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Experimental study of vortex–structure interaction noise radiated from rod–airfoil configurations

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ABSTRACT

Vortex–structure interaction noise radiated from an airfoil embedded in the wake of a rod is investigated experimentally in an anechoic wind tunnel by means of a phased microphone array for acoustic tests and particle image velocimetry (PIV) for the flow field measurements. The rod–airfoil configuration is varied by changing the rod diameter (D), adjusting the cross-stream position (Y) of the rod and the streamwise gap (L) between the rod and the airfoil leading edge. Two noise control concepts, including "air blowing" on the upstream rod and a soft-vane leading edge on the airfoil, are applied to control the vortex–structure interaction noise. The motivation behind this study is to investigate the effects of the three parameters on the characteristics of the radiated noise and then explore the influences of the noise control concepts. Both the vortex–structure interaction noise and the rod vortex shedding tonal noise are analysed. The acoustic test results show that both the position and magnitude of the dominant noise source of the rod–airfoil model are highly dependent on the parameters considered. In the case where the vortex–structure interaction noise is dominant, the application of the air blowing and the soft vane can effectively attenuate the interaction noise. Flow field measurements suggest that the intensity of the vortex–structure interaction and the flow impingement on the airfoil leading edge are suppressed by the control methods, giving a reduction in noise.

1. Introduction

Vortex–structure interaction noise is a main concern in several aeronautical and industrial applications. Two important devices involving such interaction noise are the rotor configurations of turbo-engine and helicopter rotors, in which the downstream airfoil blades lie in the wake of upstream blades. At any given time, vortices shed from the upstream blades interact with and impinge upon the downstream blades, giving rise to a host of noise and vibration issues. The rod–airfoil configuration consisting of an airfoil located in the near wake of a rod in a flow is believed to be a benchmark well-suited for numerical predictions of such vortex–structure interaction noise and noise generation mechanisms (Casalino et al., 2003; Jacob et al., 2005). Jacob et al. (2005) performed PIV measurement combined with proper orthogonal decomposition (POD) reconstructions to identify the coherent structures in the rod wake and compare the experimental results with the numerical simulations using Reynolds average Navier–Stokes (RANS) and large eddy simulation (LES). These analyses highlighted that strong three dimensional effects were responsible for spectral broadening around the rod vortex shedding

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Nomenclature

D	cylindrical rod diameter
H	square rod width
C	airfoil chord length
L	streamwise gap between the rod and the airfoil leading edge
Y	cross-stream position of the rod
Re_D	Reynolds number based on rod diameter D
Re_C	Reynolds number based on airfoil chord length C
x, y, z	Cartesian coordinates
U_∞	wind speed
U	streamwise (x) velocity
V	cross-stream (y) velocity
M_a	Mach number
Ω_z	spanwise vorticity ($\partial V/\partial x - \partial U/\partial y$)
f	frequency
f_{vs}	vortex shedding frequency
St	Strouhal number fD/U_∞
St_{vs}	vortex shedding Strouhal number ($f_{vs}D/U_\infty$)
ΔL_d	sound pressure level difference
PIV	particle imaging velocimetry
SPL	sound pressure level

frequency in the subcritical regime, and identified that the airfoil leading edge was the main contributor to the noise emission in a rod–airfoil configuration due to vortex–structure interaction.

The flow physics of the rod–airfoil model have been further studied by means of experimental methods. In a similar manner to Jacob et al. (2005), Takagi et al. (2006) investigated the influence of the cylinder transverse location on the turbulent development of the flow around the airfoil. Their results showed that the transverse location of the cylinder might have an impact on the radiated acoustic field. In order to identify the flow features that are responsible for the noise generation, Henning et al. (2008, 2009) performed dual PIV and simultaneous far-field microphone measurements. By means of a correlation-technique, they identified the regularities in the near-field fluctuations that are related to the radiated sound field. Lorenzoni et al. (2009, 2010) applied time-resolved PIV combined with a pressure reconstruction procedure to characterise the noise sources. The comparison with simultaneous microphone measurements revealed the ability of this method to predict reasonably well the magnitude of the tonal peak of emission and the narrow band spectrum around it. Giesler and Sarradj (2009) firstly performed microphone array measurements to investigate the influences of the rod diameter and the streamwise gap between the rod and the airfoil leading edge on the broadband noise generation at the frequencies higher than the vortex shedding frequency. Their results showed that the noise generation for lower frequencies depended more strongly on the cylinder diameter than on the streamwise gap.

In addition to these experimental studies, further understanding of the details of the rod–airfoil interactions can be gained from numerical simulations. Casalino et al. (2003) developed an aeroacoustic code based on porous Ffows-Williams and Hawking (FW–H) in combination with unsteady RANS simulations for the acoustic prediction. In a similar manner, Magagnato et al. (2003), Sorguven et al. (2003) and Boudet et al. (2005) coupled a FW–H acoustic analogy with LES calculations which allowed capturing of the sub-Karman vortical structures responsible for noise emission at higher frequencies. Greschner et al. (2008) combined a detached eddy simulation (DES) with the FW–H analogy to evaluate far-field pressure spectra. These investigations presented results which were in agreement with the experiments, but the applied numerical methods decouple the aerodynamic and acoustic fields, which makes it difficult to determine the details of the flow physics that are responsible for the noise generation. Recently, Berland et al. (2010, 2011) performed a direct noise calculation (DNC), based on compressible LES, to predict the sound radiation from the rod–airfoil configuration. The DNC method does not require any modelling of the sound sources and computes aerodynamic and acoustic fluctuations within a single run. The good agreement between calculation and experiment demonstrated the promise of the DNC method on noise prediction and generation mechanisms.

The dominant noise source on the rod–airfoil model was demonstrated to be caused by the impingement of the Karman vortices upon the airfoil leading edge. Therefore, a modification of the leading edge aerodynamics can be expected to modify both the turbulent flow and the sound emission of the rod–airfoil configuration. Siller et al. (2005) applied a blowing and suction at the airfoil leading edge to modify the flow structure and showed that the peak sound pressure level (SPL) at vortex shedding frequency in the far-field could be significantly reduced by air blowing, while air suction might increase the main peak level.

Most of the aforementioned studies were performed on one rod–airfoil configuration with fixed streamwise gap and/or rod diameter on the centreline. However, different gaps and rod diameters may have effects on the generation of the dominant noise. Giesler and Sarradj (2009) demonstrated experimentally the effect of the rod diameter and the streamwise gap on the broadband noise of high frequencies far above the vortex shedding frequency. In addition, Berland et al. (2011) performed DNC on the influence of the streamwise gap. The current paper follows Giesler and Sarradj (2009) by investigating further the effects of these two parameters on the radiated noise, not only at the broadband frequencies but also at the vortex shedding frequency, especially the influence of the gap/diameter ratio. In addition, the effect of the rod cross-stream position has also been investigated. Based on the gained knowledge, two noise control concepts using “air blowing” on the upstream rod and a downstream soft-vane airfoil leading edge are explored here. Acoustic and flow field measurements are taken in an anechoic wind tunnel using a phased microphone array and the PIV technique respectively. The use of the microphone array combining with an advanced data processing of CLEAN algorithm is to accurately localise noise sources and determine the dominant noise at different configurations, whereas the PIV technique reveals the corresponding flow physics of the noise generation and control.