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On the role of thickness ratio and location of axis of rotation in the flat plate motions

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ABSTRACT

Wind tunnel experiments were performed to characterize the flow-induced rotations and pitching of various flat plates as a function of the thickness ratio and the location of the axis of rotation. High-resolution telemetry, laser tachometer, and hotwire were used to get time series of the plates motions and the signature of the wake flow at a specific location. Results show that small axis offset can induce high-order modes in the plate rotation due to torque unbalance, and can trigger self-initiated pitching. The spectral decomposition of the flow velocity in the plate wake reveals the existence of a dominating high-frequency mode that corresponds to a static-like vortex shedding occurring at the maximum plate pitch. The associated characteristic length scale is the projected width at maximum pitching angle. The increase of the plate thickness ratio implies lower angular velocity in rotation cases. A simple model based on aerodynamic forces is used to explain the linear relation between pitching frequency and wind speed, the pitching frequency increase with axis offset, and the onset of pitching.

1. Introduction

Flow-induced motion (FIM) of rigid bodies has been the focus of numerous studies during the last decades due to its relevance in various engineering fields. Applications include energy harvesting using passive flapping foil (Zhu, 2012), the characterization of plate tumbling under free flight (Hirata et al., 2009), and the control of unwanted rotations in rectangular prisms (Greenwell, 2014). Fundamental studies of FIM have placed attention on the vortex shedding, wake flow fluctuations and fluid-structure feedback mechanism and motion control, among others (Nemes et al., 2012).

Flat plate autorotation and pitching are two distinctive motions that are defined by the plate geometry. Autorotation phenomenon was studied by Maxwell over 150 years ago (Iversen, 1979), who pointed that the torque triggering rotation comes from the unbalance of aerodynamic force. Bustamante and Stone (1969), Iversen (1968) and Smith (1971) suggested that the autorotation of symmetric plates is mainly due to large vortices shed from the retreating faces of the cross-section. Iversen (1979) proposed an equation for the tip-speed ratio taking into account the effect of aspect and thickness ratios, bearing friction and moment of inertia. This formulation, however, is not very accurate in cases of plates with high aspect and thickness ratios, as indicated in experiments and numerical simulations (Greenwell, 2014; Skews, 1990; Zaki and Gad-

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El-Hak, 1994). A recent study by Greenwell (2014) further shows that autorotation is very sensitive to the plate end condition, and provided the range of angular velocities for various cases.

Rotational motion of plates is easily induced in the cases where the axis of rotation coincides with the geometrical axis of the plate. However, a small axis offset can trigger changes in the motion from rotational to pitching, and cause severe changes in the instantaneous torque. This can result in changes of the angular velocity, the onset of vibrations and fatigue in support structures. Comparatively few studies have focused on characterizing the flow-induced free pitching. Theodorsen (1935) and Von Karman (1938) used potential flow theory to describe pitching for small-amplitude motions. Sufficiently large pitch amplitude results in the so-called leading-edge vortex (LEV) formation, which is very difficult to account in simplified formulations. It has also been pointed out that the reduced frequency k ($=\pi f_0 c/U$, where c is the chord length of the plate, f_o is the pitching frequency and U is the incoming flow velocity) plays a significant role in describing the pitching motion (Jantzen et al., 2014; Baik et al., 2012). Recent studies also suggest that the unsteady force during pitching could also be largely dependent on the location of the axis of rotation, as demonstrated by Eldredge and Wang (2010), Yu and Bernal (2013) and Granlund et al. (2013). As pitching can magnify the lift compared to the static counterpart, the harvesting of fluid energy from the pitching of flat plates and foils has received attention during the last decade (Zhu and Peng, 2009; Xiao and Zhu, 2014; Onoue et al., 2015). These attempts consider plate motions with either active control using motor or passive oscillations with torsional spring. Although the characterization and quantitative description of plate free oscillations are the building blocks for understanding the fluid-structure feedback mechanism for energy harvesting, there are aspects to be uncovered including the effect of thickness ratio, location of the axis of rotation and effects of the background turbulence.

The current work aims to characterize and quantify the rotation and free pitching of flat plates as a function of thickness ratio, location of the axis of rotation and Reynolds number. Systematic wind tunnel experiments were performed to address the role of these parameters in the plate motions. The experimental setup is described in Section 2; the experimental results and discussion are provided in Section 3; and main conclusions are summarized in Section 4.

2. Experimental setup

Several flat plates were placed vertically and free to oscillate in the Talbot Laboratory wind tunnel of the University of Illinois at Urbana-Champaign. The wind tunnel has a rectangular test section of 0.914 m wide, 0.45 m high and 6.1 m long. More details on the facility can be found in Adrian et al. (2000). A secondary 0.05 m thick wall was placed at the top to allow space for the supporting structure of the plates and instrumentation with minimum disturbance on the flow. Three flat plates were made from balsa material of density $\rho_p = 107.5\ \mathrm{kg\ m^{-3}}$, chord $c = 76$ mm, $L = 370$ mm span and three thickness ratios $b/c = 3/16,\ 5/16,\ 7/16$, ensuring low blockage ratio ($\leq 8\%$, lower than $\sim 15\%$ in Amandolese et al. (2013) and $\sim 25\%$ in Onoue et al. (2015)). The plates were supported by two low-resistance steel bearings resting at the bottom and top walls, which allowed plate rotations with minimum resistance. The single-point support defined the axis of rotation, and was placed at six locations $x_r/c = 1/2,\ 5/12,\ 1/3,\ 1/4,\ 1/6$ and $1/12$. Here x_r represents the distance along the chord from one of the edges of the plates, as indicated in the schematic of Fig. 1. The moment of inertia I of the rotating assembly is provided in Table 1 for all the cases studied.

The plate rotations and oscillations were characterized for all b/c and x_r/c combinations at selected flow velocities ranging from $U = 2\ \mathrm{m\ s^{-1}}$ to $9\ \mathrm{m\ s^{-1}}$ or, equivalently, $Re = Uc/\nu \in [1.0\times 10^4,\ \ 4.6\times 10^4]$, where ν is the kinematic viscosity of the air. Iversen (1979) shows that plate motions exhibit low Re dependence for chord $Re = Uc/\nu > 8000$ and thickness $Re = Ub/\nu > 300$. A high-resolution MPJA laser tachometer was used to measure the mean rotation frequency of the plates with 0.05% uncertainty. In addition, two $34\times 13\times 7\ \mathrm{mm}^3$ 6-degree accelerometers were located outside the test section between the bearings and plates to track angular velocity and accelerations at a frequency $f = 256$ Hz with $0.07°\ \mathrm{s}^{-1}$ uncertainty. More details on the accelerometer can be found in Hamed et al. (2015).

A hotwire anemometer was used to get high-resolution measurements of the streamwise velocity at $5c$ downstream of the plate in the spanwise coordinate coincident with the axis of rotation (see Fig. 1c). The probe is made of 5.0 μm tungsten wire, and connected to a Dantec dynamics system and operated at a sampling frequency $f = 10$ kHz. Calibration of the probe was conducted against a pitot tube considering six flow velocities. During the calibration and measurements, the temperature was kept within ± 0.5 °C to avoid bias errors due to thermal drift of the voltage signal. The accelerometer and hotwire signatures for each case were sampled for a period 60–120 s after the steady state was reached (waiting time of at least 60 s), and each experiment was repeated at least one time to ensure repeatability.

3. Results and discussion

In this section we summarize and discuss the temporal characteristics of various flat-plate pitching and rotational motions as a function of the thickness ratio, Reynolds number and location of the center of rotation. The streamwise velocity fluctuations at a selected location in the wake of the plates are also included to aid the discussion.