SCIENCE CHINA
Information Sciences

• HIGHLIGHT •

November 2017, Vol. 60 118201:1–118201:3
doi: 10.1007/s11432-017-9095-7

Longitudinal high incidence unsteady aerodynamic modeling for advanced combat aircraft configuration from wind tunnel data

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Received March 23, 2017; accepted April 20, 2017; published online August 17, 2017

Citation Hu S, Zhu J H. Longitudinal high incidence unsteady aerodynamic modeling for advanced combat aircraft configuration from wind tunnel data. Sci China Inf Sci, 2017, 60(11): 118201, doi: 10.1007/s11432-017-9095-7

The extension of flight envelope to high angles of attack has been a key requirement for modern aircrafts. Advanced combat aircrafts should be provided with super maneuver performance to improve operational effectiveness. In this case, the incidence of aircraft could be very large, even reaching post stall angles. The aerodynamics show strong nonlinear and unsteady characteristics in the flight of high incidence, which are caused by complex flow structures such as attached flow separation and vortex burst [1]. The unsteady aerodynamic modeling at high incidences is helpful to control law design and flight simulation which has great practical significance. With its progress over two decades, unsteady aerodynamic models can mainly sum up as four types which are indicial response, state-space, differential equation and artificial intelligence model. In [2], an exponential function was utlized to simplify the indicial response model to identify unsteady aerodynamics of the F-16XL aircraft. In [3], the state-space model was improved and applied to characterizing unsteady aerodynamics of a generic jet transport at high incidences. In [4], a first order differential equation was proposed to portray the separated flow dynamics directly in stead of internal state variables which are difficult to identify. Artificial intelligence technologies have received great attentions in recent years. Neural network [5] and support vector machine [6] have been applied to the unsteady aerodynamic modeling successfully.

This article focuses on the mathematical modeling of longitudinal unsteady aerodynamics at a wide range of high incidences, taking into consideration an advanced combat aircraft configuration with two lifting surfaces of wing and horizontal tail. Two first order linear differential equations are applied to describe the unsteady effects on the wing, and the dynamic process of downwash angles induced by the wing which has influences on the aerodynamic response of horizontal tail, respectively. Model parameters are estimated from the aerodynamic data of static and large amplitude pitching forced oscillation tests conducted in a low speed wind tunnel, using the maximum likelihood method. The results demonstrate the validity of the proposed model.

Longitudinal aerodynamic modeling. In this article, the aerodynamic response is divided into a steady term with attached flow contribution, a quasi-steady term with pure rotation and incidence acceleration contribution, and an unsteady term with dynamic flow contribution. Thus, the longitudinal aerodynamic model can be described

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The authors declare that they have no conflict of interest.

as follows:

$$C_i = C_{i\mathrm{att}}(\infty,\alpha) + C_{i\mathrm{q}}(\infty,\alpha)\frac{\bar{c}\dot{\alpha}}{2V} + C_{i\mathrm{dyn}}(t,\alpha), \quad (1)$$

where $i = N, m$ for which N represents the normal force and m stands for the pitching moment. $\bar{c}$ is the mean aerodynamic chord and V is the wind speed. The symbol ∞ indicates the steady state. Thus, the steady term $C_{i\mathrm{att}}(\infty,\alpha)$ and quasi-steady term $C_{i\mathrm{q}}(\infty,\alpha)$ are only dependent on angles of attack. They can be modeled in the form of high order polynomials about incidences and fourth order is applicable in practice. However, the unsteady term $C_{i\mathrm{dyn}}(t,\alpha)$ is related to the motion time histories t and it is crucial for the longitudinal unsteady aerodynamic modeling. Considering the wing and horizontal tail combination of the specific combat aircraft configuration, the unsteady term consists of the wing and horizontal tail contributions along with their interactions. In this article, the effective angle of attack for the horizontal tail, which is dependent on the downwash angle and horizontal tail arm, is introduced to describe the wing effects on horizontal tail. Besides, it is assumed that the horizontal tail dose not affect the aerodynamic response of the wing. So the unsteady term can be divided into two parts, the wing contribution and the horizontal tail contribution which is dependent on the effective angle. It has the form as follows:

$$C_{i\mathrm{dyn}}(t,\alpha) = C^{\mathrm{W}}_{i\mathrm{dyn}}(t,\alpha) + C^{\mathrm{T}}_{i\mathrm{dyn}}(t,\alpha_{\mathrm{t}}), \quad (2)$$

where $C^{\mathrm{W}}_{i\mathrm{dyn}}(t,\alpha)$ represents the wing contribution to unsteady aerodynamics and $C^{\mathrm{T}}_{i\mathrm{dyn}}(t,\alpha_{\mathrm{t}})$ stands for the horizontal tail contribution. α_{t} means the effective angle of attack for the horizontal tail and it can be expressed as follows:

$$\alpha_{\mathrm{t}} = \alpha - \alpha_d - \varepsilon(t,\alpha), \quad (3)$$

where $\alpha_d = \frac{l_{\mathrm{t}}}{V}\dot{\alpha}$ is the dynamic angle of attack associated with the horizontal tail arm l_{t}. $\varepsilon(t,\alpha)$ represents the downwash angle at time t and its dynamic process can be described by a first order differential equation as follows:

$$\tau_{\varepsilon}(\alpha)\dot{\varepsilon}(t,\alpha) + \varepsilon(t,\alpha) = \varepsilon(\infty,\alpha), \quad (4)$$

where $\tau_{\varepsilon}(\alpha)$ is the characteristic time and $\varepsilon(\infty,\alpha)$ stands for the downwash angle in the steady state.

The wing contribution $C^{\mathrm{W}}_{i\mathrm{dyn}}(t,\alpha)$ in (2) is related to time histories and its dynamic process can also be characterized by a first order differential equation as follows:

$$\tau_{\mathrm{W}}(\alpha)\dot{C}^{\mathrm{W}}_{i\mathrm{dyn}}(t,\alpha) + C^{\mathrm{W}}_{i\mathrm{dyn}}(t,\alpha) = C^{\mathrm{W}}_{i\mathrm{dyn}}(\infty,\alpha), \quad (5)$$

where $\tau_{\mathrm{W}}(\alpha)$ is the characteristic time and $C^{\mathrm{W}}_{i\mathrm{dyn}}(\infty,\alpha)$ means the steady state of the wing contribution. The tail contribution $C^{\mathrm{T}}_{i\mathrm{dyn}}(t,\alpha_{\mathrm{t}})$ in (2) is also related to time histories and dependent on the effective angle of attack α_{t}. Known from (3) and (4), α_{t} already contains a dynamic process. Thus, $C^{\mathrm{T}}_{i\mathrm{dyn}}(t,\alpha_{\mathrm{t}})$ can be simply modeled in the form of fourth order polynomials about α_{t}.

Acoording to (4) and (5), the characteristic times $\tau_{\mathrm{W}}(\alpha)$, $\tau_{\varepsilon}(\alpha)$ and the downwash angle in steady state $\varepsilon(\infty,\alpha)$ are all dependent on angles of attack. They can be represented by the 4th order polynomials about angles of attack. Although, the steady state $C^{\mathrm{W}}_{i\mathrm{dyn}}(\infty,\alpha)$ in the right side of (5) can also apply a high order polynomial to describe its dependency of incidences. For the purpose of reducing unknown parameters to improve estimation accuracy, it can be solved by the static aerodynamic model as follows:

$$C_{i\mathrm{st}} = C_{i\mathrm{att}}(\infty,\alpha) + C^{\mathrm{W}}_{i\mathrm{dyn}}(\infty,\alpha) + C^{\mathrm{T}}_{i\mathrm{dyn}}(\infty,\alpha_{\mathrm{t}\infty}), \quad (6)$$

where $C_{i\mathrm{st}}$ is the static aerodynamics which can be directly obtained from wind tunnel static tests. $C^{\mathrm{T}}_{i\mathrm{dyn}}(\infty,\alpha_{\mathrm{t}\infty})$ is the steady state of the horizontal tail dynamic process, which has the same model with $C^{\mathrm{T}}_{i\mathrm{dyn}}(t,\alpha_{\mathrm{t}})$ but replacing the effective angle of attack α_{t} with its steady state $\alpha_{\mathrm{t}\infty}$ which can be formulated as follows

$$\alpha_{\mathrm{t}\infty} = \alpha - \alpha_d - \varepsilon(\infty,\alpha). \quad (7)$$

Summing up (1) to (7), the longitudinal unsteady aerodynamic model for an advanced combat aircraft is proposed. The complete equations of the model can be found in Appendix A.

Model parameters estimation. The unknown parameters in the proposed model can be estimated by applying the maximum likelihood method [7] to the measured aerodynamic data of wind tunnel static and pitching forced oscillation tests. It is an iterative process to obtain the optimal estimation of unknown parameters and the multiple correlation coefficient R^2 [8] is chosen as a stopping criterion. Its metric value varies between 0 and 1, and it is an indicator of model accuracy. The model outputs fit better with true values when the metric value is closer to 1.

It is worth noticing that the initial values of unknown parameters for iterative optimization can largely affect modeling results. Inappropriate initial values are likely to get the iteration process trapped into a local optimization and even diverged. In order to get appropriate initial values, we apply the least squares method to deal with wind tunnel data in advance. Another notice is that the characteristic time $\tau_{\mathrm{W}}(\alpha)$ and $\tau_{\varepsilon}(\alpha)$

should be kept greater than zero during the parameters estimation process.

Wind tunnel tests. The static tests and large amplitude pitching forced oscillation tests for the advanced combat aircraft model were conducted in a 3.5-by-2.5 meter low speed wind tunnel called FL-8 at AVIC Aerodynamics Research Institute. The aircraft model was mounted at the hydraulic dynamic test rig for two degrees of freedom large amplitude oscillations which is showed in Figure 1. All tests were performed in the conditions that the sideslip angle $\beta = 0°$, the wind speed $V = 30$ m/s, the leading edge flap deflection $\delta_{\rm lef} = 30°$ and other control surface deflections set at 0°. Appendix B presents detailed test conditions and results.

Figure 1 (Color online) Pitching forced oscillation tests in wind tunnel.

Modeling results and analysis. The static test data are extended through linear interpolation to a wide range of incidences. The dynamic test data are divided into two groups. One is for the estimation of model parameters and the other is for the verification of model validity. The results show that the model outputs for the normal force and pitching moment coefficients are in considerable accordance with not only the test data chosen for model identification, but also other data which are not utilized before. Besides, the multiple correction coefficients R^2 are calculated and most of them are greater than 0.99 which indicates a satisfying modeling result with a good capacity of model fitting and predicting. All the modeling results are recorded in Appendix B.

The model outputs for the pitching moment coefficient are slightly worse by contrast with the normal force coefficient. Especially in the range of incidences between 30° and 50°, the model output curves show obvious depression and difference from wind tunnel test curves. Note that this characteristic coincides with the static test curve in the same range of incidences.

By contrast, the conventional aerodynamic model without considering unsteady effects which is known as the quasi-steady model can be formulated just subtracting the unsteady term $C_{i\rm dyn}(t, \alpha)$ in (1). Its modeling results show that there are notable deviations between the quasi-steady model outputs and test data, especially in large angles of attack that are greater than 40°. It implies that the unsteady aerodynamics are considerable in high incidences and should be specifically considered for aerodynamic modeling.

Conclusion. In this article, the longitudinal unsteady aerodynamic model for an advanced combat aircraft is proposed and identified from wind tunnel test data. The results demonstrate the validity of the proposed model. The model outputs for the pitching moment coefficient in the range of incidences between 30° and 50° are slightly different from wind tunnel test data which requires further investigation.

Acknowledgements The advanced combat aircraft configuration model was made and corresponding wind tunnel tests were conducted by AVIC Aerodynamics Research Institute. The authors thank their great contributions to this work.

Supporting information Appendixes A and B. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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