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Numerical Investigation on Blade/Wake-Interaction Noise Generation

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This work investigates the potential of short-wave instability developing near blade tip vortex as the main source of blade/wake-interaction noise. In this aim, a numerical simulation of these instabilities is performed considering a simplified wake geometry. The aerodynamic fields are extracted to determine the blade pressure response using the unsteady compressible airfoil theory. Finally a loading-noise computation is performed. All the results obtained from these computations are compared with the experimental data and a good qualitative agreement is found.

Nomenclature

$A(k)$ = amplitude associated with wave vector **k**
a = vortex core radius
a_0 = initial vortex core radius
C = chord length
c_z = lift coefficient
d = separation distance between the two vortices
f = chordwise pressure-jump distribution function
E_k = kinetic energy associated with wave number k
k = axial wave number of the elliptic instability
$\mathbf{k}$ = wave vector associated with normal velocity perturbations
M = Mach number
md = distance between the blade and corotative vortex pair
P = pressure
P_{xc} = root-mean-square value as a function of normalized chord coordinates
R = span
(r, θ, φ) = cylindrical coordinate system
r_a = random number
U_{av} = rotor advancing speed
U_∞ = freestream velocity
(u, v, w) = velocity field in the Cartesian coordinates system
(u_0, v_0, w_0) = initial velocity field in the Cartesian coordinates system
(v_r, v_θ) = two-dimensional velocity field in the cylindrical coordinates system
β = interaction angle between blade and corotative vortex pair
Γ = circulation of the vortex
γ = blade/vortex interaction angle
Δc_p = pressure-jump coefficient
Δp = local pressure jump across the airfoil
δ = vortex center displacement in the axial direction
(η, ξ) = normalized Cartesian coordinates
λ = instability wavelength
ρ = density
σ_k = instability growth rate associated with wave number k
φ = rotor azimuth
ψ = angle between the span direction and the rotor forward-speed vector
$\mathbf{\Omega}$ = angular velocity of the rotor
Ω_0 = vortex system angular velocity

I. Introduction

BLADE/WAKE interaction (BWI) has been recognized as a significant component of main rotor noise, particularly in flight conditions such as climb or level flight, in which blade/vortex interaction (BVI) noise is less intense. In these flight conditions, BWI is a more important (or equivalent) source of noise in terms of intensity than BVI. Blade/wake interaction is characterized by broadband noise in a frequency domain between BVI noise and turboshaft engine noise (typically 1 to 3 KHz full scale).

This noise was initially identified by Brooks et al. [1]. Analyzing experimental acoustic spectra, he related BWI noise to nonperiodic blade pressure fluctuations in the midfrequency range. Brezillon et al. [2] established a relationship between these broadband pressure fluctuations and the blade wake by analyzing blade pressure measurements performed during the higher-harmonic-control aeroacoustic rotor test (HART) wind-tunnel test [3]. This work compared midfrequency blade pressure perturbation azimuthal occurrences on the rotor disk with close BVI events using a free-wake BVI prediction code. This comparison allowed us to associate BWI sources with perpendicular blade/vortex interactions. These interactions concern vortices under 180 deg of age. Glegg [4] built a BWI prediction model assuming that the noise results from the interaction between the blade and isotropic homogeneous turbulence contained in the tip vortices. His model indicated that the turbulent kinetic energy contained in an isolated vortex is not sufficient to account for BWI noise levels. This finding led Wittmer et al. [5] to look for alternative mechanisms of turbulence production within rectilinear vortices. Wittmer et al.'s work showed that the turbulent zones around vortices were larger when they had already interacted with a blade. Modifying their prediction model consequently, Glegg et al. [6] obtained BWI noise levels in agreement with experimental data. Contrary to the results of [4], analysis of experimental blade pressures in [2] showed that contributions to BWI noise from unperturbed tip vortices are comparable with those from vortices having encountered a blade.

A thorough analysis by Bouchet and Rahier [7] of the same HART experimental blade pressures, first studied in [2], demonstrated that BWI was not related to isotropic turbulence, but rather to the blade interactions with coherent large-scale structures present in the flow. Moreover, Bouchet and Rahier linked these structures to short-wave vortex instabilities. These instabilities occur when an external strain field deforms the vortex core elliptically. The deformation induces the resonant coupling of two vortex modes (Kelvin modes).

Observing that BWI pressure fluctuations occur at azimuths in which the blade interacts with two close tip vortices, Bouchet and Rahier [7] hypothesized that elliptic instabilities of corotating vortex

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