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The computational fluid dynamics modelling of the autorotation of square, flat plates

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A R T I C L E I N F O

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This paper examines the use of a coupled Computational Fluid Dynamics (CFD) – Rigid Body Dynamics (RBD) model to study the fixed-axis autorotation of a square flat plate. The calibration of the model against existing wind tunnel data is described. During the calibration, the CFD models were able to identify complex period autoration rates, which were attributable to a mass eccentricity in the experimental plate. The predicted flow fields around the autorotating plates are found to be consistent with existing observations. In addition, the pressure coefficients from the wind tunnel and computational work were found to be in good agreement. By comparing these pressure distributions and the vortex shedding patterns at various stages through an autorotation cycle, it was possible to gain important insights into the flow structures that evolve around the plate. The CFD model is also compared against existing correlation functions that relate the mean tip speed ratio of the plate to the aspect ratio, thickness ratio and mass moment of inertia of the plate. Agreement is found to be good for aspect ratios of 1, but poor away from this value. However, other aspects of the numerical modelling are consistent with the correlations.

1. Introduction

1.1. Autorotation

Autorotation is defined as the continuous rotation, in the absence of external power, of a body exposed to an air stream (Smith, 1971; Skews, 1990). The study of the theory of autorotation dates as far back as Maxwell (1854) who studied the rotation of falling cards and Riabouchinsky (1935) who introduced the term "autorotation". Some authors (Riabouchinsky, 1935; Lugt, 1983) have indicated that "classical" autorotation can occur only if one or more stable positions exist at which the fluid flow exerts no torque on the resting body – otherwise the rotation is called "pseudo-autorotation". The plates considered in the present work, because of the absence of significant aerodynamic torque at 0° or 90° angles of attack, satisfy the classical autorotation definition. No further distinction is made here between classical and pseudo–autorotation.

An object may rotate about any arbitrary axis, but two special cases have been the focus of existing literature on the subject of autorotation. These are autorotation about an axis parallel to the flow (e.g. horizontal axis wind turbines) and autorotation about an axis perpendicular to the flow (e.g. vertical axis wind turbines). The fundamental difference between

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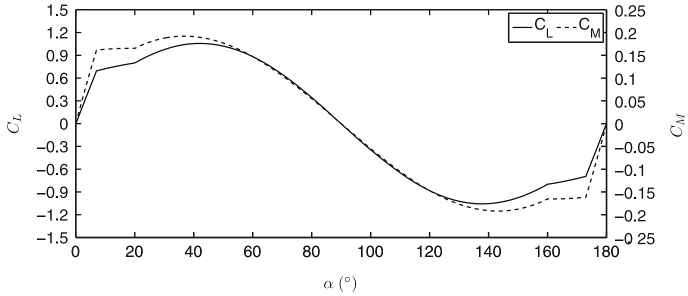

Fig. 1. Steady-state curves showing the variation of lift, C_L, and moment, C_M, coefficients with angle of attack, α for static square flat plates held in a uniform steady flow (ESDU, 1970).

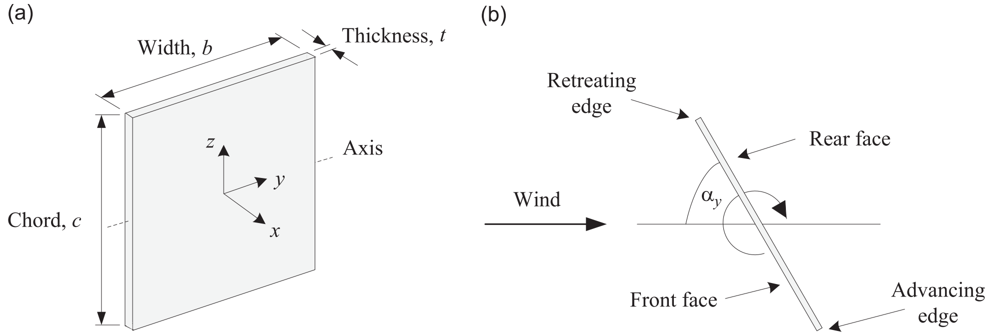

Fig. 2. (a) Dimensions and orientation of the plate and (b) the nomenclature associated with an autorotating plate.

the two cases is essentially that while the rate of stable autorotation is constant for bodies autorotating about an axis parallel to the flow (provided the wake is fairly constant), the rate of autorotation for bodies autorotating about an axis perpendicular to the flow is periodic (Lugt, 1983).

While it is clear that asymmetric plates held about an axis perpendicular to the flow should autorotate, this is not the case for symmetrical plates. Consider the steady lift and moment coefficient as shown in Fig. 1. As the angle of attack, α, slowly increases, the lift force and torque increase until the plate begins to stall. At the stall point, these values decrease and eventually become insignificant when the plate is perpendicular to the flow. As the plate continues to rotate from 90° to 180°, the cycle is repeated with reversed sign on the moment and lift. Therefore assuming a quasi-steady behaviour (i.e. that the plate is rotating so slowly that the aerodynamic forces at a given angle of attack can be assumed to be the static plate equivalents), a symmetrical plate exposed to a steady air stream would be expected to experience equal accelerating and retarding torque during different halves of the cycle, resulting in a static plate at the stable $\alpha = 90^\circ$ position, with no autorotation.

Smith (1971) experimentally investigated the autorotation of symmetrical wings about a span-wise axis perpendicular to the flow. Smith observed that in practice, a wing released from rest at an angular position at which the flow was stalled would come to rest (after a number of oscillations) in a statically stable position with the wing perpendicular to the free stream. However, if the wing was released at a small enough initial angle of attack, α_o, so that the flow was not stalled, the wing usually began autorotating with the final direction of rotation determined by the initial orientation. Smith also reported that the wing would not autorotate if its moment of inertia, I, was too low. In this case it was unable to store enough angular momentum to pass through the stalled portion of its cycle, during which it received a retarding torque. Smith (1971) found autorotation to be sensitive to the Reynolds number. Other factors influencing the rate of autorotation about an axis perpendicular to the flow are plate thickness, plate aspect ratio, lift and drag coefficients and the moment of inertia (Lugt, 1983).

Fig. 2 shows the dimensions and orientation of the plate in all that follows. To account for the influence of plate thickness ratio, $\tau = t/c$, and aspect ratio, $A = b/c$, Iversen (1979) obtained the correlation functions for tip speed ratio (TSR), Υ, based on data from experiments by Bustamante and Stone (1969), Smith (1971) and Glaser and Northup (1971):

$$\Upsilon = \frac{V}{U} = f_1(A) f_2(\tau), \tag{1}$$

where V is the speed of the tip of the plate and U is the speed of the incoming air, while the functions $f_1(A)$ and $f_2(\tau)$ are defined as

$$f_1(A) = \left\{ \left[\frac{A}{2 + (4 + A^2)^{1/2}} \right] \left[2 - \left(\frac{A}{A + 0.595} \right)^{0.76} \right] \right\}^{2/3}, \tag{2}$$