Engineering Notes

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"Spilled" Leading-Edge Vortex Effects on Dynamic Stall Characteristics

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Introduction

In response to a request from Dr. McCroskey in connection with his recent review of dynamic stall[1] the engineering analysis methods of Ref. 2 were applied to predict the dynamic stall characteristics of the NACA-0012 airfoil describing large-amplitude oscillations around the quarter chord axis. Because of the very high pitch rates existing at the time of (dynamic) stall very large transient effects of the "spilled" leading edge vortex were observed in the test.[1,3] The question was therefore raised as to the possibility of incorporating the "spilled" vortex effects in the analysis of Ref. 2 without destroying its simplicity. The present Note describes how this can be done. (The nomenclature of Ref. 2 will be followed.)

Discussion

Comparing the large-amplitude oscillatory data of McCroskey et al.[3] (Fig. 1) with the α ramp data of Ham et al.[4] (Fig. 2) one finds great similarities in the "upstroke" characteristics. It appears that the first half cycle of the post-stall oscillation in Fig. 2 is captured by the large-amplitude oscillation in Fig. 1. It is discussed in Ref. 5 how the ramp data by Ham et al.[4] are similar to those obtained by Lambourne[6] at high subsonic speed where shock-induced flow separation is the prevailing stall type. In both cases the separation point is describing a pseudo-harmonic oscillation around a quasi-steady mean position. In the low-speed stall case the separation point overshoots all the way to the leading edge in the first half cycle before a leading-edge vortex is "spilled." In subsequent oscillatory cycles the separation point does not reach as far forward, and the "spilled" vortices become more diminutive.[7] Figure 1 shows that it can be important to include the transient "spilled" vortex effect.

McCroskey et al.[3] measured the phase angle (ωt) at which three dynamic events take place, viz., Begin of Moment Stall, $c_{n\,max}$, and $-c_{m\,max}$ (Fig. 3). The first event should coincide with the phase angle $(\omega t)_{vs}$ at which the leading-edge vortex is (first) "spilled" downstream. The analysis method of Ref. 2 can be applied to give this phase angle $(\omega t)_{vs}$. First the quasi-steady phase angle $(\omega t)_s$, from which the transient pseudo-harmonic oscillation starts, is determined as follows

$$\alpha_s + K_a \Delta\theta \bar{\omega} \cos(\omega t)_s = \alpha_o + \Delta\theta \sin[(\omega t)_s - \theta] \quad (1)$$

For the special case $\alpha_0 = \alpha_s$, Eq. (1) gives

$$(\omega t)_s = \tan^{-1}\left(\frac{K_a \bar{\omega} + \sin\phi}{\cos\phi}\right) \quad (2)$$

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The test data in Figs. 1 and 3 are for $\alpha_o = 15°$. According to the available static data [8] the stall angle for NACA-0012 is $\alpha_s = 15.5°$ for an effective Reynolds number of 3.5 million. The test data in Figs. 1 and 3 are for $Re = 2.5 \times 10^6$, and Eq. (2) should be valid (within the expected accuracy). At high frequencies the left-hand side of Eq. (1) is limited to the "infinite" Reynolds number limit $(\alpha_s)_{Re\to\infty}$. In Fig. 3 this "ceiling" happens to coincide with the frequency $\bar{\omega} = 0.16$, at which the Karman-Sears wake lag $\phi = 1.5\,\bar{\omega}$ reaches its saturation limit, $\phi = 0.245$. For the 25% oscillation center one has $K_a = 3$, giving the $(\omega t)_s$ values shown by the solid line in Fig. 3.

If one wants to include the first half cycle of the transient oscillatory phase and compute $(\omega t)_{vs}$, this can be done by including the moving separation point effect in Eq. (1). This gives[2] (again for $\alpha_0 = \alpha_s$)

$$(\omega t)_{vs} = \tan^{-1}\left(\frac{K_a \bar{\omega} + \sin(\phi + \phi_s)}{\cos(\phi + \phi_s)}\right) \quad (3)$$

McCroskey et al.[3] showed that the dynamic stall for the data shown in Fig. 3 is for a turbulent boundary layer. Thus, $\phi_s = 0.75\bar{\omega}$ according to our engineering analysis.[2,9] Equation (3) gives the $(\omega t)_{vs}$ values shown by the dashed line in Fig. 3. The agreement with the corresponding measured event, Begin of Moment Stall, is very satisfactory.

According to measurements,[10,11] the "spilled" leading-edge vortex travels down the chord with a velocity $\bar{U}_v \approx 0.55\, U_\infty$. The phase lag, $(\Delta\omega t)_{vTE}$, corresponding to the time needed for the vortex to travel from the leading edge to the trailing edge is simply

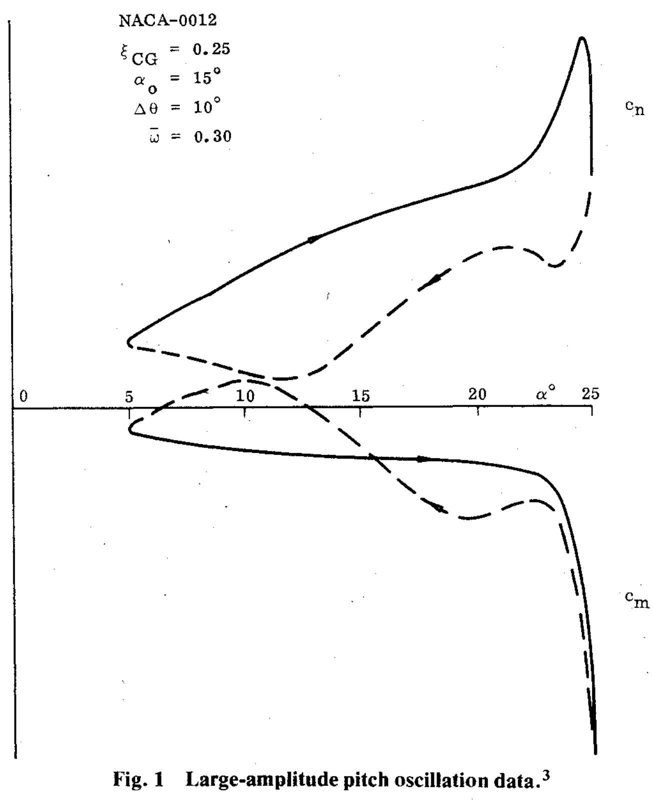

Fig. 1 Large-amplitude pitch oscillation data.[3]

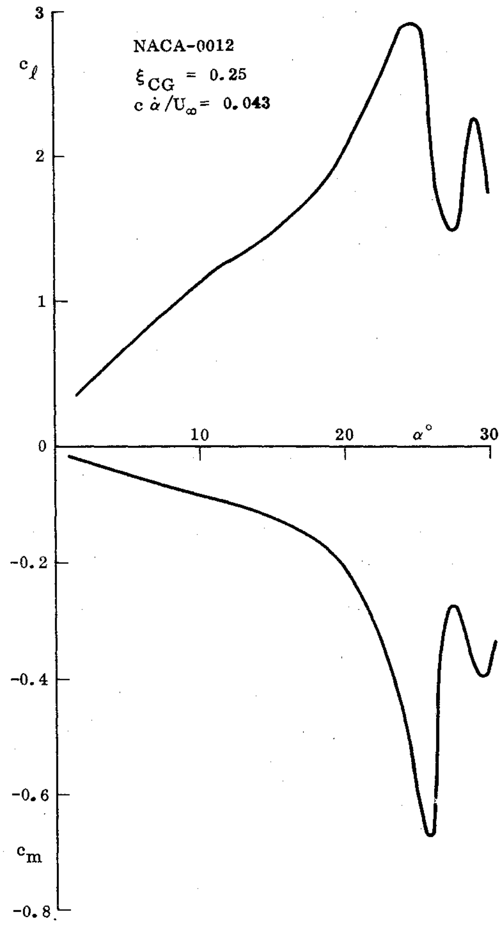

Fig. 2 Data for α ramp overshoot of static stall.[4]

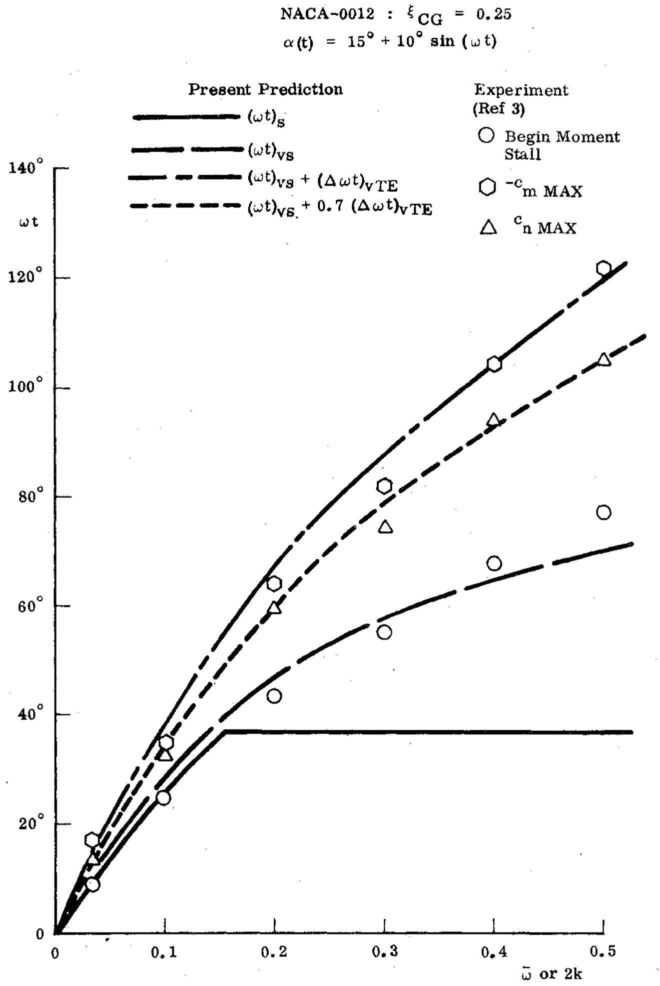

Fig. 3 Comparison between predicted and measured phase angles for dynamic stall events.

$$(\Delta\omega t)_{vTE} = (U_\infty / \bar{U}_v)\bar{\omega} \approx 1.8\bar{\omega} \quad (4)$$

Adding this phase lag to $(\omega t)_{vs}$ gives the phase angle for vortex passage over the trailing edge, which is shown by the dash-dotted line in Fig. 3. It agrees very well with the measured phase lag for the occurrence of $-c_{m\text{MAX}}$. The moment should, of course, peak just before the vortex leaves the airfoil[12]; and $c_{n\text{MAX}}$ should occur somewhat earlier.[12] The test data in Fig. 3 indicate that the phase lag that should be added to $(\omega t)_{vs}$ to predict the occurrence of $c_{n\text{MAX}}$ is approximately 70% of $(\Delta\omega t)_{v\text{TE}}$. This estimate is shown by the short-dashed line in Fig. 3.

With the phase characteristics of the "spilled" vortex phenomenon known, it remains to determine the magnitude of the vortex-induced load before the full effects on dyanmic stall characteristics can be predicted. The transient "spilled" leading-edge vortex is the two-dimensional time-dependent equivalent to the three-dimensional steady-state leading-edge vortex shedding off a highly swept leading edge. For a sharp-edged delta wing with apex half angle θ_{LE} and center chord c_0, Polhamus' leading-edge suction analogy[13] gives the following vortex-induced normal force

$$n_v = q_\infty c_0 \bar{c} \pi \sin^2\alpha \quad (5)$$

where

$$\bar{c} = (c_0/2)\tan\theta_{\text{LE}}$$

The angle of attack normal to the leading edge is

$$\alpha_\perp = \tan^{-1}\left(\frac{\tan\alpha}{\sin\theta_{\text{LE}}}\right) \quad (6)$$

The corresponding dynamic pressure $q_\perp$ as a fraction of freestream dynamic pressure, q_∞, is

$$q_\perp / q_\infty = \sin^2\alpha + \cos^2\alpha \sin^2\theta_{\text{LE}} \quad (7)$$

Combining Eqs. (5)-(7) gives the following average strip load

$$c_{n\perp} = n_v / q_\perp c_0 \bar{c} = \pi \sin^2\alpha_\perp \quad (8)$$

With $\alpha_\perp$ subsituted by the stall angle, Eq. (8) should give an estimate of the normal force associated with the "spilled" leading-edge vortex. Static data show the lift $\Delta c_{\ell v}$ lost with the "spilled" leading-edge vortex (see inset in Fig. 4). With $\Delta c_{\ell v} = c_{n\perp} \cos\alpha$, Eq. (8) gives rather good prediction of the measured vortex lift loss[8,14] (Fig. 4).

The effect on $-(c_{m\,\text{MAX}})_{\text{DYN}}$ of the vortex travel from the leading edge to the trailing edge is simply

$$-(\Delta c_{m\,\text{MAX}})_v = (\Delta c_{n\,\text{MAX}})_v \quad (9)$$

For the data in Fig. 1, the predicted vortex effect is

$$-(\Delta c_{m\,\text{MAX}})_v = (\Delta c_{n\,\text{MAX}})_v = 0.49$$

This compares reasonably well with the experimental values[15] $0.44 \le \Delta c_{n\,\text{MAX}} \le 0.68$; $0.5 \le -\Delta c_{m\,\text{MAX}} \le 0.7$.

Conclusions

An analysis of experimentally observed large effects of the "spilled" leading-edge vortex on dynamic stall characteristics has shown that the simple engineering analysis described in

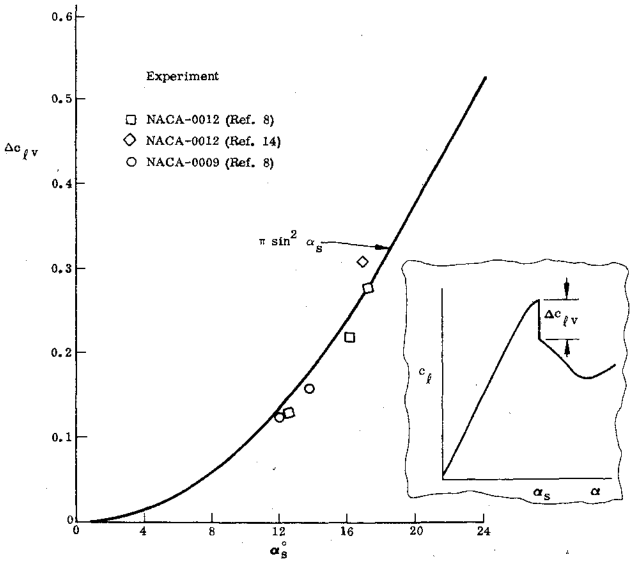

Fig. 4 Comparison between predicted and measured lift loss due to "spilled" leading-edge vortex.

Refs. 2 and 9 can, without undue complications, be extended to include the "spilled" vortex effects. These effects are always important when predicting $c_{n\,\mathrm{MAX}}$ and $-c_{m\mathrm{MAX}}$ during dynamic stall, whereas the effects on the damping in pitch become important only at rather high frequencies. At $\bar{\omega}=0.30$, for example, the α width of the vortex-induced c_m peak is very modest and does not significantly affect the enclosed area‡ (see Fig. 1). The simple means by which the "spilled" leading-edge vortex effects can be described are as follows. The initial transient phase during which the separation point overshoots its quasi-steady position can be desribed by including the moving separation point effect[2,9], and the subsequent transient phase during which the "spilled" vortec travels from the leading edge to the trailing edge can be described by a simple application of the concept of equivalence between the time-dependent two-dimensional "spilled" leading-edge vortex and the stationary three-dimensional leading-edge vortex existing on sharp-edged slender delta wings. The agreement between predictions based on this very simple "spilled" vortex concept and large-amplitude dynamic experimental data is such that the concept merits further study.

References

[1] McCroskey, W.J., "Recent Developments in Dynamic Stall," Symposium on Unsteady Aerodynamics, University of Arizona, Tucson, Ariz., March 18-20, 1975.

[2] Ericsson, L.E. and Reding, J.P., "Dynamic Stall Analysis in Light of Recent Numerical and Experimental Results," *Journal of Aircraft*, this issue, pp.

[3] McCroskey, W.J., Carr, L.W., and McAllister, K.W., "Dynamic Stall Experiments on Oscillating Airfoils," AIAA Paper No. 75-125, Washington, D.C., Jan. 1975.

[4] Ham, N.D. and Garelick, M.S., "Dynamic Stall Considerations in Helicopter Rotors, *Journal of the American Helicopter Society*, Vol. 13, April 1968, pp. 44-55.

[5] Ericsson, L.E., "Dynamic Effects of Shock-Induced Flow Separation," *Journal of Aircraft*, Vol. 12, Feb. 1975, pp. 86-92.

[6] Lambourne, N.C., "Some Instabilities Arising from the Interaction Between Shock Waves and Boundary Layers," Aeronautical Research Council, Great Britain., C.P. No. 473, Feb. 1958.

[7] Martin, J.M., Empey, R.W., McCroskey, W.J., and Caradonna, F.X., "An Experimental Analysis of Dynamic Stall on an Oscillating Airfoil," *Journal of the American Helicopter Society*, Vol. 19, Jan. 1974, pp. 26-32.

‡This is, of course, the reason why the measured stall-induced negative aerodynamic damping[16] could be predicted by a theory[2,9] that did not include the "spilled" vortex effect.

[8] Jacobs, E.N. and Sherman, A., "Airfoil Section Characteristics as Affected by Variations in the Reynolds Number," NACA Tech. Rept. 586, 1937.

[9] Ericsson, L.E. and Reding, J.P., "Analytic Prediction of Dynamic Stall Characteristics," AIAA Paper No. 72-682, Boston, Mass., June 1972.

[10] Philippe, J-J., "Le Decrochage Instationnaire d'un Profil," TP No. 936, 1938, ONERA.

[11] Werle, H. et Armand, C., "Mesures et Visualisations Instationnaires sur les Rotors," ONERA T.P. No. 777, 1969.

[12] Ericsson, L.E. and Reding, J.P., "Dynamic Stall of Helicopter Blades," *Journal of the American Helicopter Society*, Vol. 8, April, pp. 193-199.

[14] Critzos, C.C., Heyson, H.H., and Boswinkle, R.W. Jr., "Aerodynamic Characteristics of NACA-0012 Airfoil Section at Angles of Attack from 0° to 180°," NACA TN 3361, 1955.

[15] McCroskey, W.J., private communication, April 3, 1975.

[16] Liiva, J., Davenport, F.J., Gray, L., and Walton, I.C., "Two-Dimensional Tests of Airfoils Oscillating Near Stall," TR 68-13, April 1968, U.S. Army Aviation Labs.

Captive Testing for Conducting Aircraft Motion Analysis Studies

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Introduction

WHEN an aircraft experiences an external configuration change (addition of stories, airframe modification, etc.), the aerodynamic data matrix used to describe the aircraft in analytical motion simulation is often invalidated. In the past, the aerodynamist has modified the original data matrix to account for configuration changes either empirically or by acquiring new aerodynamic data from additional wind tunnel tests. An alternate approach for investigating aircraft motion sensitivity to external configuration changes is through captive wind tunnel testing. Captive testing has been used successfully by the Royal Aircraft Establishment for investigating the lateral/directional stability characteristics of aircraft.[1] A pilot test[2] conducted in the AEDC Aerodynamic Wind Tunnel (4T) investigated captive testing as a tool for defining aircraft departure characteristics. Because of the success of these tests, the possibility of conducting aircraft motion analysis studies in the AEDC Propulsion Wind Tunnel (16T) with captive testing becomes attractive.

Description of Captive System

Captive testing is accomplished through a closed-loop system consisting of the model balance, model support system, and digital computer shown in Fig. 1. The test article is installed in the wind tunnel on a 6-component internal straingage balance. The model and balance are supported by a high pitch/roll positioning system.

The model is initially positioned at some angle of attack and sideslip depending on the nature of the maneuver to be generated. The model forces and moments are measured and fed input to an on-line digital computer. These measured aerodynamic data, along with the wind tunnel operating conditions, model mass characteristics, control deflection

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