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COMPUTATIONAL INVESTIGATION OF UNSTEADY AERODYNAMIC CHARACTERISTICS OF A MODERN AIRLINER

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Abstract

The results of a modern airliner unsteady aerodynamic characteristics investigation is presented in the paper. Aerodynamic derivatives are computed with the use of vortex lattice method (VLM) and the BLWF software based on unsteady Euler equations. Typical experimental results obtained on forced and free oscillations test rigs are shown. Longitudinal aerodynamic characteristics for these oscillations with the help of two nonlinear mathematical models are modeled. The first one takes into consideration the delay of flow separation development, the second one contain nonlinear dependency of pitch moment on motion angular velocity.

1 Introduction

Safety is a high priority task when an airliner is developed. So, one need mathematical models of its aerodynamic characteristics in a wide range of incidence which may be quite beyond normal flight regimes. Such models are used for flight dynamics simulation, motion stability investigation and control systems development including ones for critical regimes prevention.

Computational fluid dynamic simulation and experiments on dynamic test rigs are needed [1] for mathematical models development describing adequately unsteady nonlinear aerodynamic loads under separation conditions. At the preliminary design stages when precise aircraft geometry is unidentified, they cannot be carried out. In this case, the simplified numerical techniques are applied for preliminary characteristics evaluation. Such evaluations are approximate, but they enable make changes if necessarily in aircraft geometry and control system as early as possible and thus minimize costs.

In the paper the airliner of typical configuration is investigated. It includes swept wing of high aspect ratio and typical shape tail. Aerodynamic derivatives are computed by vortex lattice method [2]. The dynamic derivatives dependence on Mach number is calculated by BLWF software [3], which is based on unsteady Euler equations. Computational results are in good agreement with experimental ones in linear region. As angles of attack or Mach number are increased, that is in nonlinear region, these methods fail to assess aerodynamic derivatives adequately.

Then TsAGI's dynamic rigs are briefly described for small and large amplitude forced oscillations and for free oscillations. Typical experimental results for the aircraft under consideration are shown.

Longitudinal aerodynamic characteristics are simulated with the use of three mathematical models. The first one is the traditional linear model based on aerodynamic derivatives concept. The second one takes into consideration dynamic effects due to flow separation development. The third model includes nonlinear dependency of pitch moment on motion angular velocity. Linear model fail to describe hysteresis dependencies obtained in large amplitude forced oscillations experiments. Nonlinear models results agree well with experimental ones.

2 Computational methods

2.1 Vortex lattice method

The vortex lattice method has been used worldwide since 1960 [4-6]. The program with user-friendly interface was made implementing this method. The aircraft geometry is schematized by flat panels (Fig. 1) with horseshoe vortices and collocation pointes on them. Then aerodynamic derivatives of vertical and lateral forces and moments (C_N, C_Y, C_m, C_l, C_n) on kinematic parameters (α, β, p, q, r) are computed. An example for vertical force and pitch moment is shown in Fig. 2 in comparison with small amplitude experimental results. Solid and dashed lines are for the model with and without horizontal tail correspondingly. In linear region ($\alpha < 7°$) agreement is quite good for both cases.

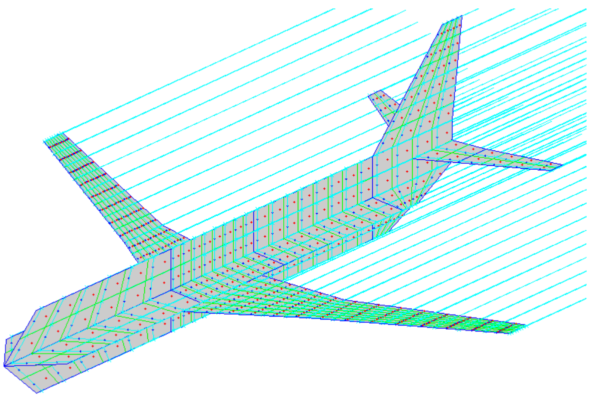

Fig. 1. Aircraft geometry schematization

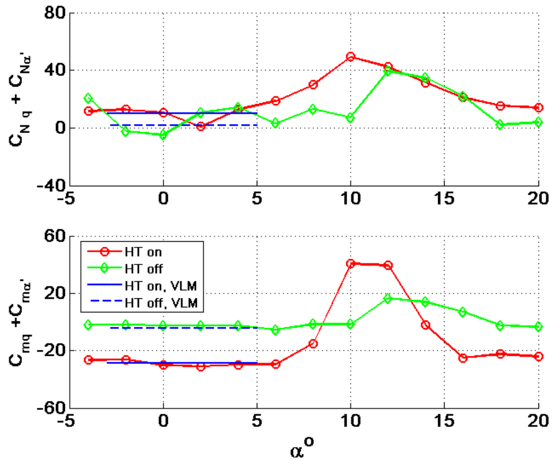

Fig. 2. Vertical force and pitch moment derivatives

2.2 BLWF software

The BLWF software [3] is developed at TsAGI and is designed for calculation of unsteady aerodynamic characteristics of complex multi-element configurations which oscillate harmonically with small amplitudes in compressible flow or fly through harmonic gust. Calculation can be carried out for sub-, trans- or supersonic flow for given Strouhal number with account of viscosity effect on the wing. Classical approach is implemented in the program algorithm based on unsteady Euler equation linearization near the steady solution. The computational grid around a complex configuration is fulfilled with Chimera grid-embedding technique. According to this technique, an independent computational grid is generated around each element of a configuration. Computational grids of the elements are generated by the code automatically on the basis of algebraic procedures. Fig. 3 shows computational grid of the wing.

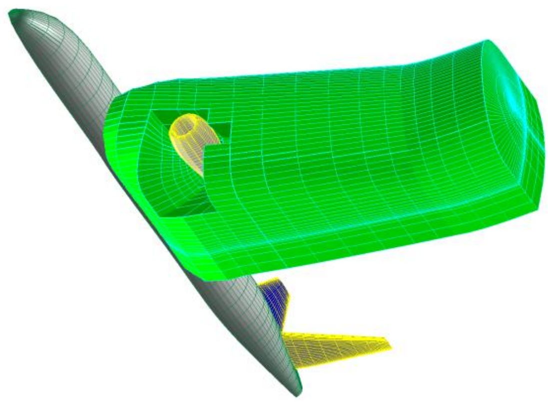

Fig. 3. Computational grid of the wing

Fig. 4 shows computational results for complexes of rotary and unsteady aerodynamic derivatives of vertical force and pitch moment in dependence on Mach number for α=0. Fig. 5 shows rotary derivatives of roll and yaw moments coefficients due to roll angular velocity p. The experimental data obtained on the dynamic test rig SKM in the wind tunnel T-128 at TsAGI [7] are shown in the figures for comparison. There is a good agreement of experimental and computational results up to Mach numbers 0.7-0.8 where compressibility effect becomes considerable. The assessment of aerodynamic derivatives with the use of BLWF code is more precise than for VLM and also BLWF code allows of dependencies on angle of attack calculation, what may be interesting for cross damping derivatives. The code is not time-consuming and takes around several minutes for a single point calculation for real airplane.

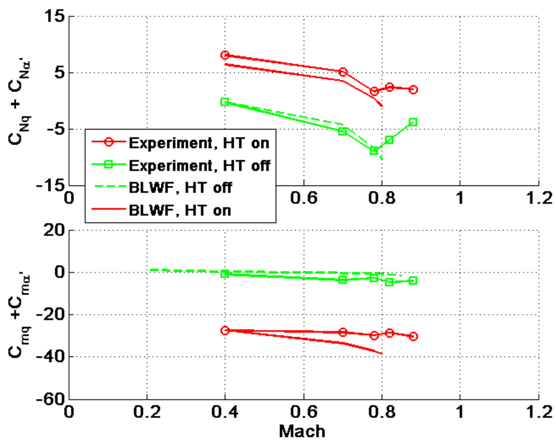

Fig. 4. Vertical force and pitch moment derivatives in dependence on Mach number

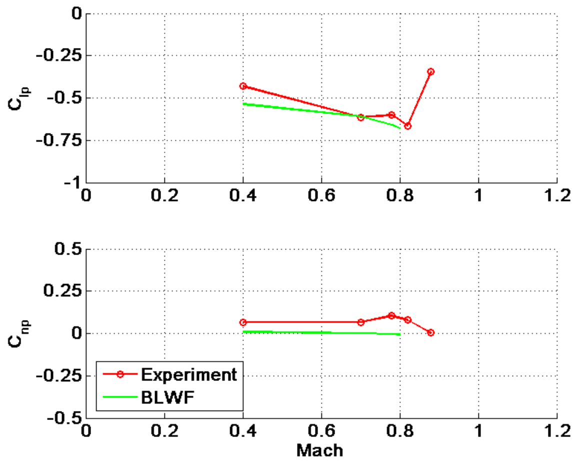

Fig. 5. Derivatives of roll and yaw moment coefficients on roll angular velocity

3 Experiment results

There are several dynamic test rigs at TsAGI for aircrafts' unsteady aerodynamic characteristics investigation. The OVP-102B test rig in the wind tunnel T-103 at TsAGI (Fig. 6) is the most often used one. It can be assembled for harmonic pitch, roll or yaw oscillations with small (3-5°) or large amplitudes (up to 26°). The frequency range is 0.2 - 2 Hz. Possible flow velocity range is 10 - 70 m/s. The detailed description of the rig and experimental technique one can find in [8, 9]. Experimental data of forced oscillations are used for mathematical models parameters identification.

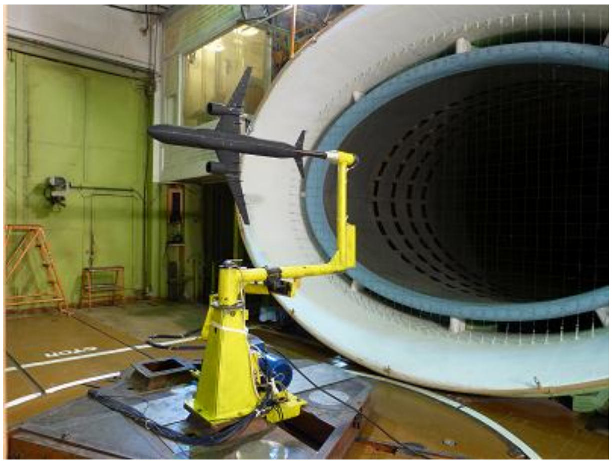

Fig. 6. The OVP-102B test rig in the working section of T-103

3.1 Small amplitude forced oscillations

During experimental investigations in-phase and out-of-phase aerodynamic derivatives are measured. There is a region of angles of attack (8-18 degrees), where pitch moment derivative depends considerably on oscillation frequency *f* (Fig.7). It is due to dynamic effects of separated flow. Flow velocity in experiments was 25 m/s, mean aerodynamic chord $\bar{c}$ was 0.1113 m.

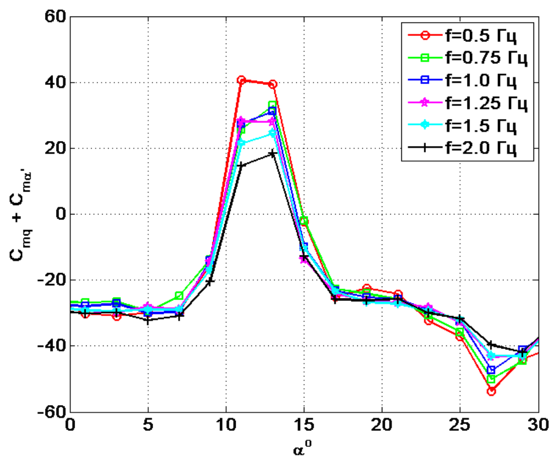

Fig. 7. Nonlinear dependence of pitch moment derivative on angle of attack

3.2 Large amplitude forced oscillations

For investigation of the phenomenon mentioned above large amplitude oscillation experiment is carried out. Oscillation equation is as follows $\alpha = \alpha_0 + \Delta\alpha \sin(2\pi f t)$, where $\Delta\alpha$ is oscillation amplitude, α_0 is the mean angle.

Fig. 8 shows pitch moment hysteresis dependencies on angle of attack for different frequencies. One can see self-crossing in the region of flow rearrangement. They vanish as frequency increase.

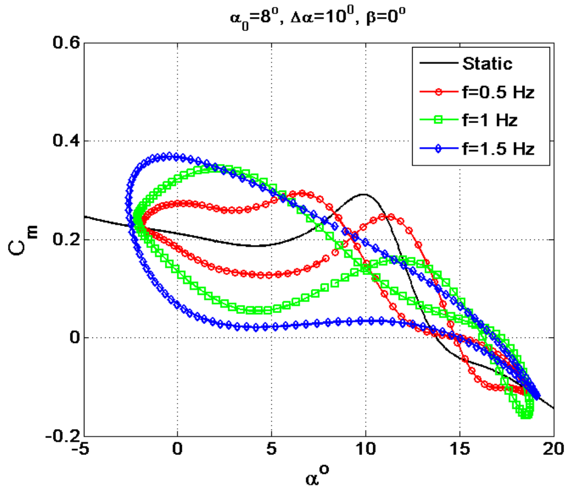

Fig. 8. Hysteresis pitch moment dependencies

3.3 Free oscillations in pitch

For free motion investigation [10], the aircraft model is mounted on the one degree of freedom gimbal with strain-gage balance inside (Fig. 9). The model is set at a certain incidence angle and then released during wind tunnel flow on. It starts free motion due to aerodynamic loads.

Fig. 9. The aircraft model on free oscillations test rig in the working section of T-103

The angle of gimbal rotation is registered. Strain-gage balance readings give the time history of aerodynamic vertical force coefficient. Aerodynamic moment dependence is recovered by processing of model angular position time dependence with the use of dynamic motion equation. Fig. 10 shows transient process (up) and pitch moment dependency on angle of attack (below) for damping oscillation case. Free motion simulation allows mathematical models developed with the use of forced oscillation experimental results to be verified.

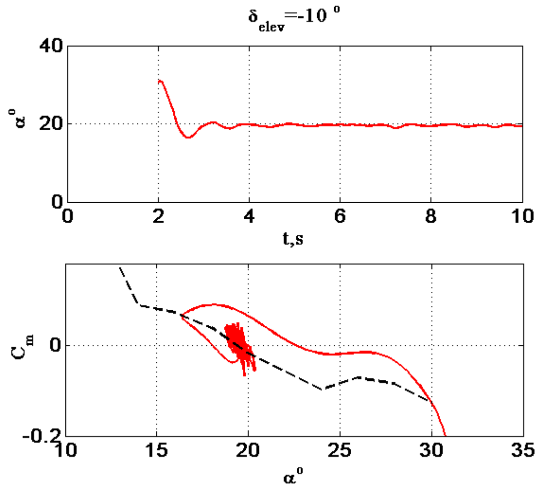

Fig. 10. Transient process (up) and pitch moment (below) for free oscillations

4 Mathematical modelling

4.1 Linear model

The linear model of longitudinal aerodynamic characteristics may be written as:

$$C_N = C_N^{st}(\alpha) + \left(C_{N\bar{q}} + C_{N\dot{\alpha}}\right)\bar{q} + C_{N\delta_e}(\alpha)\delta_e$$
$$C_m = C_m^{st}(\alpha) + \left(C_{m\bar{q}} + C_{m\dot{\alpha}}\right)\bar{q} + C_{m\delta_e}(\alpha)\delta_e$$

Static characteristics C_N^{st}, C_m^{st} depend nonlinearly on the angle of attack *α*. The complex of rotary and unsteady derivatives $C_{m\bar{q}} + C_{m\dot{\alpha}}$ is usually considered to be constant and independent on angle of attack for flight dynamic tasks. It is applicable for attached flow regimes. In the presence of flow separation the nonlinearity occur in this characteristic and antidamping region arise as it is seen in Fig.7. The linear model was developed in the paper as a starting point for comparison. Small amplitude forced oscillation experimental data were used for measurement of nonlinear damping derivative. In the expression above $\bar{q} = \frac{\bar{c}}{2V}$ is undimentional pitch angular velocity, $\bar{c}$ is mean aerodynamic chord, V is incident flow velocity, δ_e is the angle of elevator inclination, $C_{N\delta_e}, C_{m\delta_e}$ is elevator effectiveness.

When oscillation frequency is small linear model qualitatively describes experimental dependencies (Fig.11). As frequency increases agreement disappears (Fig. 12).

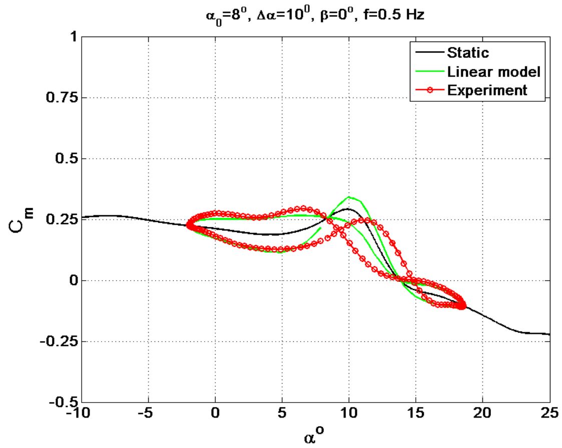

Fig. 11 Linear model and experimental results for oscillation frequency f=0.5 Hz

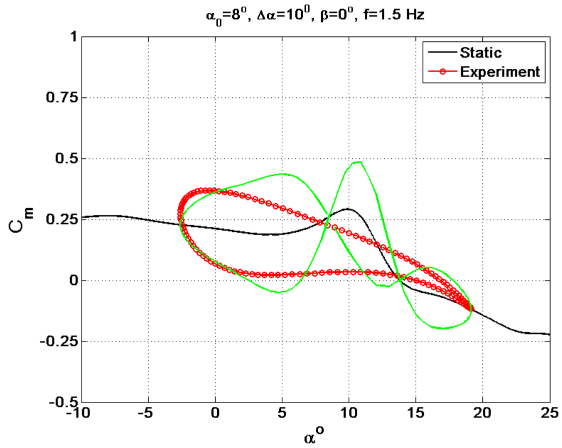

Fig. 12 Linear model and experimental results for oscillation frequency f=1.5 Hz

The kind of free motion arisen depends on the mean angle. If it is inside the region of positive damping, then self-sustained oscillations occur (Fig. 13), otherwise oscillations damp (Fig. 14). The linear model can describe self-sustained oscillations because it includes nonlinear dependence of rotary and unsteady derivatives complex with positive damping area as it is seen in experiment.

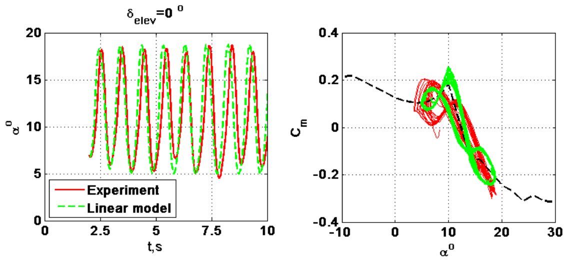

Fig. 13 Free self-sustained oscillations

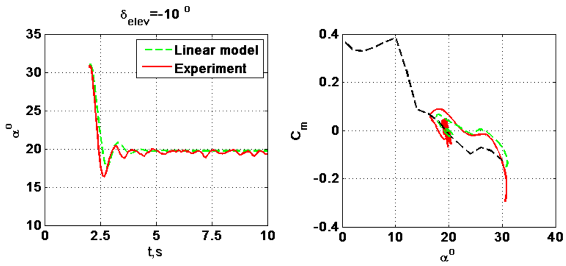

Fig. 14 Free damping oscillations

4.2 Nonlinear model with account of flow separation delay

In studies [11-13] a phenomenological approach to nonlinear characteristics simulation was proposed and developed, which enables to describe experimental results. According to this state-space approach, internal dynamic variables (vector **x**) are introduced to describe the state of separated flow about an aircraft. Thus, a dynamical system is formed, where input is a vector of kinematic parameters $\xi = (\alpha, \beta, p, q, r, \delta_e)^T$, and output is a vector of aerodynamic forces and moments coefficients $\boldsymbol{C} = (C_N, C_Y, C_l, C_m, C_n)^T$.

$$\boldsymbol{C} = f(\boldsymbol{x}, \xi), \quad (1)$$

$$\frac{d\boldsymbol{x}}{dt} = g(\boldsymbol{x}, \xi). \quad (2)$$

The form of functions f and g is determined on the base of experimental data to describe the dynamic effects of flow separation development. In the paper the mathematical model of longitudinal aerodynamic characteristics was developed in the following form [14]:

$$C_N = C_{Np}^{st}(\alpha) + C_{Ns} + C_{N\bar{q}}\bar{q} + C_{N\delta_e}(\alpha)\delta_e$$

$$C_m = C_{mp}{}^{st}(\alpha) + C_{ms} + C_{m\bar{q}}\bar{q} + C_{m\delta_e}(\alpha)\delta_e$$

$$\tau_1 \frac{dC_{Ns}}{dt} + C_{Ns} = C_{Ns}{}^{st}\left(\alpha - \tau_2\bar{\dot{\alpha}}\right) \quad (3)$$

$$\tau_3 \frac{dC_{ms}}{dt} + C_{ms} = C_{ms}{}^{st}\left(\alpha - \tau_4\bar{\dot{\alpha}}\right) \quad (4)$$

Equations (3) and (4) are written in nondimensional time. The time which flow needs to pass mean aerodynamic chord is taken as a unit. Forces and moments are divided into two parts – linear and nonlinear one. The linear part is constant in motion and equal to its static value C_{Np}^{st}, $C_{mp}{}^{st}$. The nonlinear part C_{Ns}, C_{ms} is a state variable. It describes effects of its static value C_{Ns}^{st}, C_{ms}^{st} delay according to equations (3) and (4). Characteristic delay times τ_i, $i = 1 \div 4$ are identified from small amplitude forced oscillation experimental data. The nonlinear behavior of characteristics appears in the presence of flow separation. For the aircraft under consideration separation region is in the range of incidence 8 - 16 degrees. Because of that, functions τ_i are considered to have bell shape [14] with the maximum in the center of the range. Out of the range functions τ_2, τ_4 equals to zero and τ_1, τ_3 equals to 2. This small addition has little effect on filters in the left parts of equations (3) and (4), but allows avoiding differential equation degeneration. Thus, delay functions are defined except their maximum values. For identification of the maximums the penalty functional is introduced which is the sum of squares of experimental data and modelling results disagreement for aerodynamic derivatives at different angles of incidence and oscillation frequencies.

In Fig. 15 obtained characteristic time delays τ_3, τ_4 are shown. If time delays in equations (3) and (4) are small, then dynamic components of force C_{Ns} and moment C_{ms} become equal to their static values C_{Ns}^{st} and C_{ms}^{st} respectively. In this case mathematical state-space model results in traditional unsteady linear model of aerodynamic characteristics. Comparison with experimental results shows (Fig 16, 17) that hysteresis dependencies can be described both for small and large oscillation frequencies with the use of the state-space model.

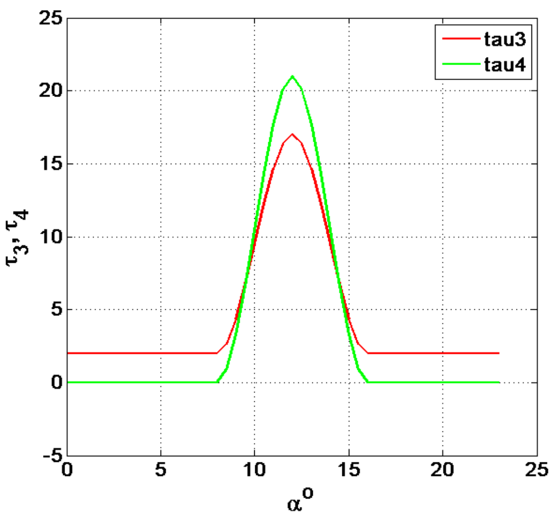

Fig. 15 Characteristic time delays for state-space model

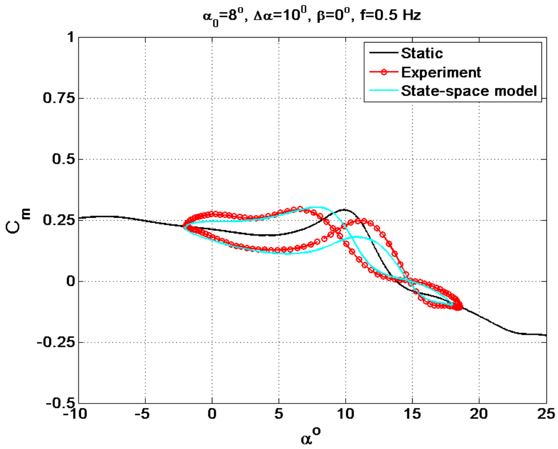

Fig. 16 State-space and experimental results for oscillation frequency f=0.5 Hz

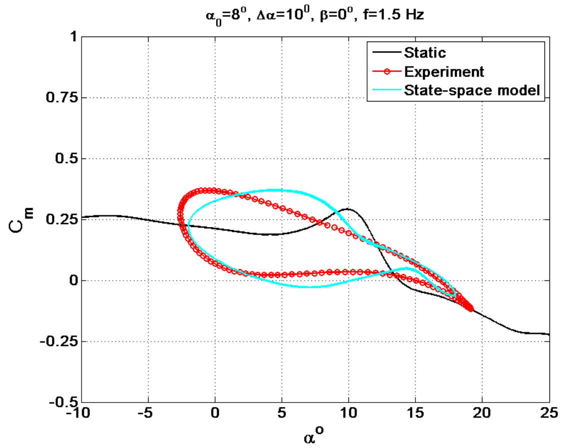

Fig. 17 State-space and experimental results for oscillation frequency f=1.5 Hz

Considerable changing of pitch moment nonlinear part relative to its static value (Fig.18, 19, below right) determines hysteresis loops behavior when free oscillations are modeled.

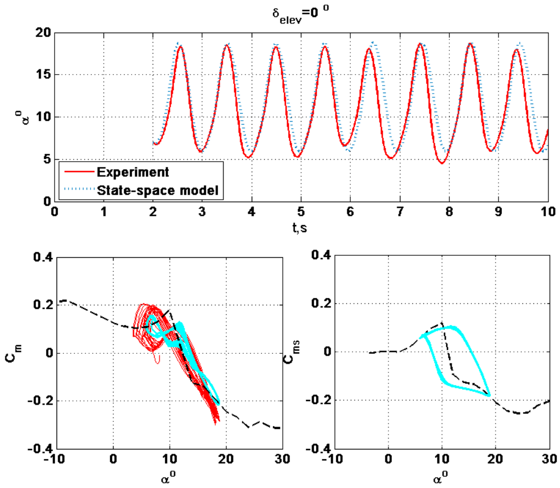

Fig. 18 Free self-sustained oscillations

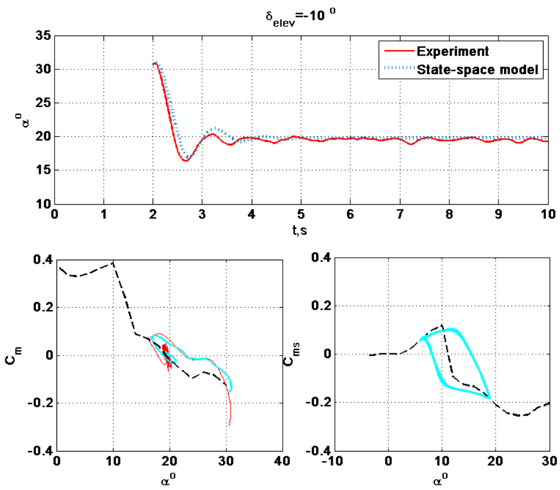

Fig. 19 Free damping oscillations

4.3 Nonlinear model without delay

Application of phenomenological approach may be difficult, because the form of dynamic system (functions ***f*** and ***g*** in equations (1) and (2)) are not known in advanced. Therefore another model is proposed for simplification of modelling nonlinear unsteady aerodynamic characteristics. It does not contain explicit dependence of aerodynamic characteristics on time, but instead of that nonlinear dependence on angular velocity is taken into account (5). Thus, only current values of parameters are used for modelling without taken into consideration motion history.

$$C_m = C_m^{st}(\alpha) + \Delta C_m(\alpha, \bar{q}) + C_{m\delta_e}\delta_e \qquad (5)$$

This model is based on large amplitude forced oscillation experimental data. The spline approximation of the term $\Delta C_m(\alpha,\bar{q})$ dependence on angular velocity $\bar{q}$ and angle of attack α is shown in Fig. 20.

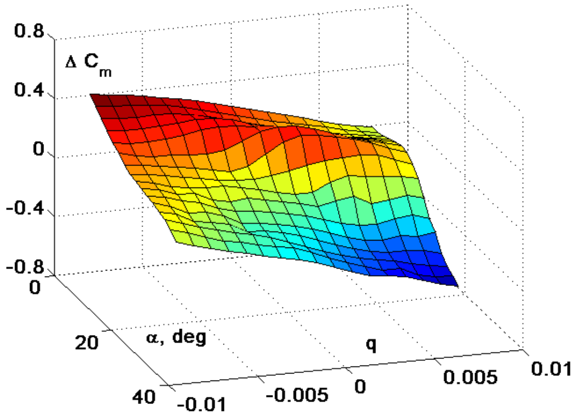

Fig. 20 The dependence of term $\Delta C_m(\alpha,\bar{q})$ on $\bar{q}$ and α

Pitch moment coefficient is considerably nonlinear on $\bar{q}$ in the range of flow separation (8 – 18 degrees), curve slope changes its sign and antidamping in pitch occurs. As angle of attack increases further, antidamping vanishes and the dependence on angular velocity becomes linear again. The main advantage of this model is its simplicity for development and use for flight dynamics analysis.

This model allows describing adequately forced oscillations with different frequencies and free motion (Fig. 21-24).

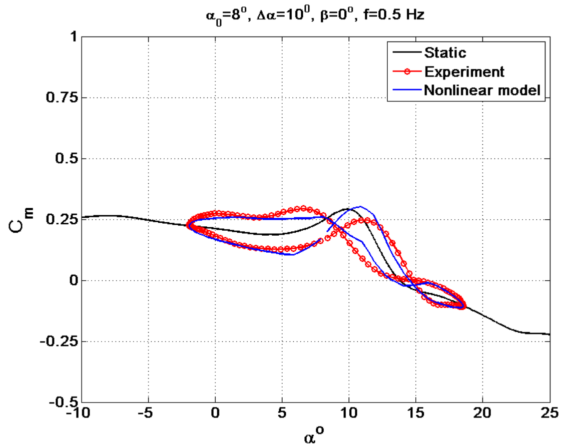

Fig. 21 Model without delay and experimental results for oscillation frequency f=0.5 Hz

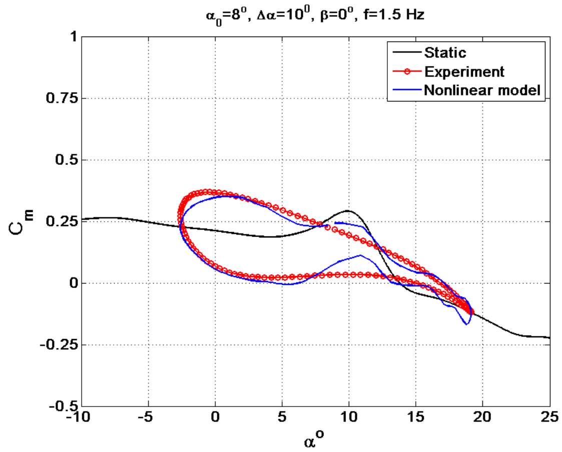

Fig. 22 Model without delay and experimental results for oscillation frequency f=1.5 Hz

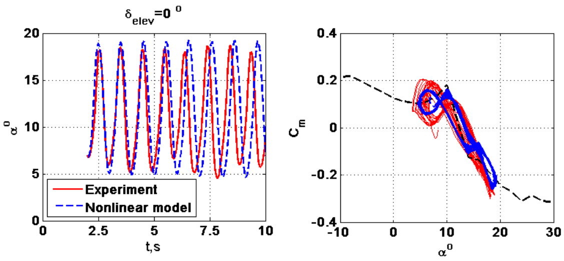

Fig. 23 Free self-sustained oscillations

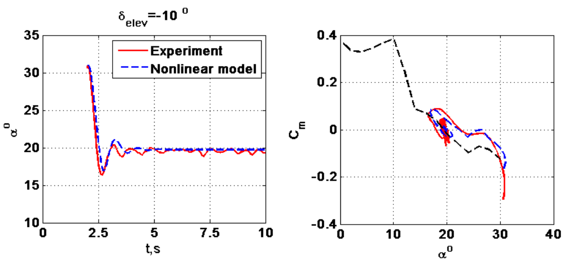

Fig. 24 Free damping oscillations

5 Conclusions

Unsteady aerodynamic characteristics of a modern airliner were investigated in the paper. The BLWF and VLM codes were used for aerodynamic derivatives computation. Forced and free pitch oscillations were modeled with the two nonlinear mathematical models. The first one takes into account dynamic effects due to the delay of flow separation development by means of additional differential equation. The second one describes nonlinear dependence of pitch moment on angular velocity by spline approximation of large amplitude forced oscillation experimental data.

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