INERTIA FORCES ROLE IN STATIC AEROELASTICITY

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Abstract

The inertia forces influence on aerodynamic characteristics of elastic aircraft is considered. Simple computational model was created and investigated, which demonstrates clearly the main relations of the influence of inertia forces and mass distribution on aerodynamic derivatives. Some mass-inertia characteristics influence on roll control effectiveness is shown for a heavy transport airplane. Method of wind tunnel experimental estimation of aerodynamic derivatives with respect to load factor is discussed.

1 Introduction

The influence of inertia forces and mass distribution on aerodynamic coefficients derivatives of elastic aircraft was considered by many researchers [1-3]. Mainly the attention was paid to inertia forces due to normal load factor and to derivatives of coefficients in longitudinal motion. Equations including angular accelerations and side load factor were derived with different fidelity but they were studied insufficiently.

A few aspects causing the relevance of today's study of inertia forces role in static aeroelasticity can be marked:

- correct transformation of results obtained in wind tunnel (WT) on fixed model for full scale free structure;
- use of inertia forces in "active aeroelasticity" concept;
- increase of requirements to the accuracy of stability and controllability characteristics to ensure the efficiency and safety of flight.

This paper presents some theoretical aspects and results of computational investigations. Main attention was paid to inertia forces conditioned by pitch and roll angular acceleration, which practically haven't been researched in the previous works. Experimental estimation of aerodynamic derivatives with respect to accelerations was also considered.

2 Role of inertia forces for aerodynamic characteristics of free structure: essence of phenomenon

Influence of mass distribution on lift slope of free (unrestrained) elastic structure is conditioned by the fact that the lift increment due to change of angle of attack causes the increment of acceleration (load factor), and additional structural deformations arises due to the acceleration. Naturally, those additional deformations (and consequently additional redistribution of aerodynamic load) depend on mass distribution. Let us consider this phenomenon in details.

Lift L for a fixed structure with angle of attack α is equal to:

$$L = qS(c_{L0} + c_L^{\alpha}\alpha + c_L^{\delta}\delta + c_L^{n_z} n_z), \qquad (1)$$

when n_z=1. Here q is the dynamic pressure, S is the reference area, c_L is the lift coefficient, α, δ are the angle of attack and the angle of deflection of control surface, correspondingly. The term $c_L^{n_z} n_z$ is the additional lift conditioned by the static deflection of elastic structure under the weight influence. Increment of lift has the following value under the change of angle of attack (as the load factor has no change):

$$\Delta L = qSc_L^{\alpha}\Delta\alpha \ . \qquad (2)$$

Lift for free structure in horizontal flight is also given by the expression (1). When the angle of attack is varied on $\Delta\alpha$ (for instance, during the penetration to the vertical gust), load factor is also varied. Let's consider the initial moment, when the angular rate has not arisen and the control surfaces have no deflection. Then

$$\Delta L_{free} = qS(c_L^{\alpha}\Delta\alpha + c_L^{n_z}\Delta n_z), \qquad (3)$$

and the load factor change is conditioned by the influence of the same lift increment:

$$\Delta n_z = \frac{\Delta L_{free}}{mg} \qquad (4)$$

It can be obtained the expression for the lift increment of free airplane under the change of angle of attack by substitution of (4) in (3):

$$\Delta L_{free} = qS\frac{c_L^{\alpha}}{1-\frac{qS}{mg}c_L^{n_z}}\Delta\alpha \qquad (5)$$

Comparing (2) and (5) one can see that the lift increment for free airplane differs on coefficient $1-\frac{qS}{mg}c_L^{n_z} = 1 - c_L^{n_z}/c_{L\,trim}$, where $c_{L\,trim}$ is the trim value of lift coefficient during the horizontal flight. It is reasonable to introduce the definition of lift coefficient derivative for "free airplane" (or "with mass distribution consideration" or "weighty airplane"):

$$c_{L\,free}^{\alpha} = \frac{c_{L\,fixed}^{\alpha}}{1-qSc_L^{n_z}/mg} = \frac{c_{L\,fixed}^{\alpha}}{1-c_L^{n_z}/c_{L\,trim}} \qquad (6)$$

Let us consider first the generalization of expression (6) for the other aerodynamic coefficients and their derivatives, and then the mechanism of inertia forces influence on static aeroelasticity characteristics for a simple computational model.

3 Analysis of inertia forces influence on aerodynamic derivatives

Aforesaid reasoning can be repeated for the common case of the lifting force increment caused by the change of any other parameters, such as control surface deflection, angular rate arising, change of setting angle or wing twist. If a fixed structure obtains the lift increment ΔL_{fixed} due to some disturbance, the same disturbance causes the following lift increment for a free structure: $\Delta L_{free} = \Delta L_{fixed} + L^{n_z}\Delta n_z$, when $\Delta n_z = \Delta L_{free}/mg$. Consequently, the expression $\Delta L_{free} = \Delta L_{fixed}/(1-L^{n_z}/mg)$ is true for all type of disturbances, and the analogue of expression (6) can be written for all components of lift coefficient $L = qS(c_{L0} + c_L^{\alpha}\alpha + c_L^{\omega_y}\omega_y + c_L^{\delta}\delta)$, for example:

$$c_{L0\,free} = \frac{c_{L0\,fixed}}{1-c_L^{n_z}/c_{L\,trim}}, \quad c_{L\,free}^{\omega_y} = \frac{c_{L\,fixed}^{\omega_y}}{1-c_L^{n_y}/c_{L\,trim}},$$

$$c_{L\,free}^{\delta} = \frac{c_{L\,fixed}^{\delta}}{1-c_L^{n_z}/c_{L\,trim}}.$$

The same reasoning can be done for the side force coefficient and analogous expression can be obtained, for example:

$$c_{y\,free}^{\beta} = \frac{c_{y\,fixed}^{\beta}}{1-qSc_y^{n_y}/mg},$$

where β is a sideslip angle, $c_y^{n_y}$ is the derivative of side force coefficient with respect to lateral load factor.

The increment of pitch moment of free airplane can be written as $\Delta M_{y\,free} = \Delta M_{y\,fixed} + M_y^{n_z}\Delta n_z$. One can obtain the expression for pitch moment coefficient of a free airplane by substitution of expression (4) for load factor increment:

$$m_{y\,free} = m_{y\,fixed} + \frac{qS}{mg}m_y^{n_z}c_{L\,free},$$

from which the expressions for corresponding derivatives are obtained.

Further generalization includes inertia forces connected with the angular acceleration. In the case of longitudinal motion it is necessary to analyze simultaneously the equation of forces and equation of moments. Taking into account angular pitch acceleration $(\dot{\omega}_y)$, relation between characteristics of free and fixed structures can be expressed as:

$$\Delta L_{free} = \Delta L_{fixed} + L^{n_z}\Delta n_z + L^{\dot{\omega}_y}\Delta\dot{\omega}_y$$

$$\Delta M_{y\,free} = \Delta M_{y\,fixed} + M_y^{n_z}\Delta n_z + M_y^{\dot{\omega}_y}\Delta\dot{\omega}_y\,,$$

when $\Delta n_z = \Delta L_{free}/mg$, $\Delta\dot{\omega}_y = \Delta M_{y\,free}/I_y$, where I_y is the inertia moment relative to Oy axis. Combining these expressions one can obtain a system of two equations for two unknown coefficients of lift and pitch moment of free structure:

$$\begin{aligned}&\left(1-\frac{qS}{mg}c_L^{n_z}\right)c_{L\,free} - \\ &-\frac{qSc_{MAC}^2}{I_y g}c_L^{\bar{\dot{\omega}}_y}m_{y\,free} = c_{L\,fixed}\,, \\ &-\frac{qS}{mg}m_y^{n_z}c_{L\,free} + \\ &+\left(1-\frac{qSc_{MAC}^2}{I_y g}m_y^{\bar{\dot{\omega}}_y}\right)m_{y\,free} = m_{y\,fixed}\,,\end{aligned} \tag{7}$$

where c_{MAC} is a mean aerodynamic chord, $c_L^{\bar{\dot{\omega}}_y}$, $m_y^{\bar{\dot{\omega}}_y}$ are the derivatives of coefficients of lift and pitch moment with respect to reduced pitch angular acceleration $\bar{\dot{\omega}}_y = \dot{\omega}_y c_{MAC}/g$.

Inertia forces influence for roll motion is presented by angular acceleration $\dot{\omega}_x$: $\Delta M_{x\,free} = \Delta M_{x\,fixed} + M_x^{\dot{\omega}_x}\Delta\dot{\omega}_x$, $\Delta\dot{\omega}_x = \Delta M_{x\,free}/I_x$. Therefore derivatives of free structure for roll moment coefficient can be written:

$$\begin{aligned}m_{x\,free}^{\delta} &= m_{x\,fixed}^{\delta}\Big/\left(1-qSb^2 m_x^{\bar{\dot{\omega}}_x}\big/2I_x g\right) \\ m_{x\,free}^{\bar{\omega}_x} &= m_{x\,fixed}^{\bar{\omega}_x}\Big/\left(1-qSb^2 m_x^{\bar{\dot{\omega}}_x}\big/2I_x g\right)\end{aligned}\,, \tag{8}$$

Here $m_x^{\bar{\omega}_x}$, $m_x^{\bar{\dot{\omega}}_x}$ are roll moment coefficient derivatives with respect to reduced roll rate ($\bar{\omega}_x = \omega_x b/2V$) and reduced roll acceleration ($\bar{\dot{\omega}}_x = \dot{\omega}_x b/2g$), V is a flight speed, b is a reference span.

In common case the interconnection of accelerations and deformations on different degrees of freedom can arise. The most common case (for linear approximation and symmetrical structure) includes the interaction of accelerations and deformations on three rigid body degrees of freedom, and on control deflections both in longitudinal and lateral motions. Different methods for computation of behavior of elastic structure in airflow are used to calculate such interaction. One of such used in TsAGI methods is presented below.

4 Analysis of elastic airplane aerodynamic derivatives by polynomial method

Several approaches have been elaborated in TsAGI to calculate the airplane static aeroelasticity characteristics. The most advanced and often-used approaches are the influence coefficients method [4] and the approach on the base of equations of polynomial method [5]. The first one is more convenient for parametric investigations of control surfaces effectiveness and for correction using experimental data; the second approach takes the inertia forces influence into consideration more precisely. The main items of aerodynamic derivatives calculation for the second approach are presented below.

Ritz's method is used, when the structure displacements are represented as polynomial function of spatial coordinates. The whole structure is modeled as a set of thin, initially plane elastic surfaces (ES), which can be placed in space arbitrarily and parallel to stream-wise direction. Distribution of mass and stiffness is given for each of these elastic surfaces. Different types of elements are used for schematization of a real structure: concentrated masses, bending and torsion beams, panels, plates, etc. Local coordinate systems for each elastic surface are chosen to obtain the coincidence of $x0y$ plane with ES plane. Normal deformation $W(x,y,t)$ of elastic surface is presented as:

$$W(x,y,t) = \sum_{k=1}^{N} f_k(x,y)u_k(\mathrm{t})\,,$$

where $f_k(x,y) = x^{m_k}y^{n_k}$, $m,n = 0,1,...$

For each elastic surface the proper polynomial can be chosen. Coefficients $u_k(t)$ are the generalized coordinates for polynomial method. ES motion and deformation in its plane is given by additional generalized coordinates.

Elastic surfaces are assembled in a united computational model by using of elastic or elastic-viscous connections, which allow modeling of different attachment conditions in points of ES joint between each other with required level of accuracy. The mass matrix is block-diagonal for assembled vector of generalized coordinates; blocks are corresponded to elastic surfaces. Stiffness matrix and structural damping matrix are full in common case due to elastic or elastic-viscous connections.

Doublet-lattice method or panel methods are used for aerodynamic forces calculation. For static aeroelasticity either steady case or unsteady one with low Strouhal numbers (reduced frequency) are considered (for more precise estimation of derivatives with respect to angular rates).

Longitudinal motion with symmetrical deformations and lateral motion with antisymmetrical deformations are considered separately. Equations of motion can be presented in matrix form:

$$C\ddot{u} + VD\dot{u} + (V^2B + G)\,u = Q_0 \qquad (9)$$

Here u is the assembled vector of generalized coordinates;

V is the flow speed;

C, D, B, G are the matrices of inertia, aerodynamic damping, aerodynamic stiffness and structural stiffness;

Q_0 is the vector of generalized forces, which are independent on generalized coordinates; in this case the forces caused by twist and camber of lifting surfaces are considered.

Special transformation of generalized coordinates is fulfilled to solve the problem of static aeroelasticity:

$$u = X\begin{pmatrix} u_1 \\ u_2 \end{pmatrix},$$

where u_1 is a vector describing an airplane rigid body motion and deflection of control surfaces, u_2 describes the elastic deformations; X is the square nonsingular matrix of transformation. Choice of variables belonging to vector u_1 is one of the most important tasks in aeroelasticity. For example, elasticity influence on aerodynamic characteristics greatly depends on how and in what section of structure the angle of attack is determined. Usually the angle of attack is determined as an angle between the stream-wise direction and the tangent to one of ES close to the airplane center of mass. The deflection angle of elastic control surface is determined as an angle between the tangents to basic and control surfaces in section, in which the actuator is places.

Aeroelasticity equation (9) can be written in matrix-block form under quasi-steady approximation without taking into consideration inertia and damping forces caused by elastic deformations u_2:

$$\left[\begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix} + \begin{pmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{pmatrix}\right]\begin{pmatrix} u_1 \\ u_2 \end{pmatrix} =$$

$$= -\begin{pmatrix} D_{11} \\ D_{21} \end{pmatrix}\dot{u}_1 - \begin{pmatrix} C_{11} \\ C_{21} \end{pmatrix}\ddot{u}_1 + \begin{pmatrix} Q_{01} \\ Q_{02} \end{pmatrix}$$

Vector u_1 can be presented as $u_1 = (u_x, u_z, \alpha, \delta)^T$ for longitudinal motion and $u_1 = (u_y, \gamma, \beta, \delta)^T$ for lateral motion. Blocks of matrixes B_{11}, D_{11} include aerodynamic derivatives of a rigid airplane. Vector u_2 from the second equation is substituted to the first one to obtain the same blocks with quasi-steady account of structure elasticity:

$$(C_{11} - B_{12}P_0)\ddot{u}_1 =$$

$$= -(B_{11} + G_{11} - B_{12}P_2)u_1 - (D_{11} - B_{12}P_1)\dot{u}_1 +$$

$$+(Q_1 - B_{12}ZQ_2).$$

Here $P_0 = ZC_{21}$; $P_1 = ZD_{21}$; $P_2 = ZB_{21}$; $Z = (B_{22} + G_{22})^{-1}$.

To find the correspondence between equation coefficients and aerodynamic derivatives it is necessary to transform the equation to the "normal" view, when the term $C_{11}\ddot{u}_1$ is in the left part. It can be done by two methods. The first one is to move the term $B_{12}P_0\ddot{u}_1$ to the right part. This term describes the influence of inertia forces on aerodynamic coefficients of elastic airplane; other terms in the right part of the equation are corresponded to aerodynamic derivatives without inertia forces account. Characteristics obtained by such method are corresponded to the "weightless" airplane. The second method is to multiply the equation from the left by matrix $C_{11}(C_{11} - B_{12}P_0)^{-1}$. In this case there are no derivatives with respect to accelerations; aerodynamic derivatives take into account the elastic deformations due to inertia forces, they are corresponded to characteristics of "weighty" airplane. Co-consideration of both type derivatives allows estimating of mass distribution influence (including the other, non-considered variants of loading) on static aeroelasticity characteristics.

Nondimensional aerodynamic derivatives depending on dynamic pressure under different Mach number are calculated for estimation of divergence and reversal characteristics. Increase of some derivatives (for example, c_L^α,...) evidences about the divergence tendency; decrease of control derivatives (for example, m_x^δ) evidences about the reversal tendency. Estimation of structure elasticity influence on aerodynamic characteristics is done by relative values ξ, which are the ratios of elastic airplane aerodynamic coefficients derivatives to the same characteristics of the "rigid" airplane ($\xi_{c_L^\alpha} = c^\alpha_{L\ elast} / c^\alpha_{L\ rig}$,...); for aerodynamic center relative displacement $\Delta\bar{x}_F = \bar{x}_{F\ elast} - \bar{x}_{F\ rig}$ is used. Influence of control actuator stiffness on characteristics of stability and controllability is investigated separately.

5 Simple computational model

Relations discussed above in items 2, 3 are illustrated on the basis of a simple computational model to make clear the main principles of inertia forces influence on aerodynamic characteristics of elastic structure.

Non-deformable lifting surface with chord c=2m and length (along span) b=3m is considered. Deflectable control surface (aileron) is located along the whole trailing edge. Mass of structure is m=250 kg; moments of inertia I_x=180 kg×m^2, I_y=80 kg×m^2; relative position of center of mass from the leading edge $X_m=X_M/c$ varies from 0.2 to 0.6. Lifting surface is attached to the weightless, non-lifting beam on the distance 0.33c from the leading edge (Fig. 1). If a fixed structure is considered it is fixed in point 1. Distance from point 1 to the middle of lifting surface b/2=10 m. The beam itself is non-deformable; attachment of lifting surface to the beam is elastic with rotation stiffness G_z =100 kN×m/rad in point 2 (Fig. 1). Such structure can be considered as the wing compartment with aileron.

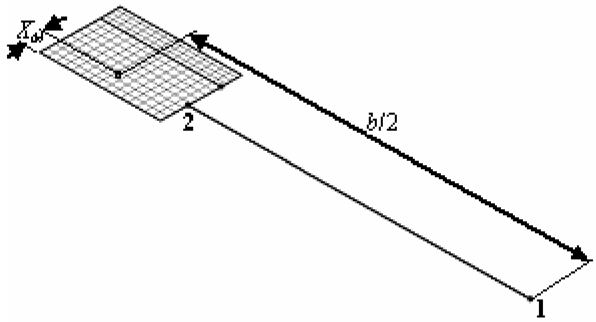

Fig. 1. Computational scheme of wing compartment

To use the computational formulas, algorithms and programs of airplane static aeroelasticity characteristics calculation it is suggested that the second symmetrical part of structure exists. It is symmetrical relative to the plane passing through the point 1 and perpendicular to the beam. Therefore the reference area S=12 m^2, chord c_{MAC}=2 m and wing-span b=20 m are used for calculation of nondimensional aerodynamic coefficients.

Simplicity of structure allows easy obtaining of formulas for aerodynamic derivatives with respect to accelerations, which are exceedingly complicated for analysis in the case of the real airplane structure. Let's consider for example the derivation of formula for roll moment coefficient derivative with respect to angular roll acceleration.

When the positive acceleration $\dot{\omega}_x$ arises, the mass of compartment on the right wing obtains the acceleration $b\dot{\omega}_x/2$ directed down. Inertia moment $M_i = mb\dot{\omega}_x\Delta x/2$ arises relative to stiffness axis (axis of compartment rotation); here Δx is the distance from the compartment center of mass to the rotation axis. For ordinary structures X_m=0.4–0.5, therefore Δx >0 is corresponded to the rear position of the center of mass relative to stiffness axis (in our case X_{axis}=0.33c). Moment M_i causes the decrease of compartment angle of attack $\Delta\alpha = M_i / G_y$, consequently, the decrease of lifting force roll moment $\Delta L = -qSc_L^{\alpha}\Delta\alpha$ and roll moment $\Delta M_x = -\Delta L b/2$ (It has been taken into consideration that positive force increment causes negative roll moment increment). Combining the formulae we obtain $M_x^{\dot{\omega}_x} = qSc_L^{\alpha}b^2 m\Delta x / 4G_y$, or in nondimensional view $m_x^{\bar{\dot{\omega}}_x} = c_L^{\alpha} mg\Delta x / 2G_y$.

Formulae for the other aerodynamic derivatives with respect to accelerations for considered structure can be obtained similarly:
$c_L^{n_z} = c_L^{\alpha} mg\Delta x / G_y$, $m_y^{n_z} = m_y^{\alpha} mg\Delta x / G_y$,
$c_L^{\bar{\dot{\omega}}_y} = c_L^{\alpha} I_y g / G_y c_{MAC}$, $m_y^{\bar{\dot{\omega}}_y} = m_y^{\alpha} I_y g / G_y c_{MAC}$.

The obtained formulae together with expressions (7), (8) allow estimating of accelerations influence on free structure aerodynamic coefficients derivatives and checking the correctness of calculations.

To investigate the static aeroelasticity characteristics of this structure its computational scheme for STAER program (KC-M software package [5]) was developed. Aerodynamic forces were calculated by doublet-lattice method for incompressible flow and zero reduced frequency. Values c_L^{α}=2.14, m_y^{α}=0.65 (relative to half-chord), c_L^{δ}=1.47 were obtained without elasticity taking into account for the computational scheme shown in Fig. 1. Other characteristics can be obtained by formulae, but the computational results of STAER program were presented here.

Longitudinal motion is the first to be investigated. Position of center of mass was accepted to be equal to X_m=0.5. Lift slope coefficient (c_L^{α}) for elastic structure was calculated with account of inertia force different components. The fixed structure has tendency to c_L^{α} growth, i.e. to divergence (Fig. 2), which is achieved at dynamic pressure q=28 kPa. The divergence dynamic pressure decreases approximately twice when the inertia forces due to load factor only is taking into account (sometimes it is done so in practice). It can be explained by the fact that resultant inertia forces behind the stiffness axis (X_m=0.5) twists the wing on additional positive angle due to attachment elasticity under the positive load factor. Vice versa, c_L^{α} decreases with increase of dynamic pressure due to inertia forces caused by pitch acceleration only, when $c_L^{n_z} = m_y^{n_z}$=0 in formulae (7), because resultant inertia forces decreases the angle of attack under $\dot{\omega}_y$>0. Derivative c_L^{α} is constant (Fig. 2) under the “correct”, full consideration of inertia forces, as it should be for the free structure in such case: weightless non-lifting beam cannot have influence on the surface aerodynamic characteristics.

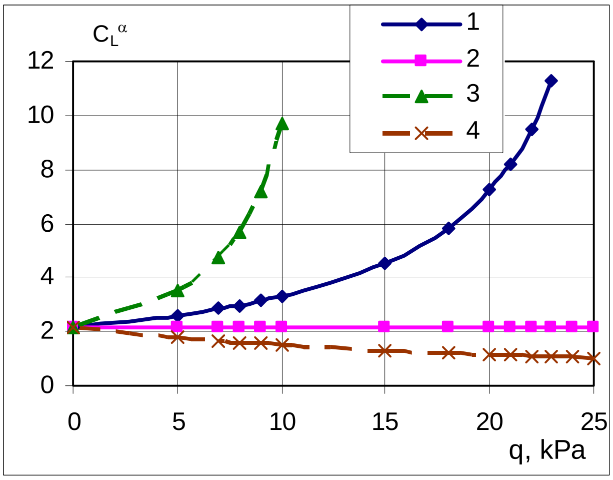

Fig. 2. Lift slope versus dynamic pressure: 1 – a fixed structure, 2 – a free structure (with full account of inertia forces, X_m=0.5), 3 – with account of inertia forces due to vertical load factor only, 4 – with account of inertia forces due to pitch acceleration only.

The effectiveness of roll control is the most interesting in the case lateral motion from aeroelasticity point of view. The developed model describes well the main relations of inertia forces influence on roll characteristics. Ailerons roll effectiveness (m_x^{δ}) decreases for the fixed structure when dynamic pressure increases; and the reversal arises at q=10 kPa (Fig. 3). It is typical for such structure. For the free structure the reversal is achieved at the same dynamic pressure; change of effectiveness depends greatly on position of compartment center of mass (X_m). The effectiveness can be lower, if $X_m < X_{axis}$, and higher, if $X_m > X_{axis}$, than for the fixed structure. The effectiveness m_x^δ begins to increase with the growth of dynamic pressure (Fig. 3) for some more rear positions of center of mass (the wing twists under the inertia forces action, and roll moment increases). This phenomenon can be used for investigation of "active aeroelasticity" concept when in addition to stiffness parameters and aerodynamic configuration the mass distribution is also optimized for better controllability on roll.

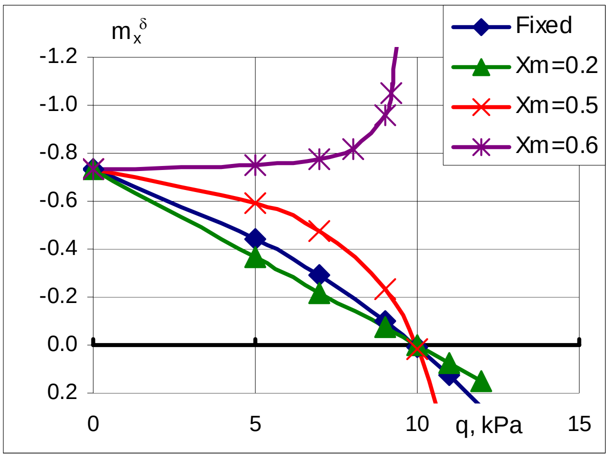

Fig. 3. Effectiveness of aileron versus dynamic pressure for various mass distribution of wing section

6 Heavy transport airplane

Some computational results about mass-inertia characteristics influence on roll control effectiveness for heavy transport airplane with engines on pylons under the wing (Fig. 4) are shown below. Influence of fuel in wing on roll control effectiveness is shown in Fig. 5. The line of centers of mass of wing sections is close to stiffness axis in this case, consequently the effectiveness changes insignificantly and is close to effectiveness for the fixed structure.

Considerable masses with offset from the stiffness axis can have more influence on aerodynamic derivatives. For example, the influence of engines mass on aileron roll effectiveness (mass of an empty airplane is 160 tons, mass of each engine is 5 tons; aerodynamic model hasn't been changed) is shown in Fig. 6. Account of engines mass decreases the value m_x^δ on 20% in the range of high dynamic pressures (q=15-20 kPa).

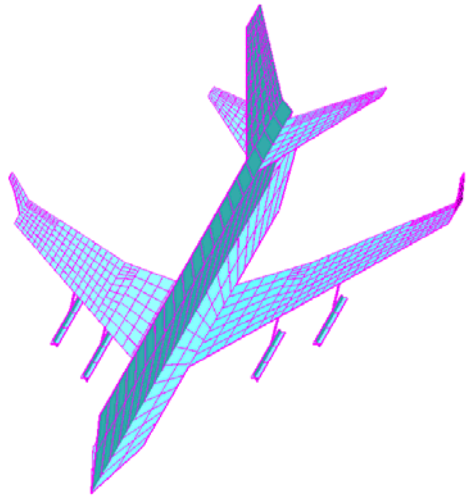

Fig. 4. Heavy transport airplane computational scheme

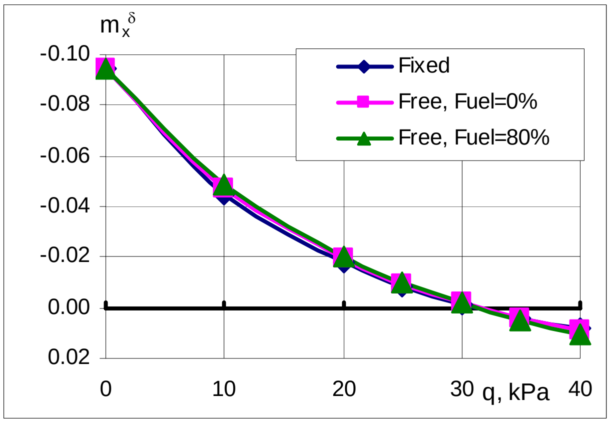

Fig.5. In-wing fuel mass influence on roll control effectiveness.

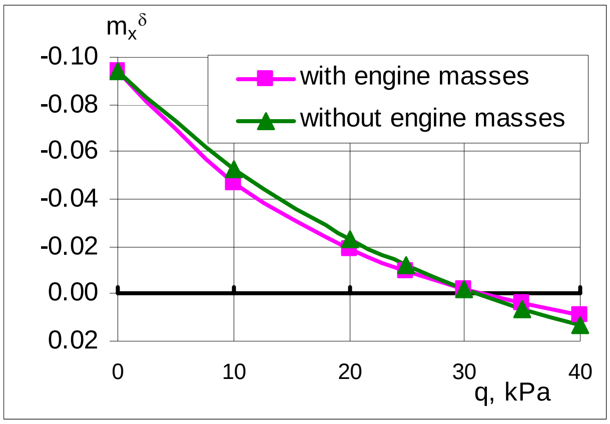

Fig.6. Engines mass influence on roll control effectiveness

Forward aileron at the wing tip (Fig. 7) is considered as one of the ways to improve the roll control in prospective researches [6]. Unlike the ordinary aileron the effectiveness of such control device practically doesn't decrease with dynamic pressure growth (Fig. 8). For free airplane (with inertia forces account) the forward aileron effectiveness is significantly higher than for the fixed structure.

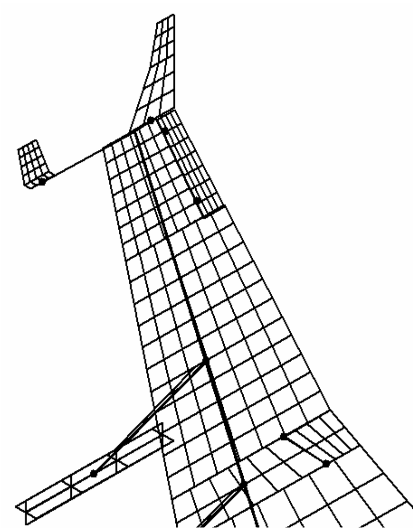

Fig. 7. Wing with the forward tip aileron.

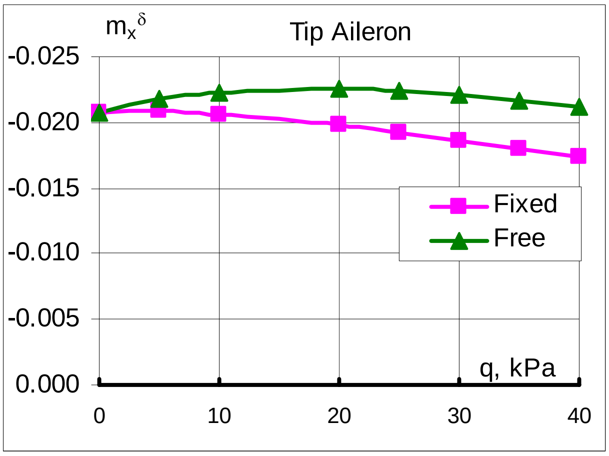

Fig.8. Inertia forces influence on roll effectiveness of forward tip aileron.

7 Experimental estimation of aerodynamic derivative with respect to accelerations

To determine the static aeroelasticity characteristics for the full-scale (free) structure on the base of a model tests in WT the derivatives of aerodynamic coefficients with respect to accelerations, such as c_L^n , m_y^n , $m_x^{\bar{\omega}_x}$ are necessary. As a rule, they are defined by calculations. The original method of experimental determination of such derivatives was suggested in TsAGI to check and confirm the calculations. Change of the roll angle of dynamically scaled model (DSM) is the basis of the method.

The essence of method is the following. DSM is attached in one point of the fuselage near the model center of mass. Change of mass-inertia forces distribution in the direction of lifting force action is fulfilled by the model roll angle varying. The angles of attack and elevator deflection are changed for each roll angle with simultaneous forces and pitch moment measurements.

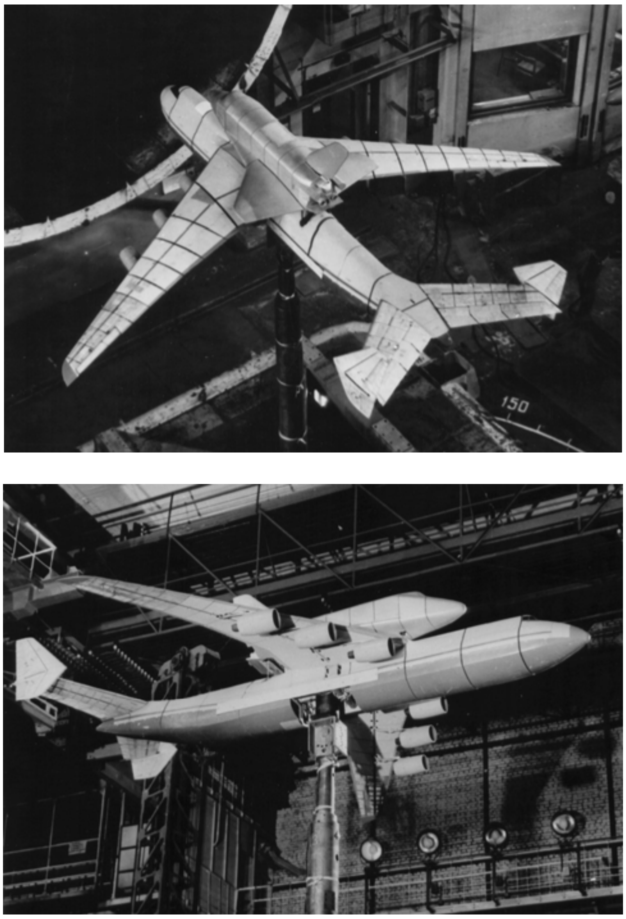

Fig. 9. Dynamically scaled model in WT T-104 TsAGI

Tests of DSM were fulfilled in T-104 TsAGI low speed wind tunnel. Variation of mass-inertia forces was proportional to variation of projection of gravity acceleration. That was achieved by roll angle change equal 180°. Model's derivatives of lifting force and pitch moment with respect to acceleration can be estimated using measurements of lifting force and pitch moment coefficients at 90° model roll angle. Derivatives with respect to acceleration for real airplane are transformed taking into account models linear and velocity scales.

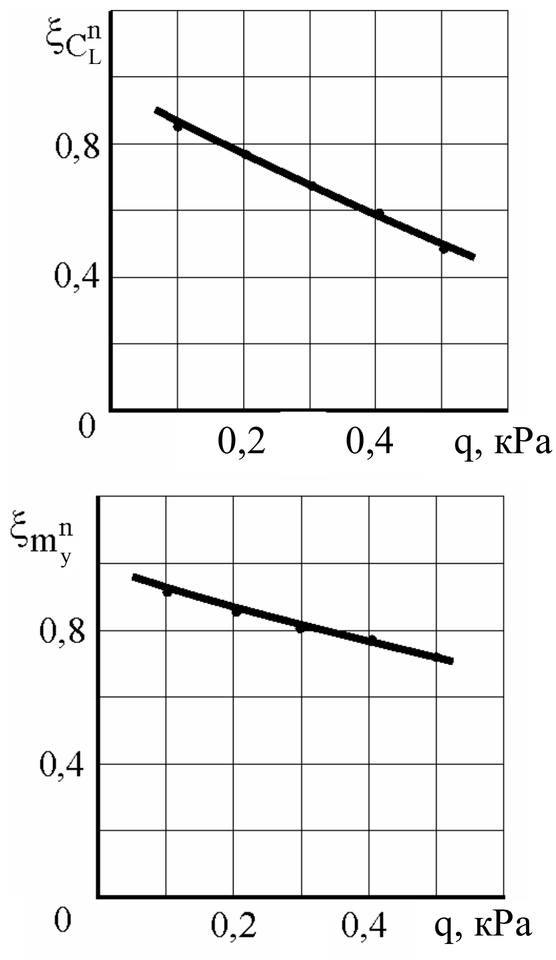

Fig.10. Influence of the mass distribution and dynamic pressure on derivatives of aerodynamic lifting force and pitch moment with respect to load factor (wind tunnel test of dynamically scaled model).

Photos of one of DSM (airplane-carrier "Mriya" with the orbiter "Buran" on the upper fuselage surface) are shown in Fig. 9. Similar moment attachment in one point on the under-fuselage support with 6-component straingage-balance was used for DSM of airplane-carrier 3MT with high aspect ratio wing. As an example, the dependence of relative derivatives of lift and pitch moment coefficients with respect to vertical load factor on dynamic pressure for DSM of airplane 3MT is shown in Fig. 10. These derivatives can be used to convert "weightless" (fixed) airplane derivatives to "weighty" (free) derivatives for actual flight.

8 Conclusion

Mechanism of inertia forces influence on aerodynamic characteristics of elastic airplane is analyzed more detailed in this paper than it has been done before. Simple computational model was created and investigated with clear illustration of the main relations of inertia forces and mass distribution influence on aerodynamic derivatives. The influence of inertia characteristics on roll control effectiveness is shown for a heavy transport airplane. Original method of WT experimental determination of aerodynamic derivatives with respect to acceleration was demonstrated to check and confirm computational results.

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