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Autorotation dynamics of a low aspect-ratio rectangular prism

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ABSTRACT

This paper presents two previously unreported aspects of the autorotation dynamics of low aspect ratio rectangular prisms, observed during an experimental study of the dynamics of helicopter underslung loads. Low-speed wind tunnel tests of a simplified container model free to rotate on a fixed axis demonstrated (a) that autorotation rate can lock-in to a structural mode and (b) that static hysteresis in autorotation rate can occur at low speeds. Autorotation lock-in behaves in a similar manner to vortex-shedding lock-in, suggesting that a similar feedback flow process between vortex wake dynamics and body motion is operating, and may provide a partial explanation for the complex changes in behaviour of rotating slung loads at high airspeeds. Static hysteresis at low speeds results in a bifurcation diagram for autorotation which is similar to that for cross-wind galloping of a square prism, including the effects of friction and inertia. The similarity in bifurcation behaviour seems likely to indicate similar dynamics rather than flow physics, suggesting that it may be possible to apply techniques developed to model the effect of non-linear damping characteristics in galloping to the modelling of autorotation.

1. Introduction

An important but hazardous aspect of military and civil helicopter operations is the carrying of external cargo as a slung load. For many loads, maximum operational airspeeds are limited not by the available power, but by the onset of divergent or limit-cycle oscillations (Matheson, 1980). Rectangular box loads are particularly susceptible to aerodynamic instabilities, especially when lightly loaded (Sheldon and Pryor, 1973b). One load instability that has been the subject of recent interest is continuous rotation in yaw of the $6 \times 6 \times 8$ ft CONEX container when slung from a single point with a swivel joint, as shown in Fig. 1 (Raz et al., 2008). For example, Fig. 2 (redrawn from Cicolani et al. (2009)) illustrates the effect of airspeed on mean yaw rate for this load. At very low airspeeds the container rotates slowly about its vertical axis at a near-constant rate, with the initial direction set by the rotation of the rotor downwash. There is a clear change in behaviour at an airspeed of around 10 m/s, above which the spin rate increases linearly up to a critical value and then decreases. The subsequent motion depends on load mass and airspeed, ranging from a steady but reduced spin rate to spin reversals with large-amplitude pendulum motions. Flight and wind tunnel tests for a number of other cuboid slung loads show similar characteristics (Raz et al., 2011; Sheldon and Pryor, 1973a). Slung load autorotation is not necessarily an adverse phenomenon; small spin rates can stabilise pendulum motions (Cicolani et al., 2009; Raz et al., 2008), and hence increase the usable airspeed envelope for the load.

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Nomenclature

AR	aspect ratio, b/c
b	span (m)
c	chord, reference length (m)
h	height (m)
I	moment of inertia (kg m^2)
I^*	non-dimensional moment of inertia, $32I/\pi\rho c^4 b$
l_a	rig offset from tunnel floor (mm)
m	mass (kg)
n	mass parameter, $\rho c^2 l/2m$
r	damping coefficient (N s/m)
St	autorotation Strouhal Number, Ω^*/π
t	thickness (m)
T	applied torque (N m)
U, U_∞	wind speed, freestream velocity (m/s)
V	tip speed (m/s)
V	reduced velocity, $U/\omega_n c$
y	galloping amplitude (m)
Y	reduced amplitude, y/c
β	reduced damping ratio, $r/2m\omega_n$
θ	yaw angle (rad)
$\dot{\theta}$	angular velocity (rad/s)
ρ	fluid density (kg/m^3)
ω	angular velocity (rad/s)
ω_n	natural frequency (rad/s)
ω_b	lock-in frequency (rad/s)
Ω^*	non-dimensional autorotation rate, $\omega c/2U$

Continuous rotation in yaw of slung cargo containers is an example of autorotation (Lugt, 1983), a well-known but still rather poorly understood aerodynamic phenomenon. There is an extensive body of experimental and computational work on the autorotation of rectangular prisms, but this is largely concerned with either (a) quasi-two-dimensional geometries or (b) low aspect ratio 'flat plate' models. Examples of the former are experimental studies on models with very high aspect ratios (Hirata et al., 2011), models with end plates (Smith, 1971), and models spanning a closed wind tunnel test section (Zaki et al., 1994). Examples of the latter include low aspect ratio thin wings (Bustamante and Stone, 1969), and tumbling bodies (Tachikawa, 1983a) or playing cards (Andersen et al., 2005). For three-dimensional geometries representative of cargo containers, the only data available is from either flight test or scaled dynamic wind tunnel tests of slung loads (Cicolani et al., 2010; Raz et al., 2008, 2011; Sheldon and Pryor, 1973b), which introduces the added complexity of large-amplitude coupled lateral and longitudinal pendulum-like load motions. Some recent work has been done on CFD simulation of rotating CONEX loads (Cicolani et al., 2009; Prosser and Smith, 2013), but validation against flight or wind tunnel data has yet been limited in extent.

For autorotating slung loads it is generally assumed that pendulum motions are driven by the unsteady drag and side forces generated by the spinning load, but that conversely the pendulum motion does not significantly impact on the yawing moment driving the rotation. The yaw degree-of-freedom can therefore be isolated and studied independently of the pendulum dynamics. On this basis, an exploratory study of the yaw motion of typical container geometries was undertaken at City University London on a fixed-axis autorotation rig. The objectives were to (a) examine initial spin-up and limiting autorotation rate behaviour, as exemplified by Fig. 2, and (b) assess the effect of geometry changes on autorotation

Fig. 1. Blackhawk with CONEX underslung load (Raz et al. (2008)).