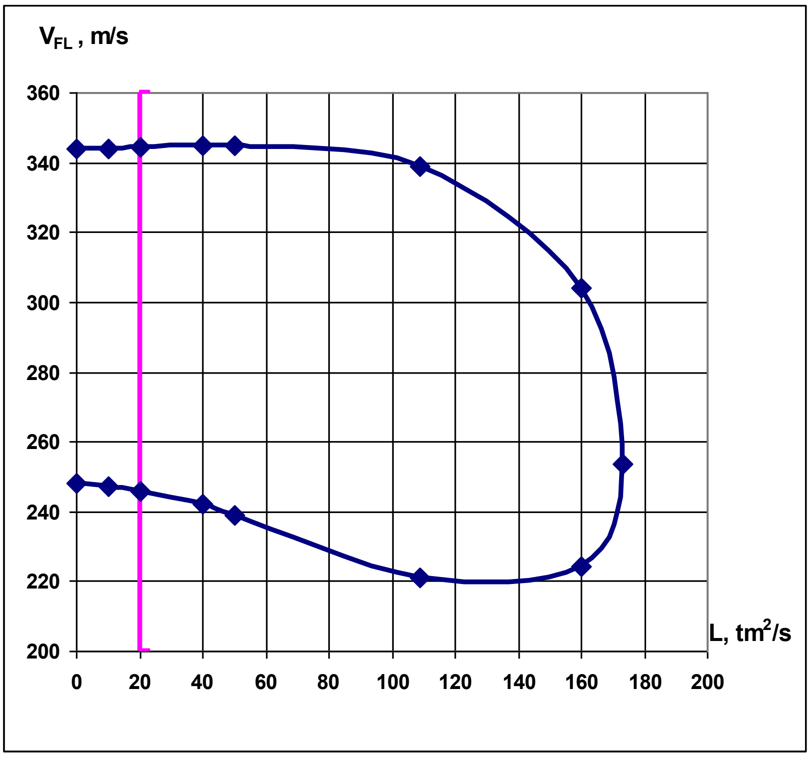

Figure 6: Dependence of flutter speed on the engine kinetic moment

The characteristic flutter depend on vertical engine vibrations frequency with which reduction flutter speed also decreases for this airplane. This influence on flutter is identified separately for the purpose of additional interaction identification between pitch and yaw (varying pitch pylon rigidity) (Figure 7). Flutter speed decreases approximately down to 220 m/s with a variation of the kinetic moment, and at a variation pitch pylon rigidity - down to 237 m/s (Figure 8). As it can be seen, double contribution is observed from gyroscopic forces influence on flutter speed. Thus, the calculation of change vibrations forms makes additional contribution on change flutter speed.

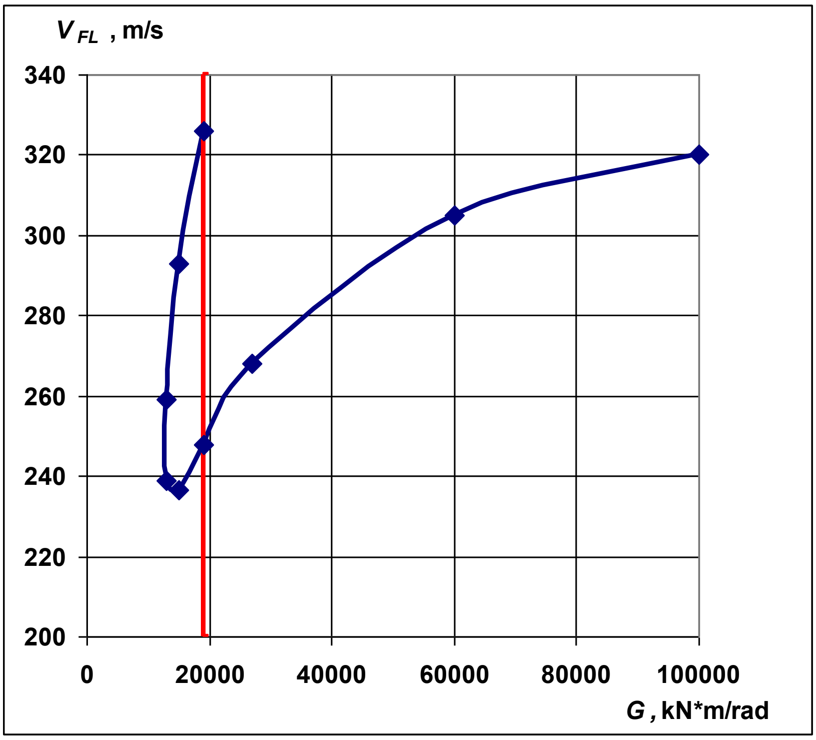

Figure 7: Dependence of flutter speed on the pitch pylon rigidity

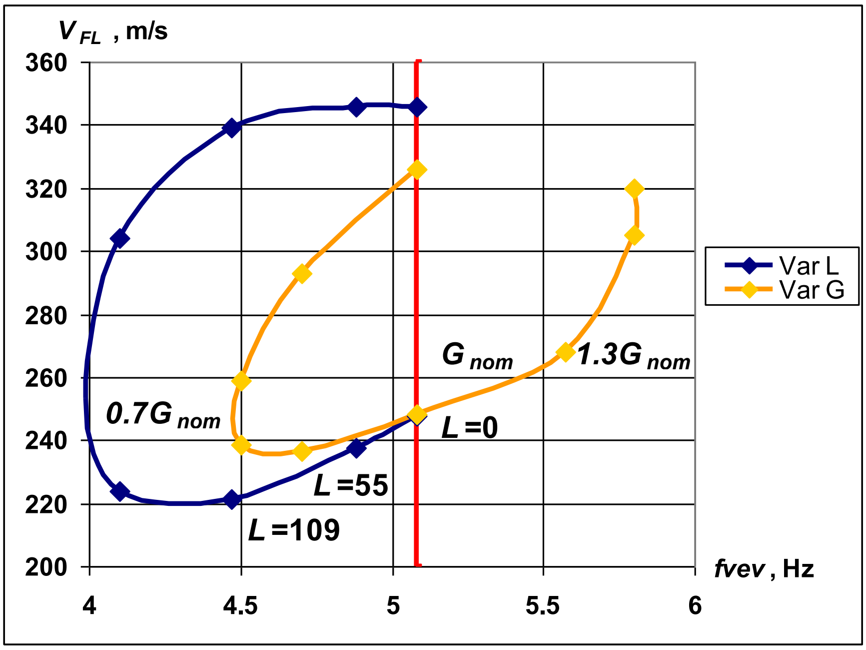

Figure 8: Dependence of flutter speed on the "vertical" engine vibrations (VEV) frequency at the variation pitch pylon rigidity and at the variation of the kinetic moment

6 GYROSCOPIC FORCES INFLUENCE ON FREQUENCY RESPONSE OF THE AIRPLANE

Calculations of frequency response on load factor and on angular speed in the place of location of the control system transducers around the cabin at harmonious influence on an elevator at different speeds of a stream are carried out for studying of dynamic characteristics of the airplane without Flight Control System. Flight Speed from 0 to 425 m/s are considered.

Essential responses of a structure on an elevator without gyroscopic forces are observed in ranges of frequencies 5 Hz (pitch engine vibrations) and 7.5 Hz (a vertical bend of the fuselage).

The pitch response essentially damped and moves in the direction of low frequencies, the bend response small decreases at increase of the kinetic moment. Thus, results are coincided with results of the modal analysis.

7 GYROSCOPIC FORCES INFLUENCE ON FLUTTER WITH FLIGHT CONTROL SYSTEM AND AEROELASTIC STABILITY MARGIN

Block diagram of the FCS longitudinal channel is shown on Figure 9. Actuator control device is the elevator. The vertical load factor n_y and pitch rate ω_z signals are input for the elevator actuator after corresponding filters and coefficient. Values of coefficient for limit speed are chosen at M=0.77.

The software package FRECAN was used for the analysis of stability of the open loop and the margin of aeroelastic stability. It was found that the margins of aeroelastic stability with FCS at the big flight speeds can decrease with taking into account gyroscopic forces.

The flutter speed decreases approximately by 1-2 % (Figure 10,12) when the kinetic moment increases. It is observed damped influence FCS at all values of the kinetic moment (Figure 11). From presented on Figure 13 and Figure 14 FR the open loop for the longitudinal channel follows that the margins of aeroelastic stability with FCS small change for limit flight speed and for the speed close to flutter.

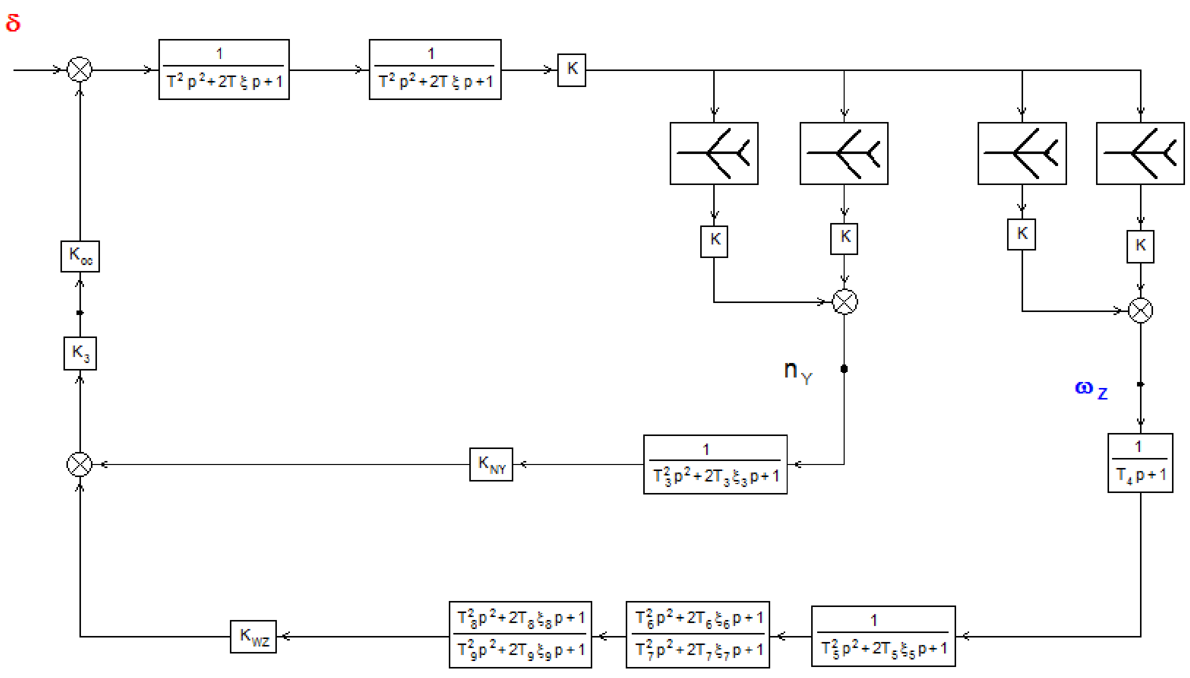

Figure 9: Block diagram of the FCS longitudinal channel

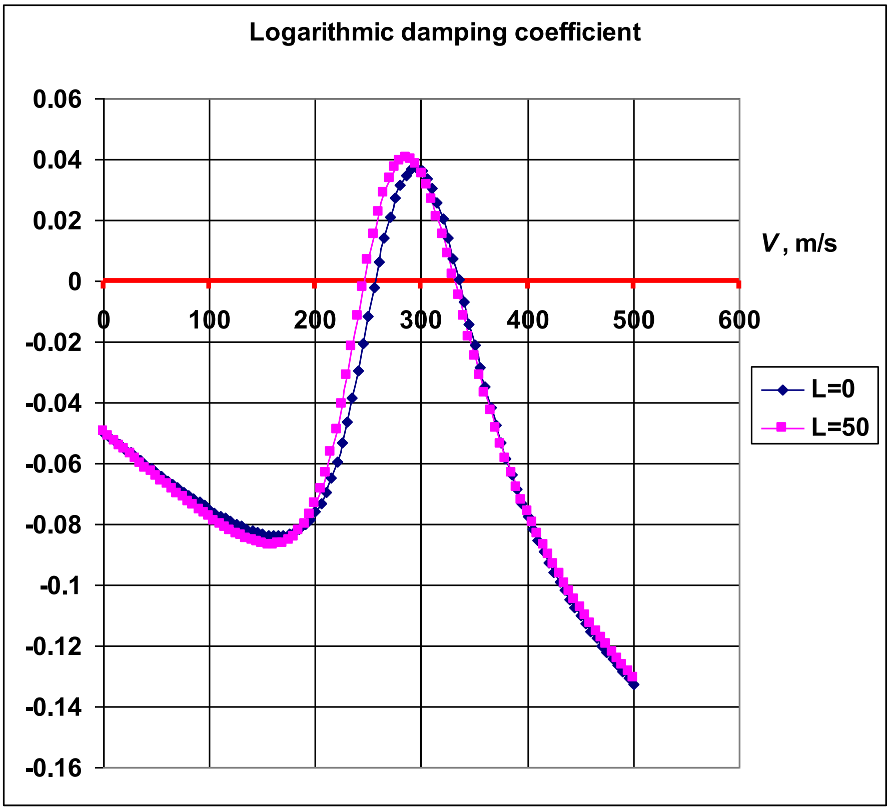

Figure 10: Dependence of flutter mode damping coefficient on the flow speed with FCS

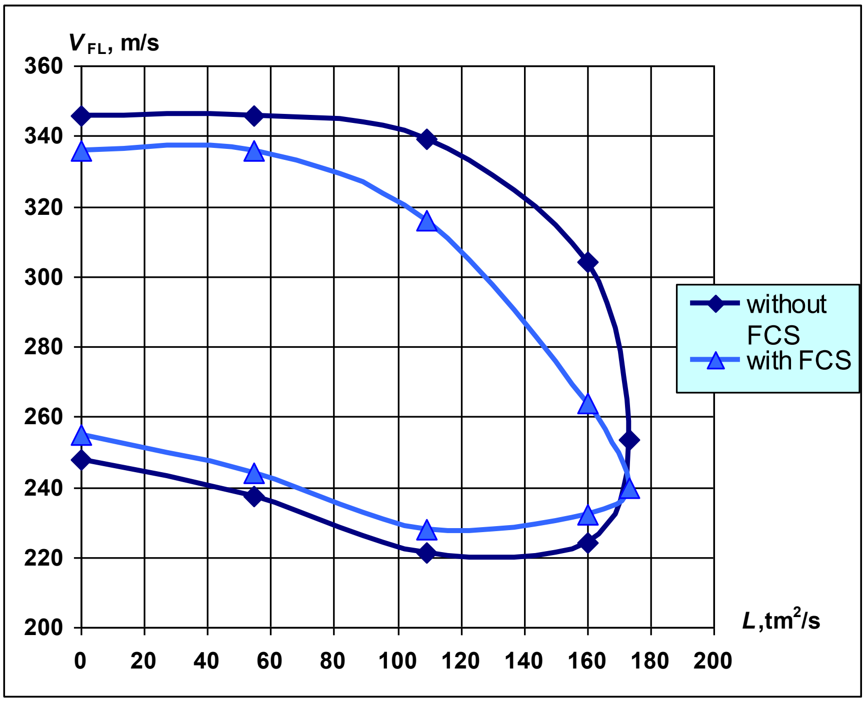

Figure 11: Dependence of flutter speed on the engine kinetic moment

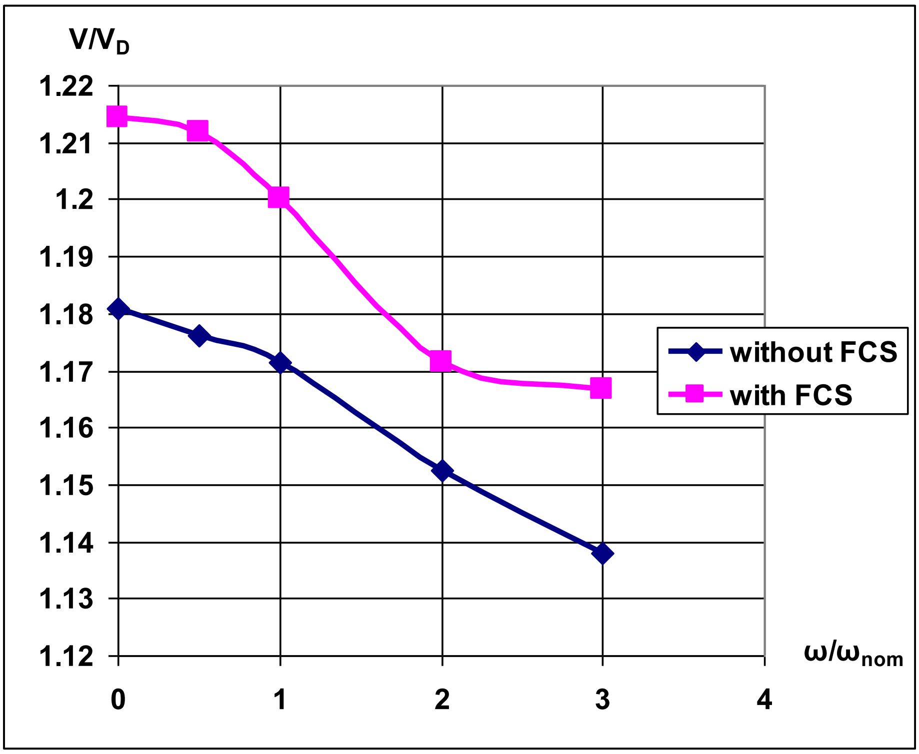

Figure 12: Dependence of the relative flutter speed on the relative angular speed

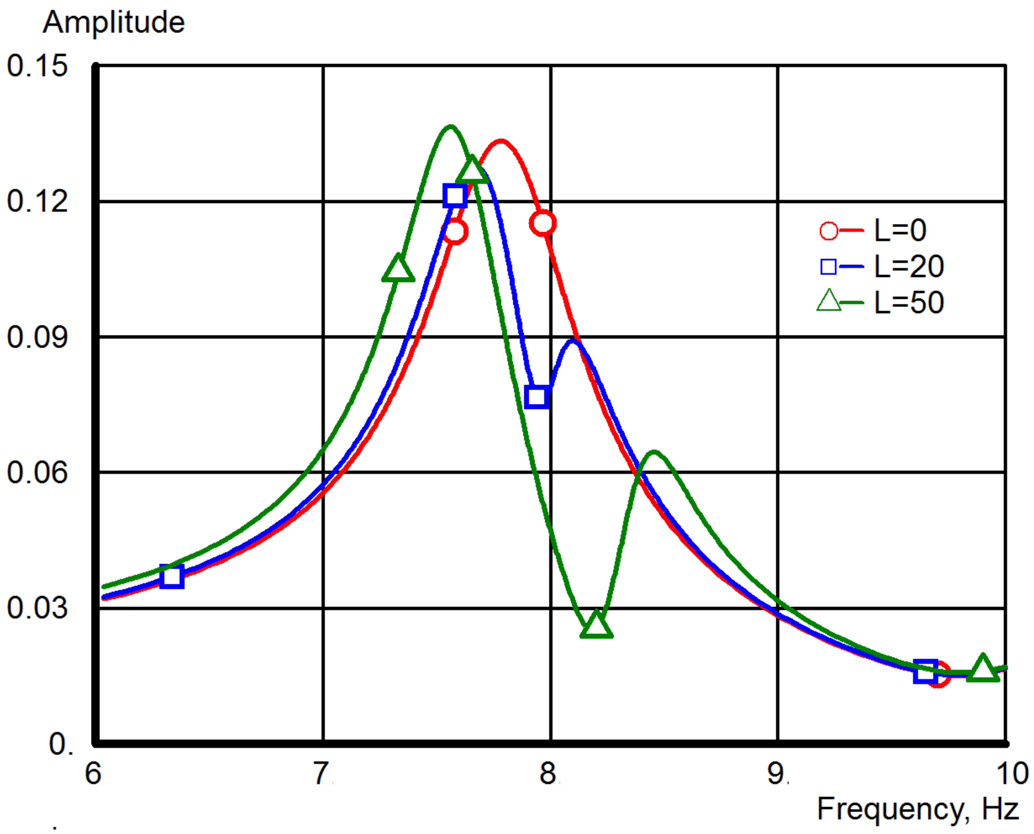

Figure 13: Open loop FR for the longitudinal channel at V=210 m/s for different value of the engine kinetic moment L [tm^2/s]

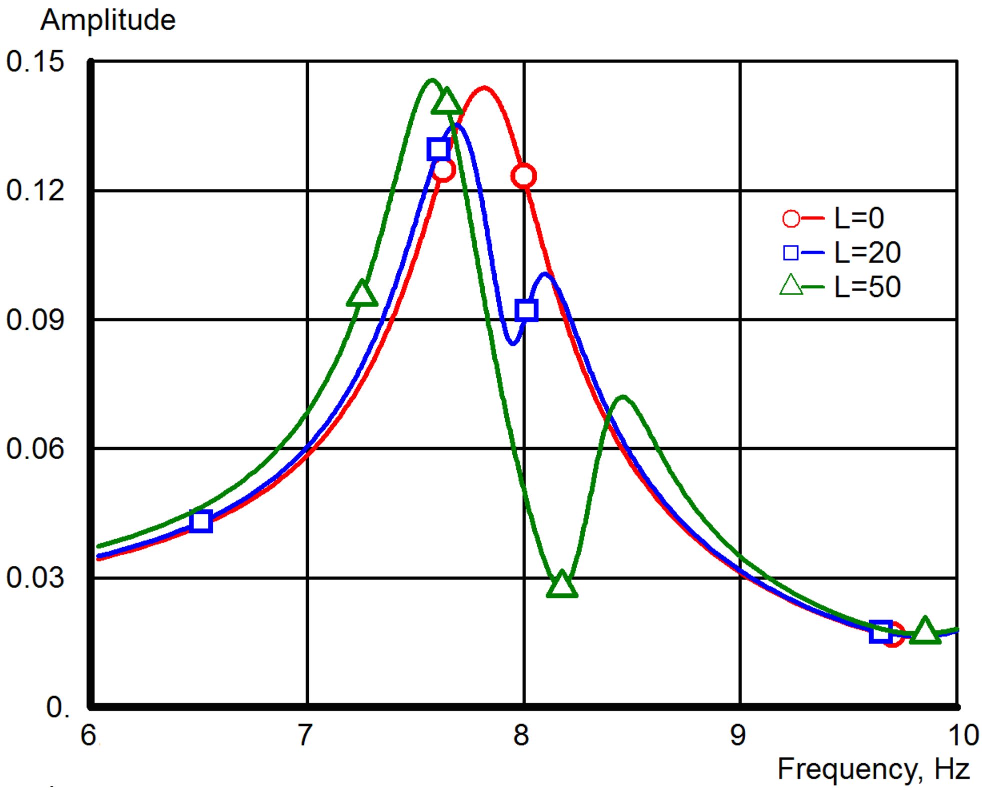

Figure 14: Open loop FR for the longitudinal channel at *V*=225 m/s for different value of the engine kinetic moment *L* [tm^2/s]

8 CONCLUSION

· The algorithm of the gyroscopic forces calculation in Ritz method for system KC-M is developed and realized.

· The results verification with taking into account of the gyroscopic forces obtained by various methods is carried out.

· Researches of the gyroscopic forces influence on frequencies of elastic vibrations, flutter characteristics and aeroservoelasticity are carried out.

· The received results show small negative influence of gyroscopic forces on dynamic stability of the airplane.

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