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Numerical investigation of a hovering micro rotor in close proximity to a ceiling plane

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ABSTRACT

This paper presents a numerical investigation into fluid interactions between a hovering micro rotor and a ceiling plane. The model consists of a two-bladed rotor with a symmetric NACA0009 airfoil section, an angle of attack of 12° and a blade tip Reynolds number of 30,000. The rotor–ceiling fluid interactions are modelled using a second order implicit finite volume solution to the incompressible Reynolds-averaged Navier–Stokes equations. Viscous effects are modelled using a Spalart–Allmaras turbulence model and an immersed boundary is used to model the ceiling plane. The methodology is validated by comparison against a two-dimensional free-vortex model as well as experimental results. The results show that the ceiling plane forces the flow upstream of the rotor to move predominantly parallel to the ceiling plane, resulting in an increase in the radial contraction of the wake downstream of the rotor. The increase in the radial component of fluid momentum causes the vertical component of fluid momentum across the rotor disk to decrease, causing the induced velocity across the blade span to decrease as the rotor–ceiling gap decreases. The change in induced velocity, which is shown to be inversely proportional to the rotor–ceiling gap, causes the local effective angle of attack along the blade span to increase with decreasing rotor–ceiling gap. This causes the sectional lift across the blade span to increase at a faster rate than sectional drag, driving an improvement in rotor efficiency as rotor–ceiling gap decreases. In principle, the improvement in rotor efficiency means that the power required to maintain a constant thrust decreases as rotor–ceiling gap decreases.

1. Introduction

Single rotor micro helicopters are a class of Micro Aerial Vehicle (MAV) that utilise a single main rotor to provide lift. Due to their hovering capability and manoeuvrability, micro helicopters are well suited to search and rescue (Chen and McKerrow, 2007), reconnaissance (Lakshminarayan et al., 2007), remote inspection (Irizarry et al., 2012), and aerial photography and videography applications (Natalizio et al., 2013). Such applications frequently require micro helicopters to operate within very confined environments. This increases the likelihood of fluid interactions occurring between rotors and nearby structures, such as a ground plane or ceiling plane. Such fluid interactions are likely to deform the structure of the wake downstream of the rotor which can subsequently induce altered flow effects near the rotor. In Fig. 1, indicative representations of velocity field deformation due to fluid interactions between a ground plane and a ceiling plane are shown. These deformed flow fields will alter the lift and drag forces acting on the blade, which

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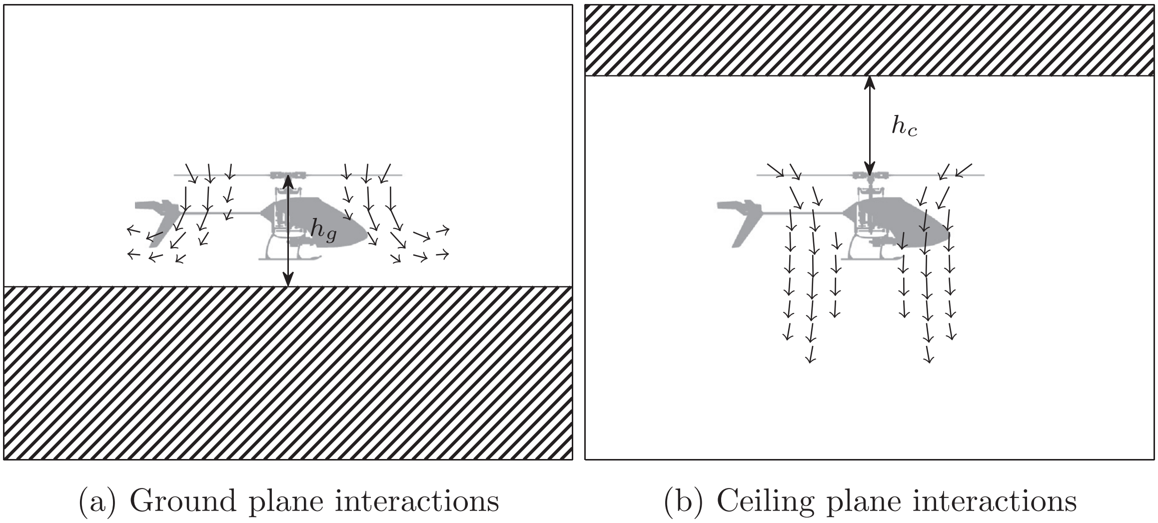

Fig. 1. Indicative representations of fluid interactions between a micro rotor and nearby horizontal planar surfaces, where h_g and h_c are rotor–ground gap and rotor–ceiling gap respectively.

can have undesirable or unexpected effects on helicopter performance. With the exception of the ground plane case (Lee et al., 2010; Lakshminarayan et al., 2013; Kalra, 2014), fluid interactions between a micro rotor and nearby structures are poorly understood. This is largely because the bulk of published helicopter research is concerned with full-scale helicopters, which are typically prohibited from operating in close proximity to structures. As such, it is clear that further research is required in order to understand the full range of fluid phenomena that micro helicopters are likely to encounter.

Conventional helicopters typically have between 2 and 4 blades attached to a single main rotor. Flow over the blades is induced by the rotation of the rotor which subsequently provides the lift required for flight. Full-scale helicopters typically operate within a blade tip Reynolds number, Re_{tip}, range of $10^6 < Re_{tip} < 10^7$ (Leishman, 2006), where

$$Re_{tip} = \frac{\Omega R c}{\nu} \tag{1}$$

where Ω, R, c and ν are angular velocity of the rotor, rotor radius, blade chord length, and kinematic viscosity respectively. Studies of full-scale helicopter aerodynamics using blade element theory (Johnson, 1980), free-vortex models (Leishman et al., 2002), particle image velocimetry (Horner et al., 1996) and numerical methods (Costes et al., 2012) are well documented in the literature. Vorticity induced by a rotating helicopter blade has been shown to form a vortex sheet and a blade-tip vortex core that convect inward radially downstream of the rotor (Leishman, 2006). Free-vortex model analysis by Leishman et al. (2002) indicates that the structure of the blade tip vortex can deform significantly due to translation of the helicopter or due to fluid interactions between the blade tip vortex and a ground plane. The structure of the blade tip vortex is of particular interest because the induced velocity field at the blade is directly affected by circulation throughout the blade tip vortex; therefore, any deformation of the wake due to fluid–structure interactions will alter the induced velocity (and hence the lift and drag forces) at the rotor.

When studying the aerodynamics of micro rotors, special consideration must be given to the lower Reynolds number range that micro rotors typically operate in: $10^3 < Re_{tip} < 10^5$ (Lakshminarayan and Baeder, 2010a). As such, micro helicopters are likely to suffer from poorer lift and drag performance due to an increased dominance of viscous effects (Lissaman, 1983; Selig, 1995). Digital particle image velocimetry studies by Ramasamy et al. (2007) have shown that the blade tip vortex core can be divided into three distinct regions: an inner laminar region, a transitional flow region and an outer turbulent region. Ramasamy et al. (2007) also observed that the helical wake sheets shed from the hub of a micro rotor become thicker and more turbulent as blade tip Reynolds number decreases. Lakshminarayan and Baeder (2010a) used a compressible Reynolds-averaged Navier–Stokes model to visualise micro rotor flow and observed similar low-Reynolds number flow characteristics, including large turbulence in separated regions and shear layer instabilities in the wake. Studies of micro rotor efficiency have shown that viscous effects contribute to a significant reduction in aerodynamic efficiency: figure of merit (a measure of rotor efficiency) is typically in the range of 0.33–0.55 for micro-scale rotors (Bohorquez et al., 2003; Ramasamy et al., 2007; Lakshminarayan and Baeder, 2010a), compared with 0.7–0.8 (Leishman, 2006) for full-scale rotors.