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Open rotor centrebody scattering

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ABSTRACT

This paper investigates the effect of acoustic scattering from the centrebody of an advanced open rotor engine. The physical mechanisms governing the scattering process are investigated and formulae for predicting noise levels are presented. It is found that centrebody scattering has a negligible effect on rotor-alone tones produced by a subsonic rotor, however, the scattering effect can be significant for rotor-alone tones produced by a supersonic rotor and certain rotor–rotor interaction tones. The paper concludes with an analysis which shows that the centrebody scattered field may be significantly reduced by applying an acoustic liner to the centrebody surface.

1. Introduction

Advanced open rotors offer potentially significant reductions in fuel burn relative to current generation turbofan engines. As a consequence of this, there is renewed interest in the open rotor among aeronautical engine manufacturers. A cut-away view showing an open rotor concept is shown in Fig. 1. Thrust is produced by two contra-rotating open rotors which are driven by a gas turbine 'core' housed within a large centrebody which extends both fore and aft of the rotor blades. The noise which is produced by an open rotor engine contains both rotor-alone and interaction tones. At take-off, rotor-alone tones are produced primarily by the steady loading and thickness of the rotating blades and occur at multiples of the blade passage frequency of each rotor. Interaction tones are caused by the interaction of the rotor blades with the unsteady flow-field produced by the adjacent rotor. Interaction tones occur at integer multiples of the 'sum and difference' of the front and rear rotor blade passage frequencies and are the dominant source of tonal noise produced by a modern open rotor at take-off and approach [1]. For these open rotors, the centrebody radius is approximately 40 percent of the rotor tip radius and thus the centrebody represents a sizeable solid surface from which sound can be scattered. It has been shown by Glegg [2] and Kingan et al. [3] that this centrebody can have a significant effect on the tones produced by the open rotor.

The first analysis of centrebody scattering that the authors are aware of was conducted by Glegg [2]. In his analysis the propeller blades were modelled as rotating point forces, the centrebody was modelled as an infinite rigid cylinder and the effect of forward flight was not considered. Glegg showed that for a subsonic propeller, scattering from the centrebody surface had a negligible effect on rotor-alone tones, but could have a significant effect on 'interaction tones' produced by an impulsive force on the rotating blade. Kingan et al. [3] performed a relatively simple extension of Glegg's formulae to include the effect of forward flight and distributed sources. They then analysed the tonal noise produced by a contra-rotating advanced open rotor and were able to show that certain tones produced by the interaction of the front-rotor wake with the rear rotor were significantly affected by scattering from the centrebody. The models of Glegg, Kingan et al. and indeed those presented in this paper make the assumption that the centrebody can be represented by an infinite, rigid circular cylinder.

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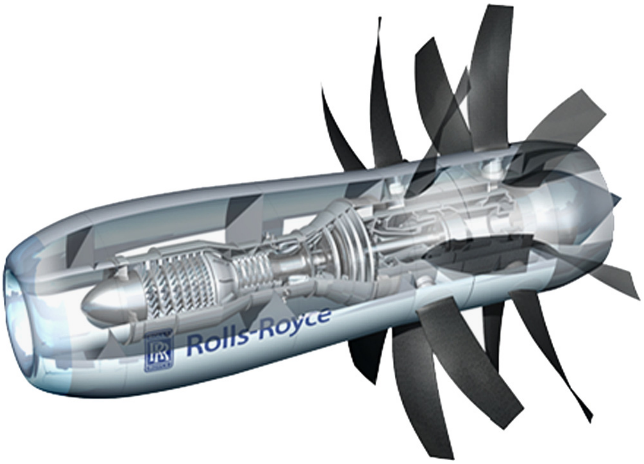

Fig. 1. Advanced open rotor concept (courtesy of Rolls-Royce plc.).

The assumption is necessary in order to allow the simple theoretical analysis presented in these studies. Of course, the fact that the assumed and actual geometries do not match will introduce some error. Nevertheless, although modelling the centrebody as an infinite circular cylinder may be somewhat crude, the analyses of Glegg [2], Kingan et al. [3] and that presented in this paper highlight the importance of considering scattering from the centrebody and provide useful simple methods for describing and understanding the physics which govern the behaviour of the incident and scattered acoustic fields.

The purpose of this paper is to analyse the acoustic field produced by an open rotor and investigate the mechanism governing centrebody scattering. Both the near-and far-fields are analysed. In Section 2, a rotating point force model, equivalent to that developed by Glegg [2], is used to investigate the near-field pressure and intensity fields produced by both subsonic and supersonic propellers/open rotors. It is shown that for supersonic propellers, there is significant acoustic radiation inboard of the source radius towards the centrebody. Because of this inboard radiation, centrebody scattering is important for rotor-alone tones produced by a highly supersonic propeller. Because some of the rotor–rotor interaction tones produced by an advanced open rotor are acoustically equivalent to supersonic propeller rotor-alone tones, centrebody scattering is also important for these tones. In Section 3, the analysis is extended to include distributed sources and axial flow through the propeller. Far-field asymptotic formulae for calculating the effect of centrebody scattering are then derived and the accuracy of these expressions is demonstrated. In Section 4 it is shown that a significant reduction in the total field produced by centrebody scattered tones can be achieved by applying an acoustic lining to the open rotor centrebody.

Although the analysis and method used for generating the near-field plots in this paper are different, they were inspired by those presented in Chapman [4,5] and Carley [6,7]. Chapman [4] investigated the nature of the field produced by rotating sources and in a subsequent publication [5] developed a novel method for the fast numerical calculation of the near-field produced by a radial distribution of multipole sources. The analysis was restricted to a stationary propeller with an even number of blades and it was assumed that the source strength was constant along the blade radius. Carley [6] extended Chapman's analysis to include the effect of forward flight and odd blade number and, in a subsequent paper Carley [7], to include arbitrary radial source distributions. The inspiration for investigating the acoustic intensity produced by the open rotor came from a paper published by Prentice [8] who developed asymptotic formulae for calculating the near-field produced by a subsonic rotating point source.

2. Analysis: rotating point forces

The analysis presented in this section will follow that of Glegg [2]. Each blade is modelled as a rotating point force which is located in a still atmosphere and does not translate. Although these are very simple assumptions, the goal of this section was to investigate the fundamental mechanisms of open rotor centrebody scattering. The analysis will be extended to include axial flow and distributed sources in Section 3.

The propeller/rotor blades are represented by point forces which rotate in the $x=0$ plane at radius $r=r_s$ and with rotational speed Ω rad/s in the positive ϕ direction. The centrebody is modelled as an infinite rigid cylinder of radius r_h. The analysis will make use of cylindrical coordinates $\mathbf{x}=\{r,\phi,x\}$ and the observer position will be denoted by a subscript o.

In Appendix A it is shown that the frequency domain pressure $\tilde{p}$ at observer position $\mathbf{x}_o$ and frequency ω produced by an arbitrary force per unit volume distribution $\mathbf{f}(\mathbf{x},\tau)$ within a fluid which occupies volume v is given by

$$\tilde{p}(\mathbf{x}_o,\omega)=\int_v \tilde{\mathbf{f}}(\mathbf{x},\omega)\cdot\nabla_{\mathbf{x}}\tilde{G}(\mathbf{x}|\mathbf{x}_o,\omega)\,\mathrm{d}\mathbf{x} \tag{1}$$

where the time domain pressure, p, and force per unit volume, $\mathbf{f}$, are converted to frequency domain expressions $\tilde{p}$ and $\tilde{\mathbf{f}}$