Journal of Fluids and Structures 69 (2017) 293–307

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

A flow control technique for noise reduction of a rod-airfoil configuration

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ARTICLE INFO

Keywords:
Computational aeroacoustics
Noise reduction
Rod-airfoil
Rotating cylinder
Flow control

ABSTRACT

Adaptive and flow control techniques have been investigated as possible noise reduction approaches in modern commercial aircraft and small unmanned air vehicles. In the present paper, a rotating cylinder is examined as a noise reduction device in a simplified airframe component. The rod-airfoil canonical benchmark is used as a test case and noise prediction is realized by a 3D hybrid computational aeroacoustics approach. The rod is rotated at frequencies ranging from 0.5 to 2 times the natural shedding frequency of the nonrotating case. Evaluation of the directivity of generated noise around the rod and airfoil demonstrated that cylinder rotation leads to reduction of noise emissions, which became more pronounced for the highest rotational frequencies. Rod rotation also proved to be beneficial from an aerodynamic perspective, generally increasing the lift forces and reducing the drag forces acting on the rod and airfoil. Evaluation of the shedding Strouhal number displayed an ascending trend with increasing rotational frequency, which in turn resulted in a shift of the dominant acoustic tonal components towards higher frequencies. Moreover, rod rotation led to gradual suppression and deflection of the vortex street away from the symmetry plane. Since periodic vortex shedding is the dominant noise mechanism, vortex shedding suppression and minimization of the airfoil interaction with the vortex street is the cause of reduced acoustic emissions. The present study thus shows the potential of the rotating cylinder as a noise reduction device in aeronautical applications, while underlining its capabilities of enhancing aerodynamic performance.

1. Introduction

Aerodynamic noise generated from airframe components has been identified as a major contributor to commercial aircraft noise emissions. The severe regulatory context governing civil aviation has led to extensive research towards optimization of noise generated from airframe and other aircraft components. Flow control and adaptive techniques have been suggested as possible solutions for noise reduction, when other methods are not applicable. Such non-conventional techniques include boundary layer excitation, exploitation of cavity resonance effects and flow distortion in airframe components (e.g. Maury et al., 2001; Cattafesta et al., 2003; Schumacher et al., 2014; Castelain et al., 2008; Angland et al., 2012; Eret et al., 2015). A technique which has not been widely investigated for noise reduction purposes is the rotating cylinder as part of an airframe component.

During the beginning of the 20th century, the well-known Magnus effect rendered rotating cylinders a very appealing means of propulsion. In 1925, Reid (Reid, 1925) suggested application of the Magnus effect for aircraft design, aiming to exploit increased lift forces generated by cylinder rotation, while Flettner (Flettner, 1925) proposed the replacement of conventional sails by rotating

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http://dx.doi.org/10.1016/j.jfluidstructs.2017.01.003
Received 19 February 2016; Received in revised form 10 November 2016; Accepted 3 January 2017
0889-9746/

cylinders for large ship propulsion. Since the Flettner rotor ship, considerable experimental research (Swanson, 1961; Tanaka and Nagano, 1974) was realized on the Magnus effect resulting in several patents in the areas of maritime or aircraft propulsion. These ideas however did not find applicability in realistic engineering problems (Seifert, 2012).

During the past few decades, the increase of available computational power and efficient numerical algorithms, has allowed computational investigation of intricate flow mechanisms. A renewed interest has thus emerged aiming to exploit the Magnus effect in practical problems (Aoki and Ito, 2001; Karabelas, 2010; Gowree and Prince, 2012; Elmiligui et al., 2004; Karabelas et al., 2012). Recent state of the art comprises of applications aimed to improve aerodynamic characteristics of wind turbines (e.g. wind turbines based on airborne buoyant rotating cylinders (Perkovic et al., 2013; Milutinovic et al., 2015) and rotating cylinders instead of traditional blades (Bychkov et al., 2007; Sedaghat, 2014)), small unmanned air vehicles (UAV) (Badalamenti, 2010; Yamada et al., 2015) and maritime propulsion (Craft et al., 2014). Rotating cylinders also find applicability in heat transfer enhancement (e.g. Kays and Bjorklund (1958)).

Despite successful application of rotating cylinders towards enhanced aerodynamic efficiency and heat exchange properties, to the authors' knowledge, the acoustics of rotating cylinders have only been studied experimentally and to a limited extent (Wilson, 1960). The flow control technique that has not been widely investigated for noise reduction purposes is the rotating cylinder as part of an airframe component. Recently, a rotating cylinder as part of the rod-airfoil configuration (Jacob et al., 2005) has been investigated by Siozos-Rousoulis et al. (2015), showing significant reduction of noise directivities at high rotational frequencies, along with generation of positive lift on the rod and airfoil. Noise reduction was associated with the tendency of the vortex shedding to be suppressed at high enough rotational frequencies (Jaminet and VA, 1969; Dol et al., 2008), which resulted in reduced amplitude of fluctuating forces on the rod and airfoil. The investigation was carried out in two dimensions, thus neglecting three dimensional flow and noise mechanisms, which are important in high Reynolds numbers. Noise prediction in 2D can thus provide estimates and trends of generated noise. However, 2D simulations usually overpredict the acoustic solution. When three-dimensional flow computations are used as input data, noise levels and frequency content are more accurately reproduced (Cox et al., 1998). Moreover, at Reynolds number investigated by (Siozos-Rousoulis et al., 2015), studies have shown that the flow field is three dimensional, leading to spanwise variation of cylinder surface pressure and vortex structure in the wake (Cox et al., 1998). Scope of the present paper is thus a three dimensional investigation of the aerodynamic and aeroacoustic effects of cylinder rotation in a rudimentary airframe configuration.

The rod-airfoil canonical benchmark (Jacob et al., 2005) is selected as an indicative airframe component, since it displays flow and noise mechanisms, encountered in landing gear and other airframe configurations. A hybrid computational aeroacoustics (CAA) approach in three dimensions is applied for noise prediction. Noise source identification is realized by URANS and acoustic propagation is performed by a moving medium solution (Ghorbaniasl and Lacor, 2012) of the Ffowcs-Williams and Hawkings (FW-H) equation (Ffowcs Williams and Hawkings, 1969) in the time domain. Although 2D and 3D URANS flow simulations tend to provide flow solutions of similar accuracy, three dimensional noise prediction provides superior accuracy compared to two-dimensional methods. A large eddy simulation (LES) can provide insight into broadband noise phenomena and mechanisms. Here, however, a URANS simulation is chosen since the influence of rod rotation is tonal, mainly affecting flow and noise mechanisms related to the periodic vortex shedding downstream of the rod (Reid, 1925).

Aim of the study is to confirm the association of vortex shedding suppression at high cylinder rotational frequencies with noise reduction and the capability of improving aerodynamic performance of the rod and airfoil. Rod rotation is introduced at rotational frequencies ranging from 0.5 to 2 times the natural shedding frequency of the cylinder, in order to explore the frequency range that proved to achieve noise reduction combined with improved aerodynamic performance in (Siozos-Rousoulis et al., 2015). The shedding frequency of the rod is determined for each case, while the influence of rotation on the forces acting on the rod and airfoil is also examined and compared against (Siozos-Rousoulis et al., 2015). Noise directivities and acoustic spectra are computed for each case. Finally, acoustic and aerodynamic results are both assessed and discussed. The outcome of the present study may provide further confirmation of the connection between vortex shedding suppression and overall noise reduction in three dimensional airframe components, thus outlining the usefulness of the presented technique as a possible noise control mechanism in realistic aeronautical applications.

2. Mathematical background

A moving medium solution of the FW-H equation suggested by Ghorbaniasl and Lacor (2012) is chosen for noise prediction. The moving medium approach includes the terms related to incidence in the acoustic sources and acoustic propagation formulae. Since the effects of mean flow are explicitly included in the formulation, application of the moving observer method is not required for wind tunnel cases.

The convected FW-H equation (Ffowcs Williams and Hawkings, 1969) for sources on a permeable surface is given as follows:

$$\left[\frac{1}{c_0^2}\frac{D^2}{Dt^2} - \nabla^2\right]\{p'(\boldsymbol{x}, t)H(f)\} = -\frac{\partial}{\partial x_j}[L_j\,\delta(f)] + \frac{D}{Dt}[Q\,\delta(f)] \tag{1}$$

The Cartesian coordinates and time are $\boldsymbol{x}$ and t respectively, whereas repeated indices follow the usual Einstein summation convention. $H(f)$ is the Heaviside step function. $D/Dt = \partial/\partial t + U_{\infty i}\partial/\partial x_i$, with $U_{\infty i}$ and x_i being the i^{th} components of the mean flow velocity and observer position, respectively. The function $f(\boldsymbol{x}, t) = 0$ defines the data surface, such that $f > 0$ outside the source region, with $\hat{n}_j = \partial f/\partial x_i$ as the outward unit normal vector. Note that the thickness type and loading type noise sources are indicated