computed shear-layer unsteadiness and roll-up are closely linked to the boundary-layer eruptive behavior induced by the vortex/surface interaction. Increasing Reynolds number and lowering leading-edge sweep are found to enhance this effect. Although the main objective is to provide an explanation of the computed shear-layer unsteady process, it is clear that the described eruptive near-wall phenomenon is important in the interpretation of experimental results as well. Finally, one must recognize that shear-layer unsteadiness could also be promoted by other mechanisms such as freestream disturbances and the onset of vortex breakdown at higher angles of attack.

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Oscillatory Behavior of Helicopter Rotor Airloads in the Blade Stall Regime

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Introduction

It is now well established[1] that the retreating blade stall regime of a helicopter rotor is dominated by dynamic vortex-shedding phenomena. Based on laser velocimeter measurements, Young and Hoad[2] found that a series of vortices are shed at regular time intervals from a stalled airfoil at Mach number $M = 0.49$, but inconclusive results were obtained at lower Mach $M = 0.15$. However, recent experimental investigations of the flowfield of an oscillating airfoil[3] show evidence of the occurrence of multiple vortices at relatively low Mach, i.e., at $M = 0.019$. A modeling study, based on the assumption that multiple vortices are shed periodically from the leading edge of an airfoil, shows undulatory behavior of unsteady airloads of a stalled airfoil.[4,5] One can expect that multiple vortices are released during the blade stall regime of a helicopter rotor and this phenomenon would induce an oscillatory time-varying behavior of rotor airloads, as for a stalled airfoil. In this short Note, we propose to show the existence of oscillations on airloads of a stalled rotor blade, by using a research rotor code that integrates the dynamic stall model established in Refs. 4 and 5 and by corroborating the calculated results with experimental results on a rotor in a wind tunnel.

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Modeling Approach

The examined experimental results were obtained in the S1 Modane wind tunnel on an articulated four-bladed rotor. The blades were instrumented with 100 pressure transducers at 5 spanwise locations, 20 hot films gauges, and 30 strain gauges. The blade deformation was measured by using the strain-pattern-analysis technique.[6]

In the research aeroelastic code used, the following assumptions are made: 1) the blade movement (which includes its forced motion and its deformation), is taken from measurements; 2) the induced flow is described by the Meijer–Drees theory[7]; and 3) the drag coefficient is supposed constant for simplification and the lift coefficient is based on the dynamic stall model established in Ref. 4.

Let us summarize the theoretical assumptions of this dynamic stall model used. It is based on the consideration of two fluid-flow mechanisms: 1) stall delay and 2) vortex-shedding phenomena. Above a critical value of the angle of attack, flow separates and vortices are shed from the airfoil. Stall delay phenomena determine the value of the angle of attack for flow separation. Stall onset is identified as a Hopf bifurcation, i.e., the replacement of steady equilibrium state of the flow by a periodic equilibrium state. According to this mathematical model, vortices are shed at regular time intervals with a characteristic frequency called Strouhal frequency, by analogy with flow past a cylinder. Beyond the Hopf bifurcation, the lift coefficient C_L has a steady component C_{L_s} and an unsteady component C_{L_u}:

$$C_L = C_{L_s} + C_{L_u} \tag{1}$$

The steady component C_{L_s} is governed by a first-order ordinary differential equation (ODE):

$$\frac{\mathrm{d}C_{L_s}}{\mathrm{d}t} + bC_{L_s} = bC_{L_s}^{\mathrm{equil}}[\alpha(t), q(t)] + g_1\dot{\alpha}(t) + g_2\ddot{\alpha}(t) + g_3\dot{q}(t) + g_4\ddot{q}(t) + \vartheta(\dddot{\alpha}, \dddot{q}) \tag{2}$$

where α is the angle of attack, q the pitch rate, $C_{L_s}^{\mathrm{equil}}$ the static value of the lift coefficient; b, g_1, g_2, g_3, and g_4 are constants and $\vartheta(\dddot{\alpha}, \dddot{q})$ designates all the $\dddot{\alpha}$ and $\dddot{q}$ terms that are negligible. The derivation of Eq. (2) is done in Ref. 4. The values of the five constants b, g_1, g_2, g_3, and g_4 can be derived from two-dimensional unsteady experiments in the regime of attached flow. The unsteady flow has two different regimes, depending upon the history of $\alpha(\xi)$ (ξ: time, varying from the origin of time to the time of observation t). When $\alpha(\xi)$ increases from zero and exceeds a critical value α_{cr}^{+} (which can be significantly greater than α_{cr}, the static critical value of the angle of attack), periodic time-varying equilibrium flow replaces the steady time-invariant equilibrium. When α decreases after exceeding α_{cr}^{+}, the flow reattaches to the airfoil at a critical value α_{cr}^{-} (which can be significantly lower than α_{cr}), in these conditions, the periodic time-varying equilibrium state decays to zero. It is shown in Ref. 4 that C_{L_u} obeys a Van-der-Pol–Duffing type equation during the establishment of the periodic time-varying regime of the flow:

$$\ddot{C}_{L_u} - \omega_S(\beta_L^+ - \gamma_L^+ C_{L_u}^2)\dot{C}_{L_u} + \omega_S^2(C_{L_u} - \eta_L^+ C_{L_u}^3) = -E_L^+\omega_S\dot{\alpha} - D_L^+\ddot{\alpha} \tag{3}$$

where ω_S is Strouhal shedding frequency; the constants β_L^+, γ_L^+, η_L^+, E_L^+, and D_L^+ are given a superscript (+) to characterize the periodic time-varying regime. The decay regime of the periodic time-varying equilibrium state is simply modeled by a damped oscillator:

$$\ddot{C}_{L_u} - \omega_S \beta_L^- \dot{C}_{L_u} + \omega_S^2 C_{L_u} = 0 \qquad (4)$$

where the constant β_L^- is negative. The values of the seven constants ω_S, β_L^+, γ_L^+, η_L^+, E_L^+, D_L^+, and β_L^- can be evaluated from two-dimensional unsteady experiments in the stall regime of the flow. There are no equivalent equations to Eqs. (3) and (4) in other dynamic stall models. The present modeling lies on the existence of ω_S.

Discussion

The case study no. 596 of S1–Modane experiment is treated in this Note. This case corresponds to a high speed ($\mu = 0.40$) and to high loading (thrust coefficient $C_T/\sigma = 0.147$), and therefore, blade stall is present on the retreating side. The experimental measurements of the normalized normal force coefficient at two spanwise locations $r/R = 0.825$ and 0.50, are shown in Fig. 1, with calculated values, based on quasistatic two-dimensional aerodynamics and on the "Hopf bifurcation stall model," respectively.

Undulatory behavior is clearly shown on the blade retreating side, i.e., in the azimuthal range of 210–360 deg, for the normalized normal force coefficient at section $r/R = 0.825$. Other published experimental results[8,9] also exhibit such features. This undulatory behavior is a clear manifestation of multiple vortex-shedding phenomena. The amplitude of the oscillations of the modeled results appears smaller than that of the experimental results. The higher amplitude-observed experimentally is probably due to plunging effects that are not correctly taken into account by the dynamic stall model. For the inboard section $r/R = 0.50$, the amplitude of the oscillations is reduced, and this trend is correctly predicted by the model.

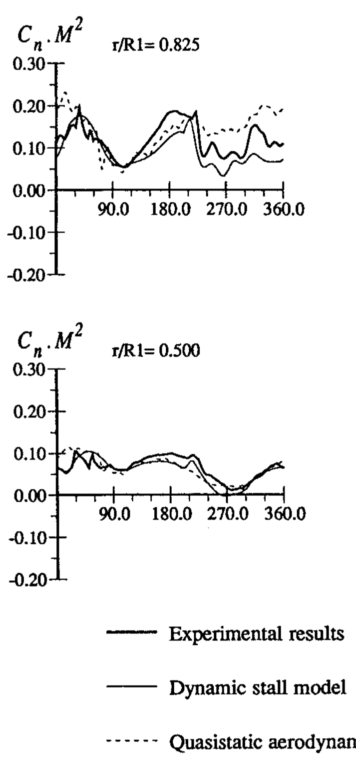

Fig. 1 Experimental and calculated results of the normalized force coefficient $C_n.M^2$ for study no. 596 of the S1-Modane wind-tunnel experiment.

As long as the amplitudes of the oscillations of the normal force coefficient are not negligible, multiple vortex-shedding phenomena cannot be ignored. The recent results on the UH-60A rotor[9] indicate that the amplitudes of the oscillations of section lift and pitching moment coefficients attain half the maximum of these values, respectively, for high thrust coefficient and a speed of $\mu = 0.24$. The results are very promising and the first author will now integrate the Hopf bifurcation dynamic stall model into an aeroelastic rotor code more elaborate than the one used here.

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Effects of Large Blockage in Wind-Tunnel Testing

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Introduction

WIND tunnels play an integral role in the aerodynamic development and refinement of virtually all airplanes and of numerous ground vehicles. Their advantage lies in the ability to generate a variety of conditions in terms of airspeed, angles of attack, and sideslip in a well-controlled environment. Test conditions are independent of atmospheric changes

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