Engineering Notes

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Two-Dimensional Model for Airfoil Unsteady Drag Below Stall

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Introduction

HELICOPTER rotor blades have a much lower stiffness and effective damping than fixed-wing aircraft for the in-plane (lead-lag) degree of freedom. Whereas the flap and torsion degrees of freedom are primarily influenced by the lift and pitching moment, respectively, the lead-lag degree of freedom is strongly influenced by the drag. Furthermore, the blade lead-lag motion may couple with the flap or torsion degrees of freedom and may lead to an aeroelastic instability of the blade. These coupling effects are due to both the Coriolis forces and the aerodynamic loads. Thus, for a comprehensive model of the rotor system it is necessary to include aerodynamic loads for all three degrees of freedom.

For forward flight, the rotor blades also encounter a complex time-varying aerodynamic environment and operate into transonic flow conditions on the advancing side of the rotor disk. These operational requirements dictate that the prediction of the aerodynamic loads be considered as unsteady and subject to significant compressibility effects. In most rotor analyses, the airfoil unsteady lift and pitching moment behavior are normally considered to some degree,[1] however, the drag calculation is usually based on airfoil static test data.[2] Any unsteady effects on the drag component are generally neglected. However, it can be established from potential flow considerations that the unsteady pressure drag exhibits a hysteresis of sufficient magnitude that it may not be neglected for all forms of aeroelastic analysis. This analysis presents a method by which the unsteady pressure drag under attached flow conditions may be computed in a form compatible with the unsteady lift for a rotor aeroelastic calculation.

Analysis

For steady flow conditions, the pressure drag coefficient C_{D_P} may be computed by resolving the normal force and chord force (generally known as the leading-edge suction force) coefficients through the angle-of-attack α using

$$C_{D_P} = C_N \sin\alpha - \eta C_C \cos\alpha \tag{1}$$

where the normal force coefficient is given in terms of the force curve slope $C_{N_\alpha}(M)$ at a given Mach number M as

$$C_N = C_{N_\alpha}(M)\alpha \tag{2}$$

and with the leading-edge suction coefficient given by

$$C_C = C_{N_\alpha}(M)\alpha \tan\alpha \tag{3}$$

For steady potential flow $C_{D_P} = 0$; however, for a real flow the inability of the airfoil to attain 100% leading-edge suction is made via the factor η. The value of η may be adjusted to give the best fit with the static drag test data. Typically, for rotor airfoils, the value of η is approximately 0.95 to 0.97. The viscous drag is represented by the term C_{D_0} and is a function of Mach number, but is nominally constant for the angle-of-attack range below stall. Thus, the total drag is given by

$$C_D = C_{D_0} + C_{D_P} \tag{4}$$

Figure 1 shows the reconstruction of the static drag behavior using Eq. (4) for a NACA 0012 airfoil at a Mach number of 0.3. Near the stall angle of attack (about 14 deg), Eq. (4) becomes less valid because of the additional nonlinear effects on the drag due to boundary-layer displacement and trailing-edge flow separation.

For unsteady flow, it is possible to formulate the unsteady drag in terms of the aerodynamic response to a step change in the forcing: the indicial response. The total response is then obtained by a superposition of step inputs which, in aggregate, represent the unsteady aerodynamic response to an arbitrary forcing. Denoting the circulatory component of the normal force indicial function to a step change in angle of attack by ϕ_α^C, the circulatory normal force coefficient can be represented by

$$C_N^C(S) = C_{N_\alpha}(M)\phi_\alpha^C(S,M)\alpha \tag{5}$$

where the aerodynamic time $S = 2Ut/C$ represents the relative distance traveled by the airfoil in semichords. The freestream velocity is denoted by U and the airfoil chord by C. The product $\phi_\alpha^C\alpha$ may be considered an effective angle-of-attack α_E and accounts for the influence of the unsteady shed wake behind the airfoil. Similarly, denoting the noncirculatory component of the indicial function by ϕ_α^I, the noncirculatory normal force coefficient can be represented by

$$C_N^I(S) = \frac{4}{M}\phi_\alpha^I(S,M)\alpha \tag{6}$$

The initial value of the noncirculatory response ($4/M$) is given by piston theory[3] (a result that is valid for any Mach number at $S = 0$). The function ϕ_α^I physically represents a global approximation for the subsequent airfoil loading due to propagating pressure waves. It may be considered as the compressible analog of the apparent mass terms used for incompressible analyses. Both the circulatory function ϕ_α^C and the noncirculatory function ϕ_α^I are based on an exponential series approximation and are fully defined in Ref. 4. The unsteady leading-edge suction depends only on the circulatory component of the loading and so is given in terms of the effective angle-of-attack α_E by

$$C_C(S) = C_{N_\alpha}(M) \tan\alpha_E \alpha_E \tag{7}$$

Thus, the unsteady pressure drag C_{D_P} to a step change in angle-of-attack α is given by

$$C_{D_P}(S) = [C_N^C(S) + C_N^I(S)] \sin\alpha - \eta C_C(S) \cos\alpha \tag{8}$$

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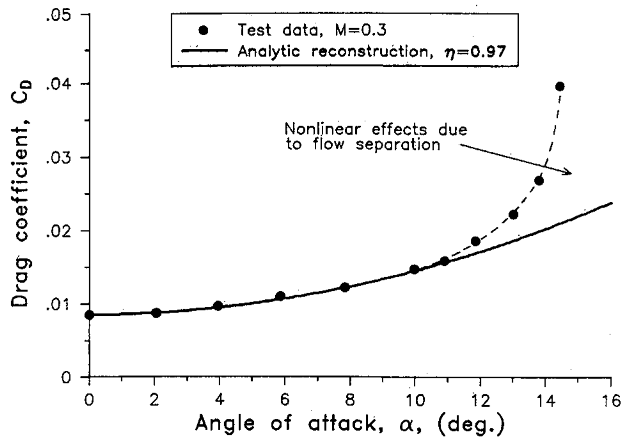

Fig. 1 Modeling of steady drag for nominally attached flow.

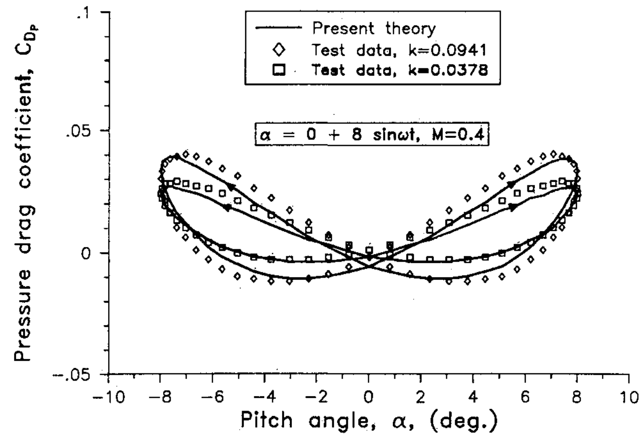

Fig. 3 Modeling of unsteady pressure drag for a harmonic pitch oscillation.

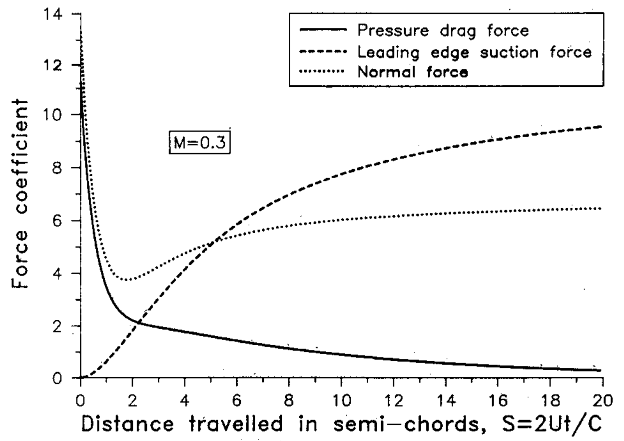

Fig. 2 Indicial normal force, leading-edge suction, and pressure drag coefficients for a step change in angle of attack.

The response of the normal force, leading-edge suction, and pressure drag coefficients to a step change in angle of attack are shown in Fig. 2 for a Mach number of 0.3.

The unsteady drag response to an arbitrary forcing condition may be computed by obtaining the aggregate unsteady normal force and leading-edge suction response using Duhamel's superposition principle[3] with the angle of attack defined at the airfoil 3/4-chord position. Efficient numerical algorithms to implement this superposition procedure are given in Refs. 5 or 6. In addition, the formulation can accommodate different modes of forcing, Mach number effects, and the effects of a varying onset velocity. The most general expression for the unsteady drag at time t can be written as

$$C_D(t) = C_{D_o} + C_N(t)\sin\alpha(t) - \eta C_C(t)\cos\alpha(t) \tag{9}$$

where α is now the airfoil (geometric) pitch angle through which the forces are resolved. The normal force coefficient C_N includes both circulatory and noncirculatory components. In this analysis, the viscous drag component is considered constant for a given Mach number and set equal to C_{D_o}. This assumption appears justified from the unsteady viscous drag calculations performed by Kottapalli et al.,[7] who have shown that unsteady viscous drag fluctuations are generally quite small.

To illustrate the significance of the unsteady pressure drag variation in the attached flow regime, the drag was computed for a pure sinusoidal pitch forcing about zero mean angle of attack at a Mach number of 0.4. As shown in Fig. 3, the theoretical unsteady pressure drag behavior is a second harmonic variation with time at a given phase. Both the amplitude and phase of the response are dependent on the reduced frequency $k = \omega C/2U$ of the oscillation, where ω is the circular frequency. It should be noted that this unsteady drag behavior occurs even for potential flow ($\eta = 1$). The computed pressure drag coefficient was also compared in Fig. 3 with test data for an oscillating airfoil. These data were taken from tests performed on a NACA 0012 airfoil, as documented in Ref. 8. The data were obtained by integration of instantaneous airfoil pressure distributions to obtain the normal and leading-edge suction forces, and were subsequently resolved through the instantaneous pitch angle to obtain the unsteady pressure drag. As shown in Fig. 3, the computed results were found to be in excellent agreement with the test data. Further correlation studies at higher Mach numbers and reduced frequencies for nominally attached flow conditions have been undertaken with equal success. The total drag is finally obtained for rotor calculation by adding the component of viscous drag C_{D_o}.

Conclusions

Based on potential flow considerations, the unsteady pressure drag variation on a nonstationary airfoil has been shown to be relatively significant. A practical method has been developed to compute the unsteady drag on a two-dimensional airfoil undergoing arbitrary motion in compressible flow. The method is computationally efficient and is suitable for inclusion within helicopter rotor aeroelasticity analyses. Including the model in these analyses may provide a better definition of higher harmonics of the blade lag excitation and improve prediction of aeroelastic coupling effects.

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