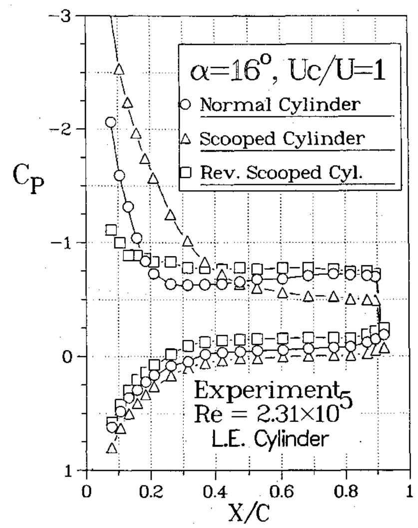

Fig. 6 Effect of different leading-edge cylinder configurations on the pressure distribution around the Joukowsky airfoil: $U_c/U = 1$; $\alpha = 16$ deg.

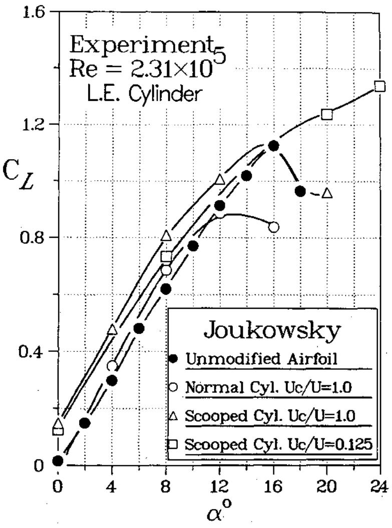

Fig. 7 Plots showing improvements in the lift coefficient of a Joukowsky airfoil with various leading-edge cylinder configurations and speeds.

The partially separated flow with the solid cylinder is reattached when the normal scoop configuration is used but completely detaches with the reversed scoop.

The corresponding lift data are summarized in Fig. 7. Typical results for a normal solid cylinder at $U_c/U = 1$ are also included to facilitate comparison. A slight shift of the lift plots to the left suggests a small increase in circulation due to the scooped geometry. The main advantage of the scooped geometry is that it can provide the same beneficial effect of the normal rotating cylinder but at a much lower speed. Note that this configuration substantially delays separation leading to higher $C_{L\max}$ and delayed separation, however, at a relatively lower speed. The concept appears promising and needs to be explored further.

It may be pointed out that the wind-tunnel test results were complemented by an extensive flow-visualization study carried out in a closed-circuit water channel. The model was constructed from Plexiglas and fitted with a leading-edge cylinder driven by a compressed-air motor. A suspension of fine polyvinylchloride powder was used in conjuction with slit lighting to visualize streaklines. Both angle of attack and cylinder speeds were changed systematically, and still photographs as well as a video movie were taken. The study showed, rather dramatically, effectiveness of this form of boundary-layer control.[3]

Conclusions

Effectiveness of the leading-edge cylinder can be improved at lower speeds of rotation by using a scooped configuration. The rotating air scoop appears to redirect more air over the upper surface. However, at high rates of rotation, it appears to the flow effectively as a solid cylinder, and there is no particular advantage in using the scoop configuration.

Acknowledgments

The investigation reported here was supported by the Natural Sciences and Engineering Council of Canada, Grant A-2181. The models were fabricated in the Mechanical Engineering workshop. The assistance of Mr. Ed Abell, Senior Technician, in design and construction of the models is gratefully acknowledged.

References

[1]Mokhtarian, F. and Modi, V. J., "Fluid Dynamics of Airfoils with Moving Surface Boundary-Layer Control," *Journal of Aircraft*, Vol. 25, 1988, pp. 163–169.

[2]Mokhtarian, F., "Fluid Dynamics of Airfoils with Moving Surface Boundary-Layer Control," Ph.D. Thesis, University of British Columbia, Vancouver, Canada, Feb. 1988.

[3]Mokhtarian, F. and Modi, V. J., "On the Effect of Moving Surfaces on Airfoil Boundary-Layer Control," AIAA paper 88-4337, Aug. 1988.

Technical Comments

Comment on "Aeroelastic Oscillations Caused by Transitional Boundary Layers and Their Attenuation"

L. E. Ericsson*
Lockheed Missiles & Space Company, Sunnyvale, California

WHILE the experimental results in Ref. 1 are important and merit publication, the accompanying explanation of the physical flow phenomenon does not, as it is replete with errors, including a complete misinterpretation of the quasisteady flow concept. According to the classical quasisteady flow concept, for small perturbations around $\alpha = \alpha_0$, the lift coefficient can be expressed in the following linearized form:

$$C_L = C_L(\alpha_0) + C_{L\alpha}\tilde{\alpha}, \quad \tilde{\alpha} = \theta + \dot{z}/U_\infty \tag{1}$$

For the bending oscillations in Ref. 1, $\alpha_0 = 0$ and the generalized angle of attack is $\tilde{\alpha} = \dot{z}/U_\infty$. According to the discussion in the last paragraph on p. 466 of Ref. 1, "...the lift curve slope with natural transition is close to zero," one would conclude that $C_{L\alpha}$ in Eq. (1) can be written as

$$C_{L\alpha} = (C_{L\alpha})_{FT} - (\Delta^i C_{L\alpha})_{TR} \tag{2}$$

where $(C_{L\alpha})_{FT}$ is the lift slope with fixed transition and $(\Delta^i C_{L\alpha})_{TR}$ is the lift loss due to free transition, reducing the lift

Received Nov. 9, 1987; revision received March 15, 1988. Copyright © American Institute of Aeronautics and Astronautics, Inc., 1988. All rights reserved.

*Senior Consulting Engineer. Fellow AIAA.

slope to a small but still positive value. In order to obtain quasisteady negative damping, the total aerodynamic derivative, $(C_{L\alpha})_{FT} - (\Delta^i C_{L\alpha})_{TR}$, must be negative. Actually, before divergent oscillations will result, the negative aerodynamic damping must be of a magnitude sufficient to overcome the structural damping present in the test, being 0.5% or more of critical.

Thus, the classic quasisteady flow concept cannot explain the observed divergent oscillations, and the distorted quasisteady flow concept offered in conjunction with Fig. 8 in Ref. 1 should never have been allowed to be published. Even more incredible is the claim made on p. 467, that "...the flow sketches of Fig. 8 could give a physical explanation for losses in pitch damping observed with transitional boundary layers." For pitching oscillations at $\alpha_0 = 0$, the generalized quasisteady angle of attack is $\tilde{\alpha} = \theta$, and the pitching moment coefficient is

$$C_m = [(C_{m\alpha})_{FT} - (\Delta^i C_{m\alpha})_{TR}]\theta \tag{3}$$

That is, the classical quasisteady aerodynamics affect only the aerodynamic stiffness and, thereby, the frequency of the oscillation. They have no effect on the damping and, therefore, cannot influence the amplitude of the oscillation.

The experimentally observed effect of free transition on the pitch damping[2] is caused by convective flow time lag, through the associated phase lag, as is explained in detail in Ref. 3. Adding the time lag effect, Eq. (3) can be written as

$$C_m(t) = (C_{m\alpha})_{FT}\,\theta(t - \Delta t_i) - (\Delta^i C_{m\alpha})_{TR}\,\theta(t - \Delta t_i - \Delta t_v) \tag{4}$$

where Δt_i is the inviscid flow circulation lag and Δt_v is the convective viscous flow time lag. For the low reduced frequencies of interest here, Eq. (4) can be expanded in a Taylor series to yield

$$C_m(t) = (C_{m\alpha})_{FT}\,[\theta(t) - \Delta t_i\,\dot{\theta}(t)\ldots] - (\Delta^i C_{m\alpha})_{TR}\,[\theta(t) - (\Delta t_i + \Delta t_v)\,\dot{\theta}(t)\ldots] \tag{5}$$

That is, if the quasisteady effect is to decrease the aerodynamic stiffness (and thereby the oscillation frequency), the effect of the phase lag is to increase the aerodynamic damping, thereby decreasing the oscillation amplitude. This is exactly the effect predicted[4] and observed experimentally[5] on slender bodies of revolution; i.e., the aerodynamic damping is increased – not decreased, as the authors of Ref. 1 erroneously claim – by the effect of free transition.

References

[1]Mabey, D. G., Ashill, P. R., and Welsh, B. L., "Aeroelastic Oscillations Caused by Transitional Boundary Layers and Their Attenuation," *Journal of Aircraft*, Vol. 24, July 1987, pp. 463–469.

[2]Greydanus, J. H., Van de Vooren, A. I., and Bergh, H., "Experimental Determination of the Aerodynamic Coefficients of an Oscillating Wing in Incompressible Two-Dimensional Flow, Part I; Wing with Fixed Axis of Rotation," Rept. F101, National Aeronautical Labs, the Netherlands, 1952.

[2]Ericsson, L. E. and Reding, J. P., "Dynamic Stall of Helicopter Blades," *Journal of the American Helicopter Society*, Vol. 7, Jan. 1972, pp. 10–19.

[4]Ericsson, L. E., "Effect of Boundary Layer Transition on Vehicle Dynamics," *Journal of Spacecraft and Rockets*, Vol. 6, Dec. 1969, pp. 1404–1409.

[5]Ward, L. K., "Influence of Boundary-Layer Transition on Dynamic Stability at Hypersonic Speeds," *Transactions of the Second Technical Workshop on Dynamic Stability Testing*, Paper 9, Vol. II, Arnold Engineering Development Center, Arnold Air Force Station, TN, April 1965.

Reply by Authors to L. E. Ericsson

D. G. Mabey,* P. R. Ashill,† and B. L. Welsh†
Royal Aircraft Establishment,
Bedford, England, United Kingdom

We would like to thank Dr. Ericsson for his comment on our paper.[1]

We accept that the quasisteady concept cannot yield a change in pitch damping for which some consideration of phase is essential. Our point is that the sketches regarding the relation between steady incidence and transition position could, with knowledge of or an assumption about phasing, give an explanation for the loss in pitch damping. We regret that we omitted to make the need for phase information explicit.

We referred (Ref. 1, p. 463) "to a loss of pitch damping on full-scale re-entry bodies at high supersonic speeds." This is an appropriate warning, because the summary of Ref. 2 also refers to a serious decrease in damping on bluff bodies at hypersonic speeds due to transition movements. Reference 2 also cites an increase in pitch damping on slender bodies due to transition movements, but this seemed inappropriate for the warning we wanted to give.

With regard to the bending vibrations observed, we see no conflict between ourselves and Dr. Ericsson. We agree that, on a quasisteady basis, the aerodynamic damping for bending oscillations is related to the slope of the lift curve. In Fig. 8c of Ref. 1, transition case B is related to a reduced, but still positive, slope (the dashed line), while transition case C *is* related to a negative slope (the other dashed line).

The validity of the quasisteady theory would be tested by local static lift measurements over outboard positions close to $C_L = 0$, $\alpha = 0$. Such local lift measurements were not possible during our tests, but the *overall lift curve* for the complete wing with natural transition is close to zero at $R_{\bar{c}} = 6 \times 10^6$, whereas with transition complete it is positive, as would be expected.

We regard our explanation [Ref. 1, Eq. (2)] of an effective lift/curve slope, which is the product of a constant lift/curve slope and a term expressing the effective camber, as being physically sound. As shown in Fig. 9 of Ref. 1, the loss of effective camber with forward movement of transition becomes more marked with increasing adverse pressure gradients over the rear of the section. This is consistent with our observation that the oscillations were more pronounced for section RAE 5238 than for RAE 5237, the former being closer to separation at the trailing edge than the latter. Any explanation ignoring this physical feature of the flow is incomplete. The camber effect for dynamic motion might be somewhat different from that for quasistatic motion. Nevertheless, we think that the remark on p. 466 on Ref. 1 pertaining to the locally reduced value of the quasisteady lift/curve slope is relevant to any explanation of the phenomenon. We both agree that the phenomenon has potentially serious implications whenever transitional boundary layers occur, because it can modify aerodynamic damping in both rigid-body and structural modes.

References

[1]Mabey D. G. Ashill, P. R. and Welsh, B. L., "Aeroelastic Oscillations Caused by Transitional Boundary Layers and Their Attenuation," *Journal of Aircraft*, Vol. 24, July 1987, pp. 463–469.

[2]Ericsson, L. E., "Effect of Boundary Layer Transition on Vehicle Dynamics," *Journal of Spacecraft and Rockets*, Vol. 6, Dec. 1969, pp. 1404–1409.

Received Nov. 9, 1987; revision received March 15, 1988. Copyright © 1988 by HMSO London. Published by the American Institute of Aeronautics and Astronautics, Inc., with permission.

*Senior Principal Scientific Officer.
†Principal Scientific Officer.