Effect of Chordwise Flexibility on Flapping Wing Aerodynamics

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Abstract In this study, the effect of chordwise flexibility has been investigated experimentally for a plunging foil. A Digital Particle Image Velocimetry (DPIV) system is used to determine instantaneous velocity and vorticity fields around and in the near-wake of the wings in conjunction with simultaneous direct force/moment measurements. The aerodynamic/hydrodynamic performance is studied for rigid and flexible wings undergoing plunge motion at different amplitudes and frequencies in a freestream of Re = 10 000. The thrust coefficient (C_T), the power input coefficient (C_P) and the efficiency (η) values are also obtained and linked with the flexibility, trailing edge motion and flow structures in the near-wake.

1 Introduction

Flexible flapping wings have drawn attention in recent years due to their possible high performance efficiencies compared to rigid ones. Since all natural flyers and swimmers have some degree of flexibility on their wings, it is important to understand the phenomena for a more effective aerial/nautical vehicle design. Although various experimental [1–5] and numerical [6–9] research have been performed on the topic, yet further examination is required to provide further insight into the physics of the flow-structure interaction.

Due to the simplicity of the motion, the earliest theories concerning flapping wing flight are related to purely plunging airfoils. The theory of thrust generation using flapping foils was first proposed by Knoller [10] and Betz [11] and then experimentally confirmed by Katzmayr [12]. The Knoller-Betz theory states that a harmonically plunging wing in a freestream flow results in generation of an effective angle

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of attack and when the airfoil is oscillated at sufficiently high amplitude and frequency, the downstream velocity distribution becomes jet-like and thus is indicative of a net thrust on the airfoil. A large number of recent studies, both experimental and numerical, have been focusing on the effects of flexibility to mimic the nature with the aim of not only producing energy from flapping but also increasing the efficiency of flapping using the storage and release of elastic energy appropriately. The review paper of Gursul et al. [13] on the control of low Reynolds number flows by means of fluid-structure interactions gives an overall coverage of studies and findings focusing on lift and thrust enhancement of flexible wings. The experimental investigation of Anderson et al. [14] on rigid flapping wings showed that optimum propulsive efficiencies were obtained within an approximate range of Strouhal numbers 0.2-0.4. This range coincides with that presented by Triantafyllou et al. [15] for observed fish and cetaceans swimming at or near their maximum observed speed. Consistent with experimental and computational simulations of rigid airfoils in coupled plunge and pitch motions, for chordwise flexible airfoils, Heathcote and Gursul [1] showed that propulsive efficiency peaks at a Strouhal number of 0.29 which lies in the middle of the range observed in nature. They also concluded that the effect of chordwise flexibility is beneficial for purely plunging airfoils at low Reynolds numbers. Thrust coefficient and propulsive efficiency are found to increase with a degree of flexibility. Higher thrust coefficients are determined with stronger trailing-edge vortices and higher efficiencies are obtained in cases producing weaker leading-edge vortices. Earlier, Prempraneerach et al. [16] also experimentally showed that chordwise flexibility can increase the propulsive efficiency up to 36 % compared to rigid foils undergoing plunging and pitching motion. Timing of shed vortices is also an important issue affecting the performance of the flapping wing. Monnier et al. [17] investigated harmonically pitching airfoils with a flexible tail and focused on circulation, the streamwise and cross-stream spacing of the vortices and the vortex core radius. They found out that flexibility has an effect of switching the wake vortex pattern to reverse von Karman street. Ramaninova et al. [18] suggest that the optimum performance is related to the temporal evolution of the wing shape rather than the resonance of the wing. Phase lag between the leading and trailing edges of the flapping wing up to some level is found to be useful for exploiting the elastic energy. A detailed review on the relation between performance and lower, near, and upper natural frequencies is given in Shyy et al. [19].

The present investigation considers three flat plate wings with different flexibilities, undergoing sinusoidal plunge motion in a freestream of $\mathrm{Re} = 10\,000$, at different frequencies related to fractions of their natural frequencies. The model is either rigid or chordwise flexible and connected to a force/torque sensor which records the variation of performance during a cycle of motion. Instantaneous flow fields around and in the near-wake of flat plates are obtained using a 2D2C DPIV (Digital Particle Image Velocimetry) System which also gives the position of the trailing edges.

2 Experimental Setup

Experiments are performed in the large scale free-surface water channel of Trisonic Laboratories at the Faculty of Aeronautics and Astronautics of Istanbul Technical University. The cross-sectional dimensions of the main test section are 1010 mm × 790 mm. The models are mounted in a vertical cantilevered arrangement in the water channel from their leading edge. The experimental setup is shown in Fig. 1. The rigid model is a thin rectangular plate (t = 0.5 cm) manufactured of transparent plexiglas to allow laser light to illuminate both the suction and pressure sides. The chord length of the models is 10 cm and the span length 20 cm. The flexible wings are produced of polycarbonate (lexan) and acetate and have a metal part of 1 cm on the leading edge that allows chordwise flexibility, however they are rigid in spanwise direction. The experiments are conducted at a Reynolds number of 10,000 which corresponds to a flow speed of U = 0.1 m/s. Force data is collected at 1000 Hz starting after the 3rd period of the motion. The current study on flapping wings considers only plunging of a flat plate. The plunge motion is defined by the sinusoidal function (1) given below, where a is the amplitude and f is the flapping frequency:

$$h(t) = asin(2\pi ft) \tag{1}$$

50 periods of plunge motion data are recorded for each case. Taking into account the natural frequencies of the wing models, a range of 0.222–2.220 Hz is considered for plunging frequencies. Force and moments acting on the plunging flat plate are measured using a six-component ATI NANO-17 IP68 Force/Torque (F/T) sensor. The sensor is attached to the vertical cantilevered mounting beam of the test model, oriented with its cylindrical z-axis normal to the pitch-plunge plane. The plunge motion of the model is accomplished with Kollmorgen/ Danaher Motion AKM54K

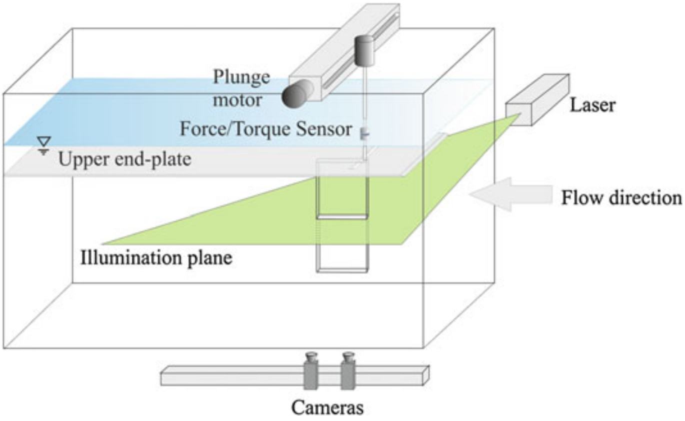

Fig. 1 Experimental setup

servo motor which was connected to a computer via ServoSTAR S700 digital servo amplifier.

3 Results

The frequencies for plunge motion are determined depending on the natural frequency of the materials and limited by the maximum frequency allowed by the motion rig and force/torque sensor. The natural frequency of the rigid, lexan and acetate plates are 7.40 Hz, 2.22 Hz and 0.64 Hz, respectively. The experiments are undertaken for four different amplitudes and five different frequencies of motion; time-averaged power-input and thrust coefficients along with the propulsive efficiency with respect to the motion frequency are shown in Fig. 2. Coefficients are

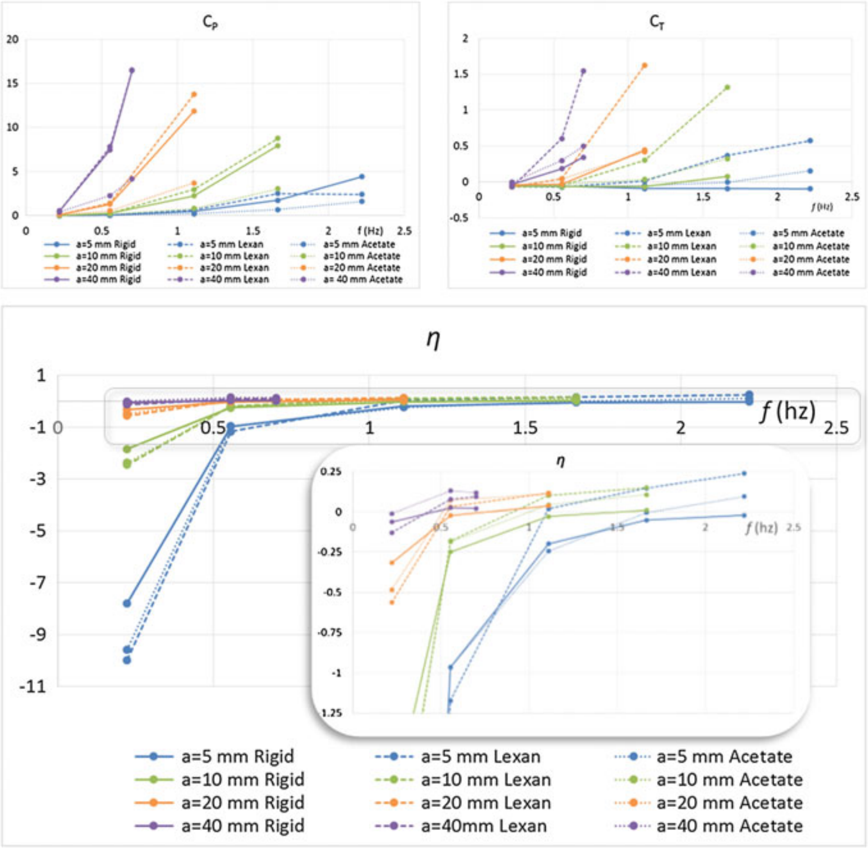

Fig. 2 Time-averaged power-input and thrust coefficients, and the propulsive efficiency

defined according to [1] and given in (2) where the T is time-averaged thrust (or drag) per unit span, F_y is the lift force and v is the instantaneous leading edge velocity.

$$C_T = \frac{T}{\frac{1}{2}\rho U_0^2 c}$$
$$C_P = \frac{\overline{F_y v}}{\frac{1}{2}\rho U_0^3 c}$$
$$\eta = \frac{C_T}{C_P} \tag{2}$$

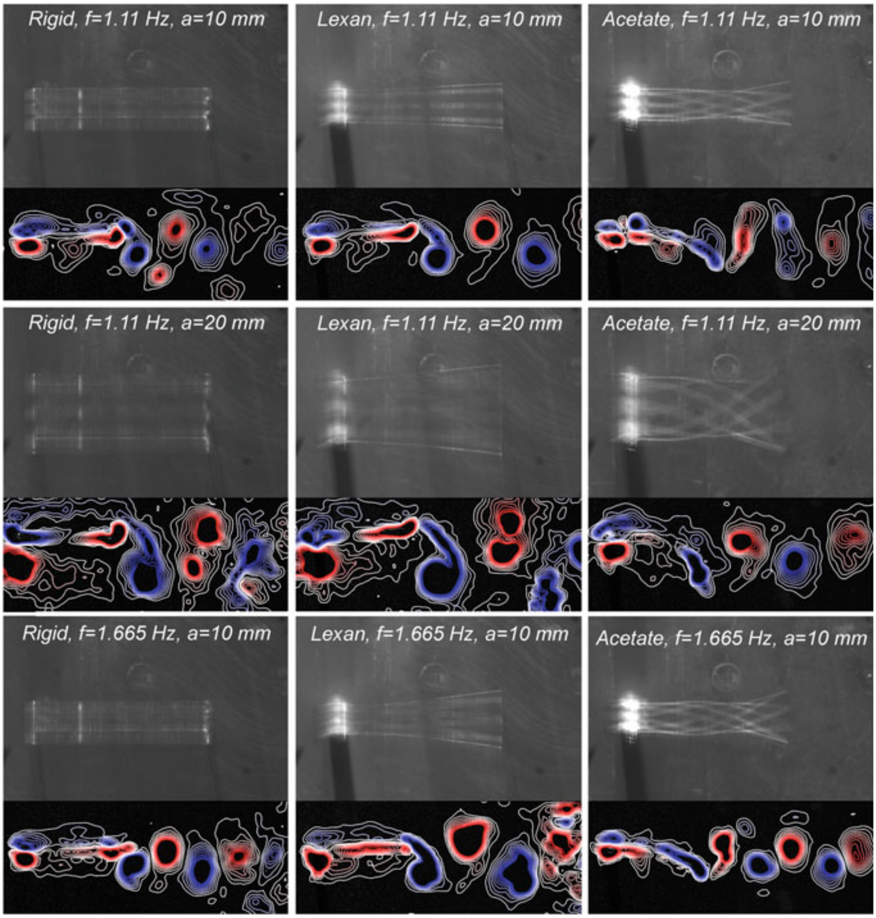

Fig. 3 Instantaneous vorticity plots along with the superposed raw DPIV pictures

As the Reynolds number is fixed, the x-axis can be also regarded as the reduced frequency. We do not prefer to use Strouhal number for the x-axis as different combinations of frequency and amplitude of motion yield the same Strouhal number, however, with different performance results. For each investigated cases, the power-input coefficient increases as the frequency of motion or its amplitude increases. For all investigated frequencies, the acetate plate extracts less power from the fluid. The lexan plate in general extracts the most; however, its power extraction is less than that of the rigid plate when it oscillates around its natural frequency. Figure 2 shows also the thrust production for motions above a certain frequency and/or amplitude. When the plate is flexible, the thrust production is possible for lower frequency and/or amplitude of motion. The lexan plate exhibits the best thrust performance. However, as the acetate plate extracts less power, the efficiency would be a suitable parameter to assess the overall performance. As can also be seen in Fig. 2, especially based on the acetate, the plates seems to show better performance when they plunge near their natural frequency. The efficiency values peak in a Strouhal number range of 0.2–0.3 for the rigid plate, in agreement with the literature.

Figure 3 shows instantaneous vorticity plots when the leading edge (LE) of the plate is about its maximum position, along with the superposed raw DPIV pictures to visualize the bending of the plates. Combined with force measurement results, it is possible to conclude that the vortices should be strong, preferably intact and the vertical distance between the centers of the vortices of opposite sign should be large for a better efficiency. According to the bending shape of the plates, the propulsive efficiency is generally high when the trailing edge (TE) of the plate follows the motion closely, reaching its maximum when LE reaches its. Acetate plates bend more and the delay of TE in following LE is increased, resulting in a decrease of vertical distance between vortices of opposite sign and of vortex strength which in turn degrades the thrust performance. In order to combine the information about the deformation of the plate with the imposed motion and the timing of the vortical structures which is

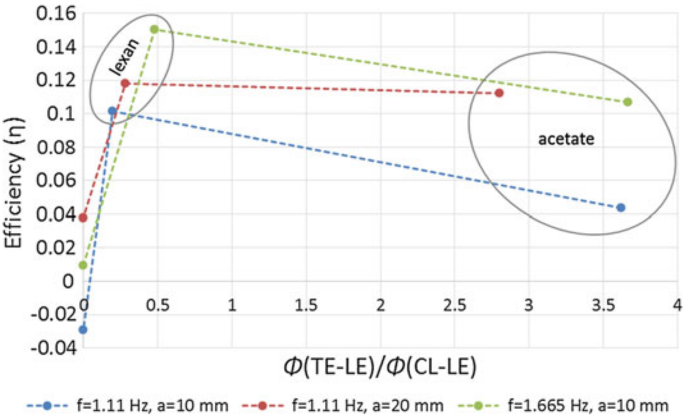

Fig. 4 The propulsive efficiency with respect to the ratio of ϕ (TE-LE)/ϕ (CL-LE)

directly connected to force-time history, the ratio of the phase angle between the TE and the LE to the phase angle between lift coefficient and TE is calculated. Figure 4 shows the propulsive efficiency with respect to this ratio and summarizes the findings. The ratio is zero for the rigid plate as TE and LE moves in parallel. The graph is expected to peak at the ratio of one. The ratios obtained for the lexan plate is between 0 and 0.5 and those obtained for the acetate plate is above 2.5. It is concluded that there is an optimum flexibility for the propulsive efficiency, in agreement with the literature.

4 Conclusion

Chordwise flexibility of a flat plate undergoing sinusoidal plunge motion is investigated using DPIV and direct force measurements. The best thrust performance is obtained when the trailing edge of the plate is closely followed by the lift variation and in general for the lexan plate. On the other hand, the most flexible plate made of acetate extracts less power for all investigated cases. In combination, the plates seem to show better performance in terms of propulsive efficiency when they plunge near their natural frequency. The results show that there is an optimum flexibility for the propulsive efficiency which is close to that of lexan in the current investigation. The existence of the optimum flexibility is shown based on the phase ratio between the lift force vs the imposed motion and LE vs TE, namely the shape of the flexible wing. Further studies will be focused on obtaining a phase ratio around 1–1.5 to lead to the expected higher efficiency.

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