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HEURISTIC MODEL OF NON-STEADY LONGITUDINAL AERODYNAMIC CHARACTERISTICS AT HIGH ANGLES OF ATTACK

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Abstract

A heuristic correction of longitudinal aerodynamic characteristics $C_L(\alpha)$ and $C_m(\alpha)$ at high angle of attack is considered. Two correction components are considered: regular and random. Regular component is designed as piecewise linear dependence of angle of attack filtered by first order lag block. Random component is used for buffeting simulation.

Introduction

The hysteresis of aerodynamic characteristics of an aircraft at high angles of attack was studied by many authors. In [1-5] was paid much attention to the study of the hysteresis phenomenon in the dependences of the lift coefficient $C_L(\alpha)$ and pitch moment $C_m(\alpha)$ of aircraft models on the angle of attack, according to the results obtained by wind tunnel (WT) tests. Back in 1979, the problem of the Re number effect on the hysteresis parameters was discussed in [6].

Identification of longitudinal aerodynamic characteristics on the base of middle range airplane flight tests demonstrated an existence of hysteresis. For example in Fig. 1 a dependences $\bar{C}_L(\alpha)$ and $\bar{C}_m(\alpha)$ for M=0.35 obtained as a result of identification procedure, are presented. They compared with aerodynamic database.

Coefficients $\bar{C}_L(\alpha)$ and $\bar{C}_m(\alpha)$ are presented as relative values

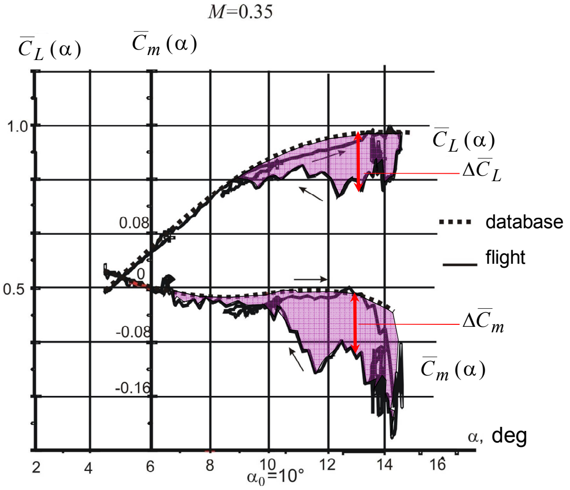

Figure 1

$$\bar{C}_L(\alpha)=\frac{C_L(\alpha)}{C_{L\,\max}},$$

$$\bar{C}_m(\alpha)=\frac{C_m(\alpha)}{C_{L\,\max}}.$$

The angle of attack α_0 in Fig. 1 corresponds to the beginning of the area of characteristics nonuniqueness.

However, to date a clearly justified mathematical model of this phenomenon, which would allow simulating the nonuniqueness of the aerodynamic characteristics for aircraft arbitrary maneuvers, does not exist in the open scientific literature.

Such a model is required for both calculation and flight simulator study of the aircraft behavior at high angles of attack, when it is necessary to calculate with the real time scale in simulating and get more consistent characteristics of the aircraft controllability.

A more difficult problem is the preliminary creation of such a model based on the results of aircraft model tests in WT at different dynamic facilities [3,4]. Creation of mathematical models describing the behavior of aerodynamic characteristics in a WT is of limited interest, because of the problem of the conversion from the WT characteristics into the airplane full-scale flight conditions. Therefore, it makes sense to try to develop easy but reliable model of longitudinal aerodynamic characteristics based on the results of flight tests, to capture the main features of the characteristics behavior at high angles of attack.

Flight tests data analysis

An analysis of flight tests results at M=0.3÷0.35, 0.6 and 0.8 was conducted. For M=0.3÷0.35 aerodynamic characteristics were obtained as a result of decelerations and pilot's step "pitch up" inputs (kicks) and for M=0.6 and M=0.8 – only pilot's step "kicks".

Analysis shows that from angle of attack α_0, depended on M, an ambiguity of aerodynamic characteristics $C_L(\alpha)$ and $C_m(\alpha)$ is appeared. Values $C_L(\alpha)$ and $C_m(\alpha)$ at direct movement ($\dot{\alpha} > 0$), bigger (in modulo) than $C_L(\alpha)$ and $C_m(\alpha)$ at return movement ($\dot{\alpha} < 0$), i.e.

$$C_L(\alpha, \dot{\alpha} > 0) > C_L(\alpha, \dot{\alpha} < 0)$$

and

$$C_m(\alpha, \dot{\alpha} > 0) > C_m(\alpha, \dot{\alpha} < 0),$$

when $\alpha > \alpha_0$.

Similar results were obtained by many researchers in the WT model tests [1,2,3,6]. For example, $C_L(\alpha)$ and $C_m(\alpha)$ given in [3] were obtained from model tests on a dynamic rig allowing one to simulate a quick high-angle-of-attack departure. The results indicating a significant excess of $C_L(\alpha)$ and $C_m(\alpha)$ in the direct motion ($\dot{\alpha} > 0$) and of $C_L(\alpha)$ and $C_m(\alpha)$ during the return motion ($\dot{\alpha} < 0$) were obtained in these experiments. Moreover, $C_L(\alpha)$ and $C_m(\alpha)$ at $\alpha > \alpha_0$ and $\dot{\alpha} > 0$ even exceed the static values of these aerodynamic characteristics. This phenomenon has not yet been found from the results of flight data processing.

Here we attempt to describe mathematically the characteristic features of the behavior of $C_L(\alpha)$ and $C_m(\alpha)$ at high angles of attack based on the results of identification by aircraft flight tests.

Let us compare the pitch moment $C_m(\alpha)$ at M=0.35 taken from the database of the aircraft aerodynamic characteristics composed of the results of model WT tests, with the pitch moment value obtained in flight. Fig. 2 shows the coincidence between the pitch moments $C_m(\alpha)$ obtained from the databank and in flight up to angles of attack of 13–14° at $\dot{\alpha} > 0$.

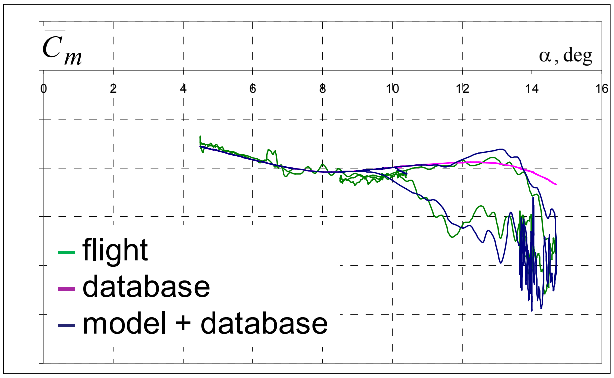

Figure 2

Let's consider difference of pitch moment dependencies

$$C_{m\,flight}(\alpha) - C_{m\,database}(\alpha) = \Delta C_m(\alpha)$$

Dependency

$$\Delta \bar{C}_m(\alpha) = \frac{\Delta C_m(\alpha)}{C_{L\,max}}$$

is presented on Fig. 3.

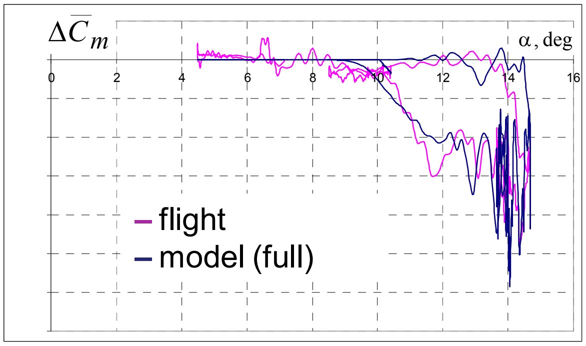

Figure 3

We can see that up to α≈14° flight and database dependencies are about the same, then they are significantly differ. In flight dependency appears a "nose down" moment, that reduces with reducing angle of attack and disappeared at α~10°.

Analysis of $\Delta\overline{C}_m(\alpha)$ dependency for flight data, presented in Fig. 3, shows that it could be splitted on two components: regular – $\Delta\overline{C}_{m\,REG}(\alpha)$ and random – $\Delta\overline{C}_{m\,RAN}(\alpha)$.

Regular component could be described as low frequency (slow) component of dependency $\Delta\overline{C}_m(\alpha)$. Random component could be described as difference between $\Delta\overline{C}_m(\alpha)$ obtained from in-flight data and regular component.

In the Fig. 4 regular component $\Delta\overline{C}_{m\,REG}(\alpha)$ and summary $\Delta\overline{C}_m(\alpha)$ dependency are presented.

So, summary model addition for aerodynamics is

$$\Delta\overline{C}_{m\,sum} = \Delta\overline{C}_{m\,REG} + \Delta\overline{C}_{m\,RAN},$$

where

$$\Delta\overline{C}_{m\,REG}(\alpha) = \frac{\Delta C_{m\,REG}(\alpha)}{C_{L\,max}},$$

$$\Delta\overline{C}_{m\,RAN}(\alpha) = \frac{\Delta C_{m\,RAN}(\alpha)}{C_{L\,max}}.$$

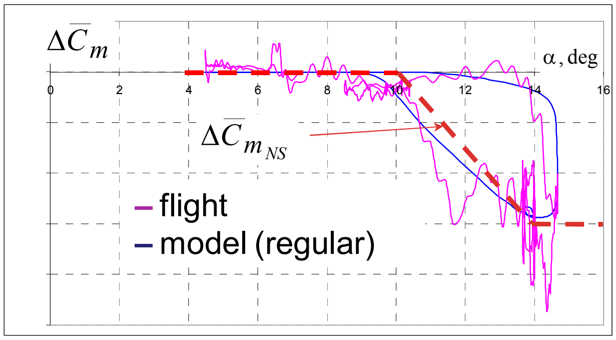

Figure 4

Model of lift force $\Delta\overline{C}_{L\,sum}(\alpha)$ addition is analogous to pitch moment model and consists of regular $\Delta\overline{C}_{L\,REG}(\alpha)$ and random $\Delta\overline{C}_{L\,RAN}(\alpha)$ components (Fig 5):

$$\Delta\overline{C}_{L\,sum} = \Delta\overline{C}_{L\,REG} + \Delta\overline{C}_{L\,RAN},$$

Random component $\Delta\overline{C}_{L\,RAN}(\alpha)$ could be estimated on the base of difference between flight data $\Delta\overline{C}_L(\alpha)$, and regular component $\Delta\overline{C}_{L\,REG}(\alpha)$. In Fig. 5 considered dependences are presented in dimensionless form

$$\Delta\overline{C}_L(\alpha) = \frac{\Delta C_L(\alpha)}{C_{L\,\max}}$$

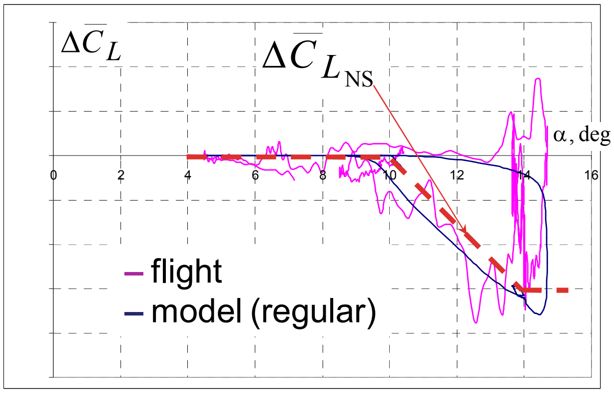

Figure 5

Summary database, flight and model lift force dependencies in dimensionless form $\overline{C}_L(\alpha)$, are presented in Fig. 6.

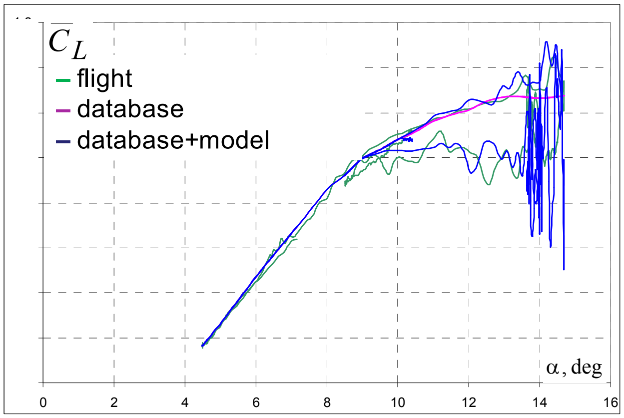

Figure 6

Model Description and Verification

Summary pitch moment addition due to non-state flow could be described by equation:

$$\Delta\bar{C}_{m\,sum} = \frac{\Delta\bar{C}_{m_{NS}}}{T_2 s+1}\left(1+K_1\eta\frac{1}{T_c s+1}\right),$$

where regular component $\Delta\bar{C}_{m\,REG}$

$$\Delta\bar{C}_{m\,REG} = \frac{\Delta\bar{C}_{m_{NS}}}{T_2 s+1}.$$

and random component

$$\Delta\bar{C}_{m\,RAN} = \frac{\Delta\bar{C}_{m_{NS}}}{T_2 s+1}K_1\eta\cdot\frac{1}{T_c s+1}.$$

Here $\Delta\bar{C}_{m_{NS}}$ – piecewise-linear function of angle of attack; T_2 – time constant depending on the angle of attack rate; η – white noise (±0.5); T_c – is the constant of the filter that forms the frequency content of the random component; K_1 is the coefficient determining the buffeting intensity.

First order lag block with time parameter T_2 determines time delay of appearing additional “nose down” pitch moment, which is described by the regular component $\Delta\bar{C}_{m\,REG}(\alpha)$. It is clear that the increase of angle of attack rate $\dot{\alpha}$ leads to the higher angle is reached by the aircraft with a weak destruction of the unseparated flow, i.e. the higher angles of attack at which the negative pitch component $\Delta\bar{C}_{m\,REG}(\alpha)$ appears, which means the revealing of separated flow effects. Hence, the constant T_2 should be proportional to $\dot{\alpha}$.

Model of lift force $\Delta\bar{C}_{L\,sum}(\alpha)$ addition is analogous to pitch moment addition model.

$$\Delta\bar{C}_{L\,sum} = \frac{\Delta\bar{C}_{L_{NS}}}{T_2 s+1}\left(1+K_2\eta\frac{1}{T_c s+1}\right).$$

Dependency $\Delta\bar{C}_{L_{NS}}$ could be presented in form of piecewise-linear dependence of angle of attack.

Comparison of dependencies at Fig 3-6 shows that developed heuristic model has acceptable accuracy of forming specific features such as appearance of “nose down” pitch moment and buffeting.

Developed model was verified on the base of additional identification of flights in the braking mode (with decelerations). Fig 7-8 shows $\bar{C}_L(\alpha)$ and $\bar{C}_m(\alpha)$ obtained from the results of the identification of the flight tests (braking mode). The quantities $\bar{C}_L(\alpha)$ and $\bar{C}_m(\alpha)$ obtained from the database and the proposed model are shown in Fig. 7-8 too. It can be seen that the main specific features of the dependences $\bar{C}_L(\alpha)$ and $\bar{C}_m(\alpha)$, obtained from the results of the identification of decelerations, are adequately reproduced by the model developed on the base of the identification of “kicks”.

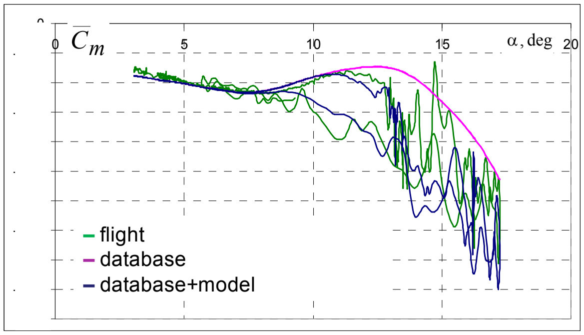

Figure 7

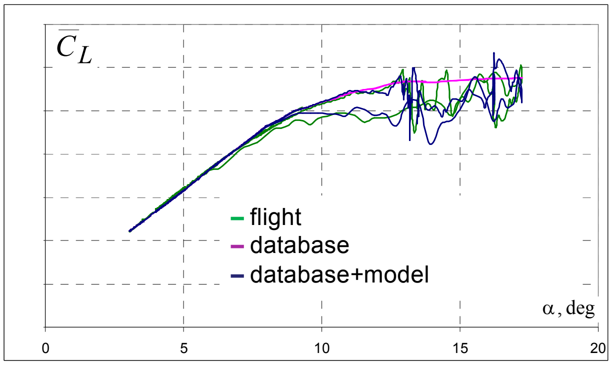

Figure 8

The identification of the aerodynamic characteristics $\bar{C}_L(\alpha)$ and $\bar{C}_m(\alpha)$ at other flight Mach numbers confirms the presence of nonuniqueness of their behavior, starting with a certain value α_0 in direct ($\dot{\alpha}>0$) and return ($\dot{\alpha}<0$) motions. For example, Figs. 9 and 10 show $C_L(\alpha)$ and $C_m(\alpha)$, obtained from the identification by the results of flight tests at M=0.6 and M=0.8.

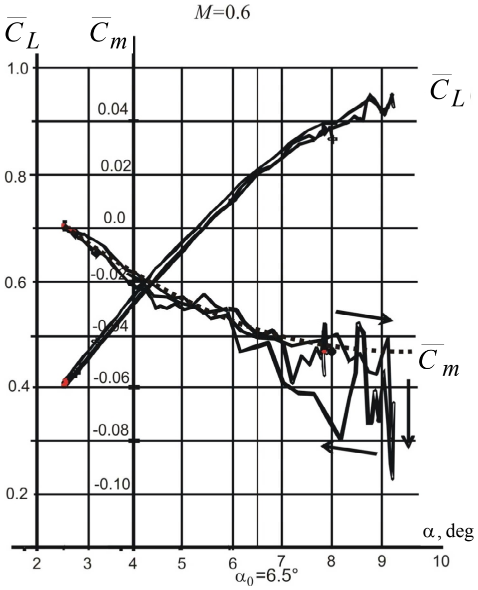

Figure 9

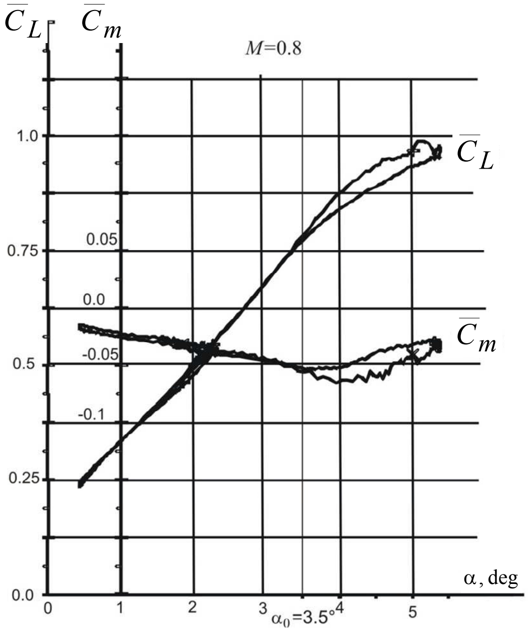

Figure 10

It should be noted that the nonuniqueness of the considered characteristics begins with different angles of attack α_0. At M=0.6, the nonuniqueness begins from $\alpha_0 \approx 6.5°$, and at M=0.8 it begins from $\alpha_0 \approx 3.5°$. With increase in the flight Mach number, the α_0 decreases and the difference in the characteristics in the direct and return motion decreases (in absolute value) too. Unfortunately, the lack of experimental data obtained from flight tests does not allow us to make definite conclusions about the maximum value of the divergence of the $C_L(\alpha)$ and $C_m(\alpha)$ branches in direct and return motion.

From the procedure of finding $\Delta\overline{C}_m(\alpha)$ and $\Delta\overline{C}_L(\alpha)$ at M=0.6 and M=0.8, you can get the model parameters to describe dependences of the increments $\Delta\overline{C}_{L\,REG}(\alpha)$ and $\Delta\overline{C}_{L\,RAN}(\alpha)$, as well as $\Delta\overline{C}_{m\,REG}(\alpha)$ and $\Delta\overline{C}_{m\,RAN}(\alpha)$ for the aforementioned Mach numbers.

For example, Fig. 11 show comparison of $\overline{C}_m(\alpha)$ dependences from flight, database and heuristic model at M = 0.6 and Fig. 11 show comparison of $\overline{C}_m(\alpha)$ dependences from flight, database and heuristic model at M = 0.8.

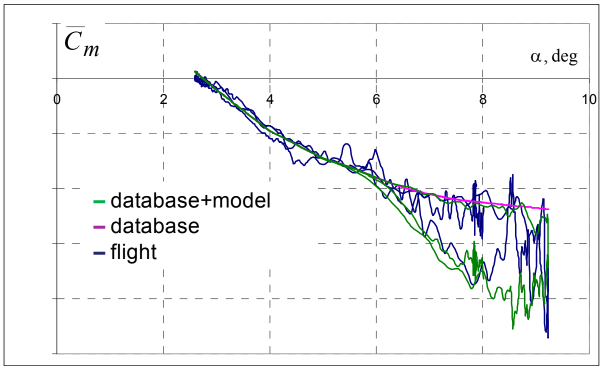

Figure 11

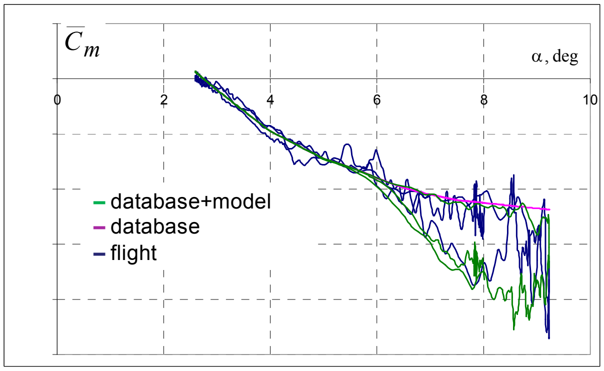

Figure 12

It shows that developed form of model is useful for all considered M numbers.

Conclusion

Thus, the mathematical model of nonsteady increments $\Delta\overline{C}_{m\,sum}(\alpha)$ and $\Delta\overline{C}_{L\,sum}(\alpha)$ to database characteristics $C_L(\alpha)$ and $C_m(\alpha)$ can be represented as:

$$\Delta\overline{C}_{m\,sum} = \frac{\Delta\overline{C}_{m_{NS}}}{T_2 s + 1}\left(1 + K_1 \eta \frac{1}{T_c s + 1}\right)$$

$$\Delta\overline{C}_{L\,sum} = \frac{\Delta\overline{C}_{L_{NS}}}{T_2 s + 1}\left(1 + K_2 \eta \frac{1}{T_c s + 1}\right),$$

where $\Delta\overline{C}_{m_{NS}}$ and $\Delta\overline{C}_{L_{NS}}$ are described by piecewise-linear functions of angle of attack and M number. T_2 – time constant depending on the angle of attack rate and M number; η – white noise (±0.5); T_c – is the constant of the filter that forms the frequency content of the random component; K_1 and K_2 are the coefficients depending on the angle of attack and M number and determining the buffeting intensity.

This model allows to reproduce the main features of the airplane behavior in longitudinal channel at high angles of attack.

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