Technical Comments

Comment on Unsteady Airfoil Stall

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THE results on unsteady airfoil stall presented by F. O. Carta at the AIAA Fifth Aerospace Sciences Meeting[1] showed very large effects of frequency on the $C_N(\alpha)$ loops of a pitching airfoil (Fig. 1). These effects were so large, in fact, that this author suspected that the frequency effects may have brought about a change from leading-edge airfoil stall to the so-called sudden stall.[2-4] It did not, however, take long to realize that the thin airfoil stall (or sudden stall) could not be associated with the 12%-thick NACA 0012 airfoil tested by Carta. It was of some concern to this author to find out what caused these large frequency effects, as they may indicate that similar large frequency effects can occur for the unsteady separated flow on bodies of revolution.[5,6]

The forces on an airfoil oscillating in pitch will deviate from the static forces realized at the instantaneous angle of attack due to 1) the frequency-induced normal velocity distribution over the airfoil, the so-called q effect, and 2) the effect of angle of attack rate of change, the so-called $\dot{\alpha}$ effect.

The q effect can be visualized as a frequency-induced camber (Fig. 2a). That is, on the "upstroke" the pitching airfoil has positive camber, on the "downstroke" it has negative camber. Thus, the oscillating airfoil will describe a loop enclosed by the static characteristics obtained for airfoils with the maximum and minimum frequency-induced cambers σ^+ and σ^-, as is illustrated in Fig. 2a. The large effects on C_N shown in Fig. 2a are not for illustration purposes only, but are realistic. The frequency-induced cambers $|\sigma|$ for the airfoil in Fig. 1 are 1° and 4° at $f = 4$ and 16 cps respectively.

The $\dot{\alpha}$ effect can be visualized as frequency-induced plunging, i.e., a change of the "mean" velocity vector (Fig. 2b). It is obvious that it will take a certain time (Δt_2) before the boundary-layer build-up, and, therefore, the stall has responded to the α change. A less obvious, but probably even more important, effect is the so-called "accelerated flow effect",[7] that is, the delay (Δt_3) in pressure-gradient build-up and corresponding "overshoot" in $C_{N_{max}}$ (Fig. 2b). The oscillating (plunging) airfoil will describe the loop shown in Fig. 2b. The combined q and $\dot{\alpha}$ effects will give the C_N loop shown in Fig. 3 as a function of instantaneous angle of attack $\alpha(t)$. This loop has a marked resemblance to the loop for $f = 4$ cps in Fig. 1. In order to get to the loop for $f = 16$

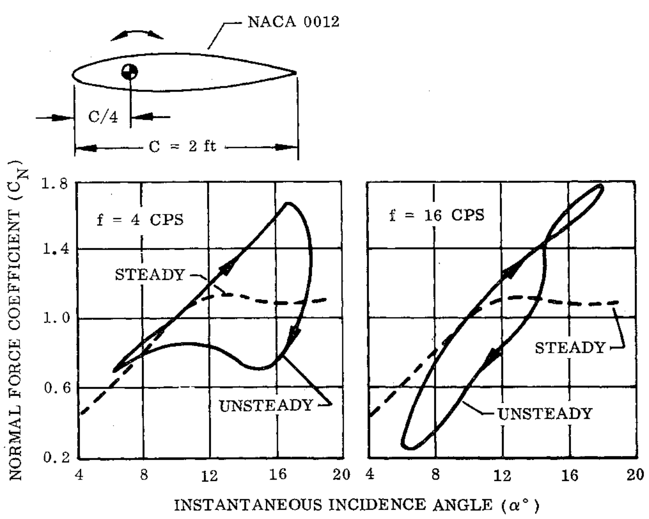

Fig. 1 Unsteady normal force loops at $M = 0.3$ for $\Delta\alpha = 6°$ and $\alpha_{mean} = 12°$.

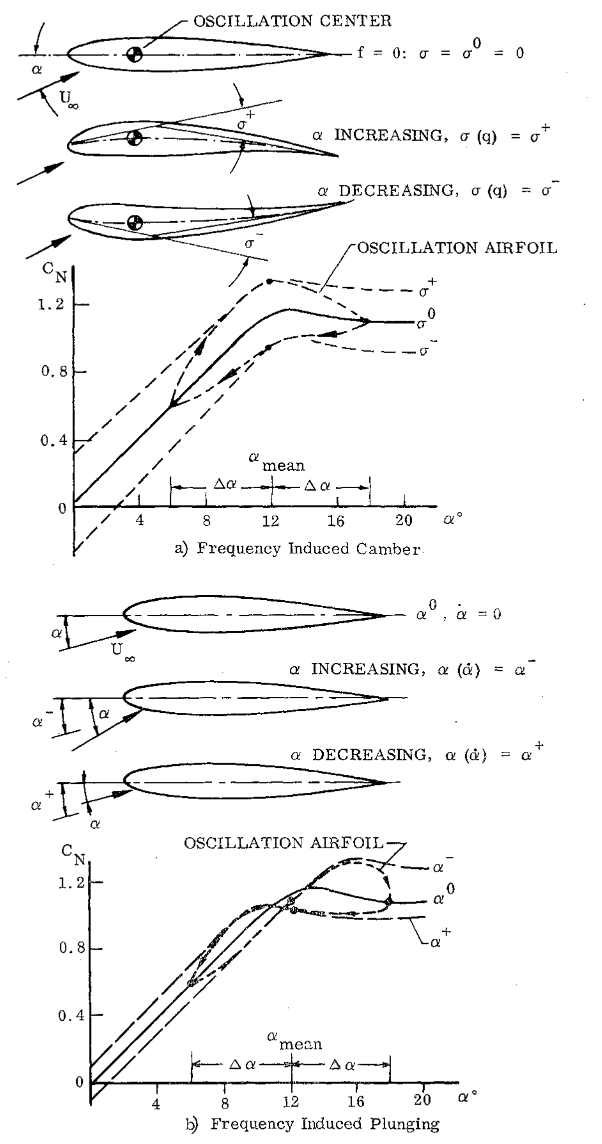

Fig. 2 Unsteady normal force loops.

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cps in Fig. 1, one must systematize the loop-production somewhat. If one assumes that the time-lag effects can be lumped into one single time lag Δt (reasonable for $\Delta t \approx \Delta t_2 + \Delta t_3$ with either $\Delta t_1 = 0$ or $\Delta t_1 = \Delta t_2$),† one may draw the static characteristics, including the $\dot{\alpha}$-induced overshoot (and undershoot) of $C_{N_{\max}}$ (Fig. 3), vs an effective angle of attack $\tilde{\alpha}$, as shown in Fig. 4a. A transformation to instantaneous angle of attack α can be accomplished by use of the α and $\tilde{\alpha}$ curves vs phase angle $\psi = \omega t$, where $\omega = 2\pi f$. Letting Fig. 4a illustrate the case of $f = 4$ cps, the phase lag $\omega\Delta t$ is small and the $C_N(\alpha)$ loop is not much different from the $C_N(\tilde{\alpha})$ loop. However, in the case of $f = 16$ cps, the phase lag $\omega\Delta t$ is four times larger and the deformation of the $C_N(\tilde{\alpha})$ loop when transformed to $C_N(\alpha)$ is substantial (Fig. 4b). Assuming a 45° phase lag, the $C_N(\alpha)$ loop takes great similarity to the loop shown for $f = 16$ cps in Fig. 1. Can the phase lag be as large as 45°? The answer is yes. With freestream velocity, a disturbance would require $\Delta t = \frac{2}{330}$ sec (the cord of the airfoil used by F. O. Carta was 2 ft) to travel between leading and trailing edges. The corresponding phase lag at 16 cps would be 35°. It is the boundary layer, not at the trailing edge, but closer to the separation point that triggers stall. That is, the foregoing estimate would be too high for Δt_2, even considering the fact that the boundary-layer build-up goes considerably slower than with freestream velocity. However, the time lag Δt_3 due to the accelerated flow effect is probably of the same order of magnitude as Δt_2,[5] and $\omega\Delta t = 45°$ is a perfectly reasonable value at $f = 16$ cps.

In the linear portions of $C_N(\alpha)$, the unsteady C_N would be proportional to $\tilde{\alpha}$, i.e., $C_N \approx C_{N\alpha}\alpha(t - \Delta t)$ where, in the case of harmonic oscillations $\alpha(t) = \alpha_0 e^{i\omega t}$, $\alpha(t - \Delta t)$ becomes

$$\begin{aligned}\alpha(t - \Delta t) &= e^{-i\omega\Delta t}\alpha(t)\\ &= [\cos(\omega\Delta t) - i\sin(\omega\Delta t)]\alpha(t)\\ &= \cos(\omega\Delta t)\alpha(t) - \omega^{-1}\sin(\omega\Delta t)\dot{\alpha}(t)\end{aligned}$$

Using c/U_∞ as the characteristic time, the lag Δt_2 to the separation location $x_s = c\xi_s$ is

$$\Delta t = \xi_s(U_\infty/U)(c/U_\infty)$$

and for small phase angles $\omega\Delta t$

$$\omega^{-1}\sin(\omega\Delta t)\dot{\alpha} = (\xi_s + \eta)(U_\infty/U)(c\dot{\alpha}/U_\infty)‡$$

That is, the unsteady effects due to time lag are proportional to the reduced frequency $c\dot{\alpha}/U_\infty (c\dot{\alpha}/U_\infty = 2A$ using Carta's nomenclature) and the unsteady time-lag effects can be scaled by using $c\dot{\alpha}/U_\infty$ (or A), provided the phase angle is small.

Similarly, the q-induced camber is $|\sigma| = cq/U_\infty = c\dot{\alpha}/U_\infty$, and for reasonable small values on σ the camber-induced

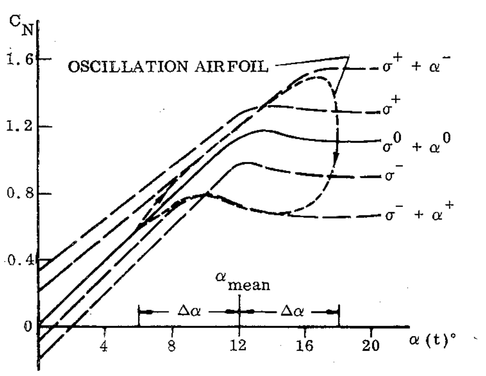

Fig. 3 Combined q and $\dot{\alpha}$ effect for pitching airfoil.

† Δt_1 is the possible time lag in realizing the frequency-induced camber.

‡ Inclusion of η accounts for the accelerated flow effect Δt_3.[5]

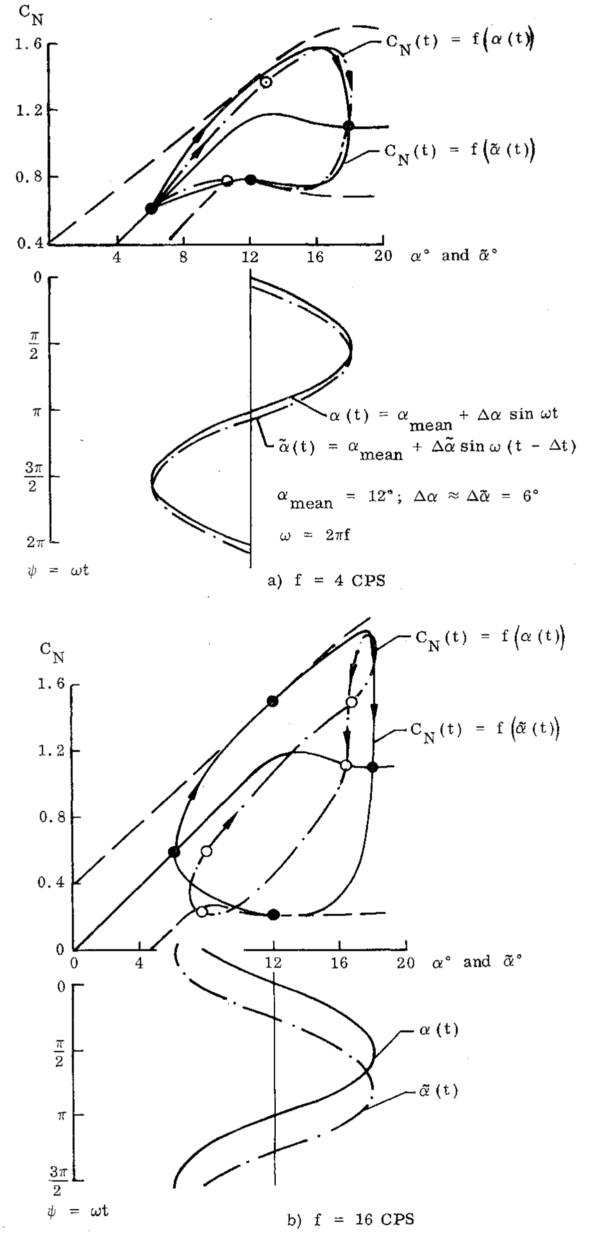

Fig. 4 $C_N(t)$ as a function of $\tilde{\alpha}(t)$ and $\alpha(t)$.

change in C_N would also be proportional to A. Consequently, Carta's scaling of the experimental data to apply to the distorted flow effect should correctly scale the time lag and q effects, at least for reasonably low reduced frequencies ($A < 0.10$). However, the accelerated flow effect on $C_{N_{\max}}$ can probably not be scaled correctly by using the concept of "equivalent local sinusoid." Rather, airfoil data for rampwise changes of $\alpha(\dot{\alpha} =$ constant)[8] are needed before a better resolution of the stall behavior is possible. There is also, in all likelihood, static hysteresis associated with the stall behavior.[9] That is, part of the stall loop is insensitive to $\dot{\alpha}$ and remains even when $\dot{\alpha}$ goes to zero.[9] These nonlinear effects (both in amplitude and frequency) will probably not seriously affect the trends that Carta wanted to illustrate.

References

[1] Carta, F. O., "The unsteady normal force response of an airfoil in a periodically distorted inlet flow including stalling effects," AIAA Paper 67-18 (1967); also J. Aircraft 4, 416–421 (1967).

[2] McCullough, G. B. and Gault, D. E., "Examples of three representative types of airfoil-section stall at low speed," NACA TN 2502 (1951).

[3] McCullough, G. B., "The effect of Reynolds number on the stalling characteristics and pressure distributions of four moderately thin airfoil sections," NACA TN 3524 (1955).

[4] Ewans, W. T. and Mort, K. W., "Analysis of computed flow parameters for a set of sudden stalls in low-speed two-dimensional flow," NASA TND-85 (1959).

[5] Woods, P. and Ericsson, L. E., "Aeroelastic considerations in a slender blunt-nose, multistage rocket," Aerospace Eng. **21**, 42–51 (May 1962).

[6] Ericcson, L. E. and Reding, J. P., "Analysis of flow separation effects on the dynamics of a large space booster," J. Spacecraft Rockets **2**, 481–490 (1965).

[7] Ericsson, L. E., "Aeroelastic instability caused by slender payloads," J. Spacecraft Rockets **4**, 69–73 (1967).

[8] Lambourne, N. C., "Experiment on an airfoil at $M = 0.75$ reported by W. P. Jones in the 1961 Minta Martin Lecture, research on unsteady flow," J. Aerospace Sci. **29**, 249–263 (March 1962).

[9] Ericsson, L. E., "Separated flow effects on the static and dynamic stability of blunt nosed cylinder flare bodies," Lockheed Missiles & Space Co., LMSC/667991 (1965).

Erratum: "Thrust Performance of Suppressor Nozzles"

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[J. Aircraft **3**, 587–588 (1966)]

THE statement between Eqs. (5) and (6) should read: "The peak velocity coefficient of Eq. (2) is represented in terms of the maximum velocity coefficient c_{vs} of the standard convergent nozzle by replacing D with $D_{he} = 1$ and 4θ with $1 - c_{vs}/(D_{he})^n$."

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Announcement: Change in Style for References in AIAA Publications

The Committee of Engineering Society Editors, of the Engineers Joint Council, has recommended a standard style for references in engineering publications. In the interest of reducing the burden on authors and editors and minimizing confusion, the AIAA Publications Department has decided to follow the recommended style. Examples of the new style will be found below and on the inside back cover of all AIAA journals. The changes will be effective with manuscripts scheduled for the January 1968 issues and thereafter.

Example—Journals

Walker, R. E., Stone, A. R., and Shandor, M., "Secondary Gas Injection in a Conical Rocket Nozzle," *AIAA Journal*, Vol. 1, No. 2, Feb. 1963, pp. 334–338.

Examples—Books

Turner, M. J., Martin, H. C., and Leible, R. C., ' Further Development and Applications of Stiffness Method," *Matrix Methods of Structural Analysis*, 1st ed., Vol. 1, Macmillan, New York, 1964, pp. 203–266.

Segrè, E., ed., *Experimental Nuclear Physics*, 1st ed., Vol. 1, Wiley, New York, 1953, pp. 6–10.

Example—Reports

Book, E. and Bratman, H., "Using Compilers to Build Compilers," SP-176, Aug. 1960, Systems Development Corp., Santa Monica, Calif.

Example—Transactions or Proceedings

Soo, S. L., "Boundary Layer Motion of a Gas-Solid Suspension," *Proceedings of the Symposium on Interaction between Fluids and Particles*, Institute of Chemical Engineers, Vol. 1, 1962, pp. 50–63.