Journal of Sound and Vibration 409 (2017) 227–240

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Noise from a rotor ingesting a thick boundary layer and relation to measurements of ingested turbulence

W. Nathan Alexander [a,*], William J. Devenport [a], Stewart A.L. Glegg [b]

[a] Department of Aerospace and Ocean Engineering, Center for Renewable Energy and Aerodynamic Testing, McBryde Hall, RM 660, Virginia Tech, 225 Stanger St., Blacksburg, VA 24061, United States

[b] Department of Ocean and Mechanical Engineering, Florida Atlantic University, 777 Glades Road, EW 185, Boca Raton, FL 33431-0991, United States

A R T I C L E I N F O

Article history:
Received 13 September 2016
Received in revised form
21 July 2017
Accepted 31 July 2017
Handling editor: M.P. Cartmell
Available online 5 August 2017

Keywords:
Turbulence ingestion
Haystacking
Boundary layer ingestion

A B S T R A C T

Haystacked peaks in rotor noise spectra are produced by the correlated unsteady loading on neighboring blades. This noise can be predicted with knowledge of the turbulent inflow and blade response function, but this is not trivial, especially for complex turbulent inflows that are both inhomogeneous and anisotropic. This paper details the radiated noise and direct measurement of the unsteady upwash correlation in the rotating frame of a 10-bladed, 457 mm diameter rotor immersed in planar wall boundary layers of different thickness at non-thrusting and thrusting advance ratios. At low thrust conditions, the measured upwash correlation can be predicted using the fixed frame space-time correlation function of the undisturbed inflow. However, as the advance ratio is lowered, predictions progressively deviate from measurements. This is shown to be due to both the distortion of the approaching turbulence and the formation of a separation region on the wall beneath the rotor. At these low advance ratios, haystacks at the blade passage frequency and harmonics are observed in the blade-to-blade upwash coherence spectra at spanwise locations near the blade tips. Also, a lateral contraction of the turbulence is not observed in measurement of the spanwise coherence with increasing thrust. Finally, increasing the boundary layer thickness increases spectral levels of the radiated noise at higher advance ratios near zero thrust by a factor similar to the increase in boundary layer thickness. At low advance ratios, peaks in the measured noise have the same approximate magnitude for similar rotational and freestream velocities regardless of the boundary layer thickness as these are likely produced by interaction with vortex structures in the separated region.

1. Introduction

Broadband sound generated by a rotor ingesting turbulence can appear drastically different to that of an isolated airfoil because of the possibility of adjacent blades producing correlated unsteady loads when they encounter large scale turbulence. The blade-to-blade correlation produces a far field broadband noise spectrum characterized by haystacking. Haystacking was first observed by Sevik [1] from a 10-bladed rotor ingesting grid turbulence. Sevik's tests were conducted at a

* Corresponding author.
E-mail addresses: alexande@vt.edu (W.N. Alexander), wdevenpo@vt.edu (W.J. Devenport), sglegg@fau.edu (S.A.L. Glegg).

http://dx.doi.org/10.1016/j.jsv.2017.07.056
0022-460X/

low thrust condition and a force balance was used to measure the unsteady lift projected in the axial direction. Measurements were compared to predictions of the blade loading response, which took into account the turbulence correlation function. The haystacking peaks in the spectrum that were measured at the blade passage frequency (BPF) and its harmonics were absent in the prediction because it omitted the possibility of blade-to-blade coherent loading.

Hanson [2] and Majumdar and Peake [3] analyzed the effect of this blade-to-blade correlation for aircraft engine fans at static and flight conditions. Majumdar and Peake [3] showed that at flight conditions at which the ingested turbulence is near isotropic the blade-to-blade correlation may be negligible. However, when the inflow conditions cause the turbulence to be stretched in the axial direction, both Hanson [2] and Majumdar and Peake [3] showed that haystacking would be expected. Hanson explains that, during static tests, coherent turbulent structures in the flow far upstream are stretched into thin filaments by the acceleration of the mean flow as it approaches the rotor. The filaments are drawn into the fan and cut many times by successive blades, thereby producing an unsteady blade loading that is correlated on each blade, and causes radiated noise at the blade passage frequency (BPF) and its harmonics. The resulting noise can be narrowband and is often confused with the noise from mean flow variations in the rotor disk plane that also cause noise at the blade passing harmonics. Hanson provides a theoretical explanation of haystacks derived from a train of enveloped blade loading lift pulses with finite duration, taking into account small random variations in pulse position and pulse amplitude. He finds that the random pulse position has an effect on the predicted spectral peaks, reducing them with increasing frequency, while the energy is displaced to a broadband component. The variations in pulse amplitude also contribute a broadband component. Current static engine tests manage this phenomenon through use of an inflow control device (ICD) surrounding the inlet, which reduces the turbulence lengthscales and intensities to more accurately reflect in-flight conditions. Still, there are applications in which the ingestion of large-scale turbulence is unavoidable, such as advanced aircraft design concepts like variants of the hybrid wing-body where the engines are buried in the suction side boundary layer of the vehicle. In this case, the ingested flow is inhomogeneous, anisotropic, and may be significantly distorted.

Wojno et al. [4,5] used the 10-bladed Sevik rotor to measure the noise from grid-generated turbulence. In these studies, they measured the undisturbed velocity characteristics downstream of three grids with various mesh sizes to define spatially averaged semi-empirical turbulence models used to simulate the ingested flow field of the rotor. Noise from the rotor was measured and compared to predictions that used the turbulence models to estimate the level of coherence between blades to resolve the haystacks. Their predictions use the summation gain approach described in Blake [6], which estimates the coherence using the defined turbulence scales and blade spacing. Their predictions peaked at frequencies below the first BPF and underpredicted the peaks at all harmonics of the BPF suggesting that the combined turbulence model and summation gain approach did not accurately represent the coherence of the fluctuating loads between blades.

Stephens and Morris [7] measured the noise produced by the Sevik rotor ingesting an anisotropic boundary layer flow on the wall of a 206 mm diameter duct. The thickness of the wall boundary layer was modified by locating the rotor at different streamwise distances from the duct inlet. This allowed the effect of the turbulent boundary on the sound to be studied independently of any self-noise. A subset of the two-point velocity correlation matrix was measured at one location 1.125 rotor diameters downstream of the inlet where the boundary layer thickness was 11 mm. A simple model was used to extrapolate this data to the complete four-dimensional correlation matrix and to scale it to other streamwise duct locations using measured momentum thicknesses. They used the correlation matrix to make predictions of the noise produced by the rotor using strip theory and showed good agreement with their acoustic measurements. Their analysis demonstrates that a reliable prediction of rotor noise can be made if an accurate description of the turbulence space-time correlation is known.

Glegg et al. [8] relate the inflow turbulence space-time correlation and the sound spectrum generated by a rotor with B blades through a correlated loading function as given in Eq. (1).

$$S_{pp}(\mathbf{x},\omega)=\frac{1}{4\pi T}\sum_{n=1}^{B}\sum_{m=1}^{B}\int_{R_{min}}^{R_{max}}\int_{R_{min}}^{R_{max}}\int_{-T}^{T}\int_{-T}^{T}\left\{\frac{\partial}{\partial x_i}\frac{n_i^{(n)}(R,\tau)e^{i\omega r^{(n)}(\tau)/c_o}}{4\pi r^{(n)}(\tau)}\right\}\left\{\frac{\partial}{\partial x_j}\frac{n_j^{(m)}(R',\tau')e^{-i\omega r^{(m)}(\tau')/c_o}}{4\pi r^{(m)}(\tau')}\right\}R_{FF}^{(n,m)}(R,R',\tau,\tau')e^{i\omega(\tau-\tau')}dRdR'd\tau d\tau' \tag{1}$$

where unit vector n_i defines the blade normals, indices n and m identify each blade in the rotor, R is the radial location on the blade, and $r(\tau)$ is the distance from each blade element to the observer specified at source time τ. The blade-to-blade loading correlation function $R_{FF}^{(n,m)}$ can be related to the correlation function of the unsteady upwash $R_{ww}^{(n,m)}$ as

$$R_{FF}^{(n,m)}(R,R',\tau,\tau')=\int_{-\infty}^{\tau}\int_{-\infty}^{\tau}s(R,\tau-\tau_o)s(R',\tau'-\tau_o')R_{ww}^{(n,m)}(R,R',\tau_o,\tau_o')d\tau_o d\tau_o' \tag{2}$$

where $R_{ww}^{(n,m)}$ is the correlation function of the upwash velocity between blades n and m, and $s(R,\tau)$ is a time-domain strip-theory approach to the blade response function for which several solutions are presented in [8]. Providing that R_{ww} is known, these integrals can be evaluated numerically in the time domain. R_{ww} can be calculated directly as a function of the turbulence space-time correlation function rotated into the frame of the local blade section.

The analysis given in Eqs. (1) and (2) does not account for the distortion of the turbulence and the non-linear evolution of the flow under the influence of the rotor unless included directly in the unsteady upwash correlation. Accurate representation of the function R_{ww} is therefore vital to predicting the rotor noise. Morton et al. [9] investigated the coherent