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Sound Generation by a Rotor Interacting with a Casing Turbulent Boundary Layer

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A new method for predicting the noise generated by a ducted rotor interacting with inhomogeneous and nonisotropic turbulence has been developed. The analytical formulation used a model of the two-point correlation function of the turbulent velocity in the space–time domain. The study focused on a specific condition where the dominant noise source was the interaction between a rotor and a casing turbulent boundary layer. The axial length scale of this turbulence was found to be large enough to generate unsteady lift that was correlated between multiple rotor blades. This led to tonal sound at the blade passing frequency in the absence of mean velocity variations. The analytical formulation was validated with a set of measurements obtained in a ducted rotor facility. The prediction accurately modeled both the tonal and broadband features of the sound spectra.

Nomenclature

B = number of rotor blades

C = rotor blade chord

c = speed of sound

D = duct diameter

f = frequency, Hz

k = acoustic wave number, $2\pi f/c$

$\mathcal{L}$ = gust response function

R = Boundary-layer dimensional two-point correlation of axial velocity

R_{ww} = airfoil spanwise two-point correlation of upwash velocity between blades m and n

r_{tip} = rotor tip radius

s, s' = rotor blade span coordinate and corresponding dummy variable for integration

$\bar{U}$ = spatial mean axial velocity inside duct

U_{tip} = tip relative fluid velocity, $V_{\mathrm{tip}}\sqrt{1+\phi^2}$

$\tilde{u}$ = unsteady axial velocity in casing reference frame

$\overline{\tilde{u}^2}$ = variance of axial velocity in casing reference frame

V_{tip} = rotor tip velocity

$\hat{w}$ = Fourier transform of unsteady upwash velocity in rotor blade reference frame

z, z_{ref} = boundary-layer wall-normal distance and reference location

α_y, α_z = stretching parameter for spanwise and wall-normal directions

$\beta(\omega)$ = abbreviation for the combined variables, $\pi\rho C U \mathcal{L}(\omega)$

Δy = boundary-layer spanwise separation distance

θ = boundary-layer momentum thickness

ρ = fluid density

τ = time lag for correlation functions

ϕ = flow coefficient, $\bar{U}/V_{\mathrm{tip}}$

ψ = head rise coefficient, $2\Delta p/\rho V_{\mathrm{tip}}^2$

ω = angular frequency, $2\pi f$

I. Introduction

AXIAL flow ducted rotors are important in numerous engineering applications, ranging from ventilation equipment to jet engines. The noise generated by these systems often imposes limitations on their size or operation. Improved understanding of the causes of unwanted noise can lead to quieter designs. The sound radiated by these systems is generated by a number of mechanisms, which have been cataloged and described by many authors, including Blake [1], Wright [2] and Morfey [3]. The present work considered a simplified system consisting of a single rotor operating at a low Mach number such that the sound generated was predominantly dipole in nature, resulting from rigid blades interacting with a turbulent inflow.

The objective of the current paper is to present a new method for predicting the frequency-dependent magnitude of the dipole sound source created by a ducted rotor interacting with a casing turbulent boundary layer. This source of inflow noise is important, considering 1) a turbulent boundary layer is nearly always present in a ducted rotor system and may have much higher turbulence intensity than the bulk flow in the duct, 2) the relative speed of the rotor blades is highest at the tip, and 3) the many scales of turbulence in the boundary layer can lead to both tonal and broadband sound. An additional benefit of investigating this noise mechanism is that the turbulence is created without generating additional sound, as can be the case with turbulence grids or other devices.

One method for predicting rotor noise due to turbulence ingestion is to classify the turbulent motions as two separate sets based on spatial scales, and use separate methods for predicting each. A review paper by Huff [4] provides a number of examples. Using the criteria described by Blake [1], turbulence can be considered small scale if it passes through the rotor while interacting with only one blade, and considered large scale if it interacts with multiple blades. In the case of small-scale turbulence, the unsteady lift between any two rotor blades is statistically uncorrelated and is a source of broadband sound. For large-scale turbulence, the unsteady lift between consecutive blades is statistically correlated, which is a much more efficient mechanism for noise generation than uncorrelated lift. Deterministic inflow disturbances, such as stator wakes, can be treated as a special case of large-scale turbulence and are a source of tonal sound, because the rotor blades interact with the wakes at regular intervals. Hanson [5] studied turbulence ingestion noise with a rotor subjected to both periodic inflow disturbances and anisotropic turbulence with extremely long axial length. He identified sharp spectral peaks resulting from both inflows and concluded that narrowband turbulence caused coherent forces on the rotor in a manner that had previously been only attributed to fixed inflow distortion.

Compared with the literature that is focused on other fan noise sources, a relatively small number of studies have considered

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