Analytic Extrapolation to Full-Scale Aircraft Dynamics

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THE extrapolation from subscale wind-tunnel data to full-scale flight becomes an especially serious problem at subsonic speeds when stall is involved and at high subsonic and transonic speeds where shock boundary-layer interaction can dominate the aerodynamics. In the case of dynamic testing, valid subscale simulation is often impossible,[1] because the coupling existing in full-scale flight between the location of the free (unfixed) boundary-layer transition and the airfoil motion has been changed drastically, if not eliminated completely, through the use of a tripping device.

One solution to this scaling problem is to supply ground testing facilities with the capability of simulating full-scale Reynolds number. Tunnels with such capability are available,[2,3] and others will undoubtedly become available. However, they will all be in too much demand to be able to accommodate all of the development testing.[4]

In spite of progress being made in computational fluid dynamics,[5] no one is presently ready to forecast when simulation of the coupling between boundary-layer transition and vehicle motion will be possible. A way out of this preliminary design dilemma is to extrapolate analytically from subscale test data to predict the full-scale aircraft dynamics.

The analytic approach is as follows:

1) Establish analytic relationships between dynamic and static aerodynamic characteristics induced by viscous flow effects.

2) Prove the veracity of the analytic method by predicting dynamic test results using corresponding static test data at the same subscale flow conditions.

3) Determine the effect of Reynolds number on static aerodynamic characteristics.

Discussion

Dynamic stall is a phenomenon that still is not well understood. As a consequence, heavy reliance has to be placed on experimental data which, as a rule, are obtained in dynamic tests where the full-scale Reynolds number cannot be simulated. It is demonstrated in Ref. 1 how this can result in dynamic stall characteristics that deviate greatly from those existing at the full-scale Reynolds number.

For small oscillation amplitudes and low frequencies, $|\dot{\alpha}c/U| \ll 1$ and $\bar{\omega}^2 \ll 1$, the local linearization concept can be applied even to the nonlinear separated flow aerodynamics as long as the characteristics are continuous in nature. This permits the dynamic stall characteristics to be determined by very simple analytic means, as is described in Ref. 6. The results in Fig. 1 show that the experimental subscale dynamic stall characteristics[7] can be computed[8] using corresponding experimental static characteristics to define the separation-induced effect on the static stability. As it was shown in Ref. 9 that the analytic relationship between unsteady and steady boundary-layer transition was of the same form as that between unsteady and steady separation characteristics, Fig. 1 demonstrates that analytic extrapolation is possible if the

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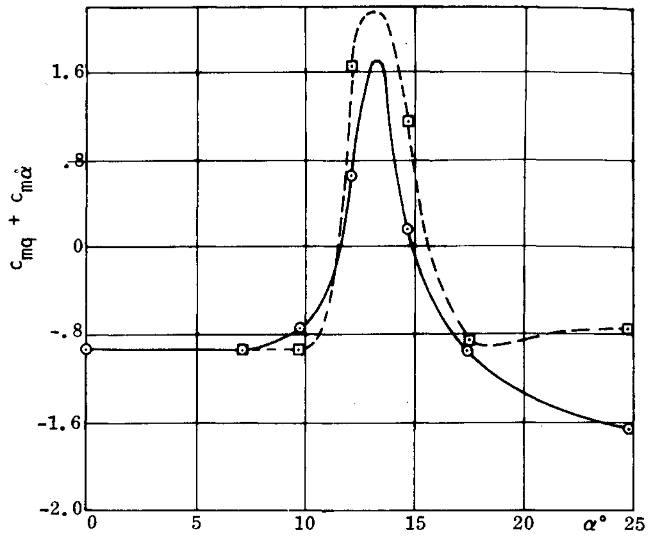

Fig. 1 Predicted and measured pitch damping, Vertol 23010-1.58 airfoil. $M = .4$; $\bar{\omega} = .122$; $\Delta\theta = 5$ deg, — ○ denotes experimental results. --- □ denotes analytic predictions.

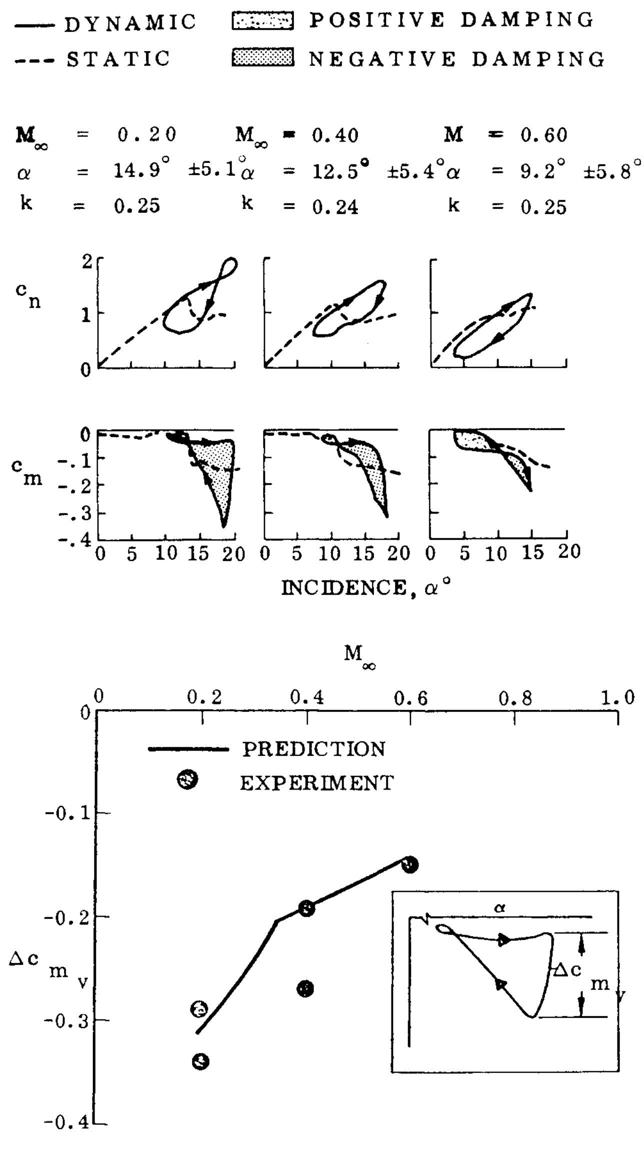

Fig. 2 Effect of Mach number on dynamic stall of the NACA-0012 airfoil.

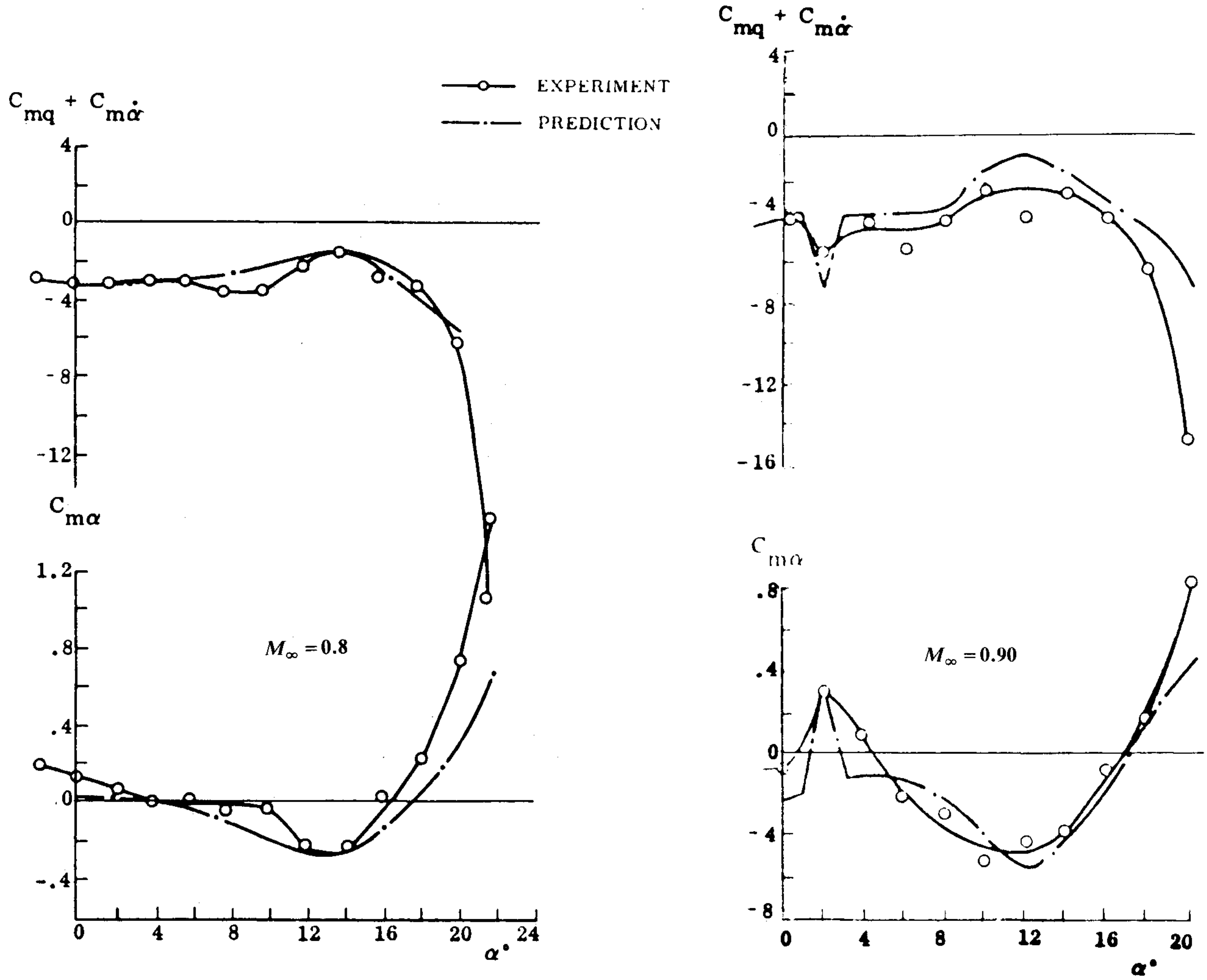

Fig. 3 Predicted and measured Orbiter dynamics at high subsonic Mach numbers.

correct static characteristics are obtained. This usually will require static tests up to the full-scale Reynolds number. Such tests may already have been run to determine the static loads. In any case, static tests are relatively easy to perform compared to dynamic tests.

The scaling difficulties existing in incompressible flow are complicated greatly when considering the effects of compressibility, which are always significant at stall. Even if the freestream Mach number is $M_\infty = 0.1$, the maximum Mach number on the stalling airfoil can easily exceed $M = 0.4$, the "incompressible limit."[8] There does not exist any incompressible stall data (dynamic or static). As most low-speed wind tunnels cannot change the Reynolds number significantly without simultaneously changing the freestream Mach number, stall experiments (dynamic and static) normally show Reynolds number effects that are distorted by compressibility effects.[8] It can be shown that the compressibility effect often dominates over the Reynolds number effect and dictates the α-range for stall flutter.[8] The analysis in Ref. 8 provides the needed capability to extrapolate analytically to full-scale flutter boundaries, a conclusion supported by the good agreement between predicted[10] and measured[7] effects of compressibility on the negative damping loop causing the stall flutter (Fig. 2).

It has been possible even in the case of three-dimensional flow to develop analytic static-dynamic relationships[11,12] that provide means for prediction of the dynamic effects of not only shock-induced flow separation but also of the leading-edge separation occurring at higher angles of attack on the Space Shuttle Orbiter[13] (Fig. 3). Also the much more complex separation-induced effects on the Space Shuttle launch configuration[14] could be predicted in this manner.[15] Based on the agreement shown in Fig. 3 for the rigid body dynamics, the elastic vehicle dynamics of the Space Shuttle launch vehicle could be predicted with the needed confidence level.[15]

The present paper focuses on the various flow problems typical for airfoils and wings. The corresponding analysis for slender bodies of revolution, which would, of course, apply to the aircraft fuselage, is contained in Ref. 16.

Conclusions

A review of the scaling problem in dynamic tests of aircraft like configurations has revealed the following:

1) Full-scale unsteady aerodynamics cannot be simulated in dynamic tests at subscale Reynolds numbers, nor can they be obtained by purely theoretical means when boundary-layer transition and flow separation are involved.

2) It is illustrated how full-scale vehicle dynamics can be simulated through "analytic extrapolation."

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