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Wake structures of a heaving airfoil

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Abstract

Two-dimensional wake structures of a sinusoidally heaving airfoil are investigated using Particle Image Velocimetry at a Reynolds number of about 1000. The advance ratio and reduced frequency are varied from 0.0919 to 0.276 and 0.1 to 2.0, respectively. Results show that thrust generation occurs consistently at moderately low reduced frequency of between 0.25 and 0.5 for all the advance ratios investigated.

Introduction

An airfoil in a heaving motion perpendicular to a uniform free stream can under certain conditions, produce thrust. In this paper, we examine the effect of the variation of the advance ratio and the reduced frequency on the wake structures behind a heaving airfoil. The objective is to determine the conditions under which a thrust generating reverse von Karman vortex street is produced.

In the case of a pitching and oscillating airfoil, high thrust efficiency of up to 87% have been obtained by Anderson et al. [1] for advance ratio of 0.15, phase angle of 75 degrees and a heave to chord ratio of 0.75. He also found that optimal thrust production occurred when the advance ratio was between 0.125 and 0.20 and the heave to chord ratio was of the order of one. A subsequent study by Read et al. [4] obtained a thrust efficiency of 71.5% for a similar motion with a phase angle of 90 to 100 degrees between the pitching and oscillating motions.

In a simply heaving airfoil, the thrust-generating flow was also investigated by Freymuth [2] using flow visualization for an advance ratio of 0.17 and reduced frequency of 0.86. And he found that increasing the plunge amplitude or advance ratio led to some severe leading edge vortex separation, causing deterioration in the thrust generation. Moreover, a reduction in reduced frequency led to wider spacing of the vortices, causing the propulsive wake to be overcome by the drag of the airfoil profile.

Computational studies by Wang [6] on single wing strokes of simple heaving wing motion show that the optimal advance ratio is linked to maximizing the angle of attack during the motion. For a fixed advance ratio, it is found that the reduced frequency determines the time window available for vortex growth and leading edge vortex shedding. Peak results are obtained at maximum relative angles of attack of 45 to 60 degrees, which correspond to advance ratios of 0.16 and 0.276, respectively.

In a study on a simply pitching airfoil, Koochesfahani [3] observed a case whereby double wake vortical structures of the same rotational sense were produced in the same half cycle for amplitude of 4 degrees and frequency of 1.85, corresponding to a reduced frequency of 0.53.

In this paper, Particle Image Velocimetry is used to study a simply heaving wing with no pitching motions. The Reynolds number based on chord length and free stream velocity is about 1000. The advance ratios considered are 0.0919, 0.16 and 0.276, which correspond to maximum relative angle of attack of 30, 45 and 60 degrees, with the reduced frequency ranging from 0.1 to 2.0.

Experimental method and setup

The experiments were conducted in a recirculating water tunnel using an elliptical airfoil of 20mm chord, 2mm thick, and 196mm long. The airfoil spanned the Perspex test section with additional endplates mounted 2mm from both ends of the airfoil to reduce three dimensional effects and spanwise flow. A further horizontal Perspex plate was placed in contact with the free surface of the water so as to minimise free surface effects.

A servo motor which is linked to a linear actuator was used to control the heaving motion of the airfoil. The motor was in turn controlled by a Labview program through National Instrument DAQ cards which sent out pulse train of positional signals to achieve a motor spatial resolution of 0.1mm.

The water was seeded with 10 micrometer diameter hollow glass beads and illuminated with the laser sheet from a pair of Nd-YAG lasers at the mid-span of the airfoil. A Kodak MegaPLus ES1.0/ Type 16 (30Hz) 1 Megapixel PIV camera was used to capture the image pairs of dimensions 130.9mm by 131.9mm (or 1008 by 1016 pixels). Both the lasers and the camera were coordinated by a Dantec PIV system and were triggered by the same Labview program upon commencement of motion.

The time interval between each image pair was set at 8.309 milliseconds or the time taken for a particle to travel 20% of the length of the 16 by 16 pixel interrogation area. All the image pairs were then masked to remove the shadow cast by the airfoil and processed with 3 step adaptive correlation of interrogation area of 16 by 16 pixels and with a 25% overlap. The resultant vectors were further smoothed with moving average validation and average filtering over an area of 3 by 3 pixels.

A total of 20 runs were conducted for each case, and the results were then ensemble-averaged over 20 realizations. A further 20 runs were conducted with the wing in a reverse motion, the purpose is to provide the flow field within the shadow cast by the airfoil. The two averaged results were then combined to produce complete streamline and vorticity plots for all the 18 cases.

Results

The advance ratio and reduced frequency used here are defined as follows:

$$St_a = fA/U \tag{1}$$

$$St_c = fc/U \tag{2}$$

Where f is the sinusoidal heaving frequency in Hz, A the maximum heaving amplitude, c the chord length (20mm) and U the free stream velocity (fixed at 50mm/s).

Three types of wake structures were observed. The first type was a normal Karman vortex street similar to that observed behind a stationary bluff body, an indication of a drag profile. The second type was a reverse Karman vortex street, which caused the flow between the vortices to be directed downstream as a jet, thus generating a thrust. The third type was a double wake structure, where vortices of the same sign were shed on each half cycle of the oscillation, thus creating a pattern of near vertical twin vortices of identical circulation alternating with twin vortices of the opposite circulation. In some cases, the shed vortices were found to dissipate rapidly downstream.

The results obtained here are summarised in Tables 1-3 for differing advance ratio. The first column shows the reduced frequency, follows by a heaving frequency, heave to chord amplitude and the resulting wake structures observed.

Stc	f (Hz)	A/c	Wake structures
0.1	0.25	0.919	Dissipation
0.25	0.625	0.3676	Weak thrust
0.5	1.25	0.184	Double wake
0.75	1.875	0.092	Weak drag
1.0	2.5	0.046	Thrust
2.0	5	0.023	Alternating vortices

Table 1. Parameters and observations for Sta = 0.0919.

Stc	f (Hz)	A/c	Wake structures
0.1	0.25	1.6	Dissipation
0.25	0.625	0.64	Thrust
0.5	1.25	0.32	Double wake/ Thrust
0.75	1.875	0.16	Weak thrust
1.0	2.5	0.08	Weak thrust
2.0	5	0.04	Weak thrust

Table 2. Parameters and observations for Sta = 0.16.

Stc	f (Hz)	A/c	Wake structures
0.1	0.25	2.76	Dissipation
0.25	0.625	1.104	Thrust/ Dissipation
0.5	1.25	0.552	Double wake/ Thrust
0.75	1.875	0.276	Thrust
1.0	2.5	0.138	Weak thrust
2.0	5	0.069	Weak thrust

Table 3. Parameters and observations for Sta = 0.276.

Streamline and vorticity plots for two of the cases studied are presented in fig 1-5, with the time t given in periods T of heaving oscillations. The flow direction is from left to right. Fig. 1-3 show the double wake structures which occur when the advance ratio is 0.16 and the reduced frequency is 0.5. Likewise, fig. 4 and 5 show the thrust producing reverse Karman vortex street structure when the advance ratio is 0.276 and reduced frequency is 0.75.

Discussion

It was observed that thrust generation was generally present at reduced frequencies of between 0.25 and 0.5 for all the three advance ratios studied.

At lower reduced frequencies, the vortices took longer to rollup, resulting in an increased distance between them. Also, for the high amplitude to chord ratio cases, severe leading edge vortex separation was found, resulting in the vortices dissipated within 2 to 3 chord lengths downstream. Based on the wake structure, very little thrust was produced in this case.

Although the reverse Karman vortex street structure was generally seen for higher reduced frequencies, the lower amplitude to chord ratio meant that the vertical separation between the top and bottom row decreased, thus limiting the amount of thrust generated. The transition to drag producing structures was not observed for the advance ratios of 0.16 and 0.276, even at the maximum reduced frequency of 2.0. At this point, the heaving cycle was just at the limit of the time window suggested by Wang [6]. For advance ratio 0.0919 and reduced frequency 2.0, the vertical separation was virtually nonexistent; yielding a pattern of a single row of alternating signed vortices.

At the reduced frequency of 0.5, the double wake structure was observed for all the advance ratios. This was similar to the flow visualization results of Koochesfahani [3] for a pitching airfoil of 4 degrees amplitude and equivalent reduced frequency of 0.53. For the advance ratio of 0.16, a “pure” case of vertical alternating pairs of same signed vortices was observed. And for advance ratios of 0.276 and 0.0919, the pair was slightly tilted and the one further downstream was found to have a higher strength. The double wake structures have previously been found in a pitching case only [3], and as far as we are aware, this is probably the first time that they have been observed in the heaving case. The mechanism for their generation, and the role they play in thrust production remain unclear.

For the advance ratio of 0.0919, and at the reduced frequencies of 0.5 and 1.0, a thrust generating reverse Karman vortex street structure was observed. Interestingly, at the intermediate reduced frequency of 0.75, a normal Karman vortex street was found instead. Why this is the case remains unclear. This anomaly requires further investigation

The advance ratios of 0.16 and 0.276 tended to have a wider range of reduced frequency for which thrust was produced. At the advance ratio of 0.0919 when heave to chord ratio is small, a smaller vertical separation of the top and bottom vortices is likely to lead to a smaller average horizontal thrust force.

Conclusion

For an elliptical airfoil at constant zero angle of attack in sinusoidal heaving motion and Reynolds number 1000, the parameters of advance ratio and reduced frequency were found to govern the type of wake structures produced.

Thrust generating conditions were observed for most of the cases but primarily for moderate reduced frequencies of 0.25 and 0.5 for the three advance ratios of 0.0919, 0.16 and 0.276. Weaker thrust conditions were also found for higher reduced frequencies of up to 2.0 for advance ratios 0.16 and 0.276. Double wake structures appeared consistently for all advance ratios at the reduced frequency of 0.5.

Although the present study provides valuable information about the wake structure, quantitative thrust forces are needed before a clearer insight into optimizing the choice of the two parameters can be better obtained.

References

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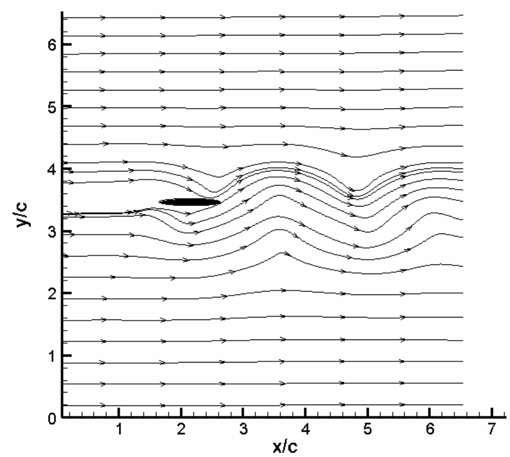

Figure 1a. Streamline plot Sta=0.16, Stc=0.5, t = 5T, airfoil descending.

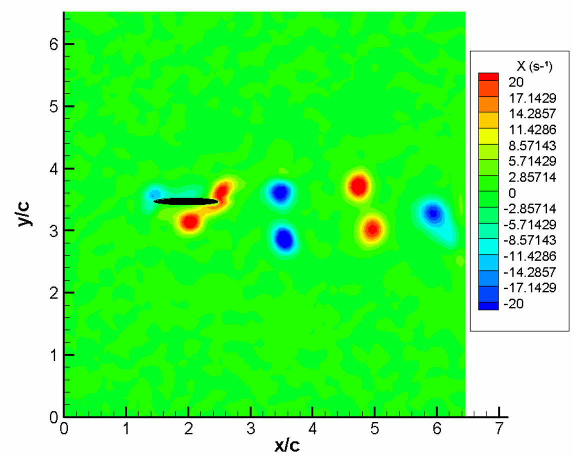

Figure 1b. Vorticity plot Sta=0.16, Stc=0.5, t = 5T, airfoil descending.

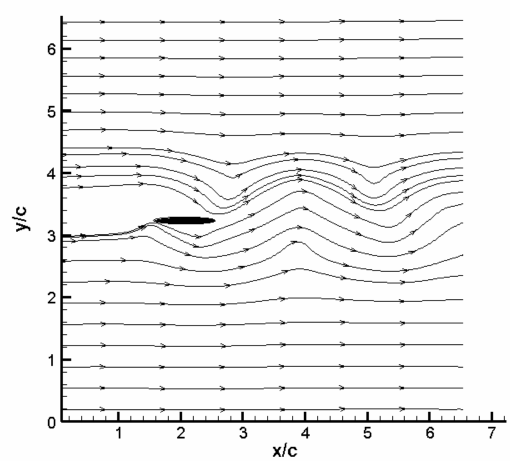

Figure 2a. Streamline plot Sta=0.16, Stc=0.5, t = 5.125T, airfoil descending.

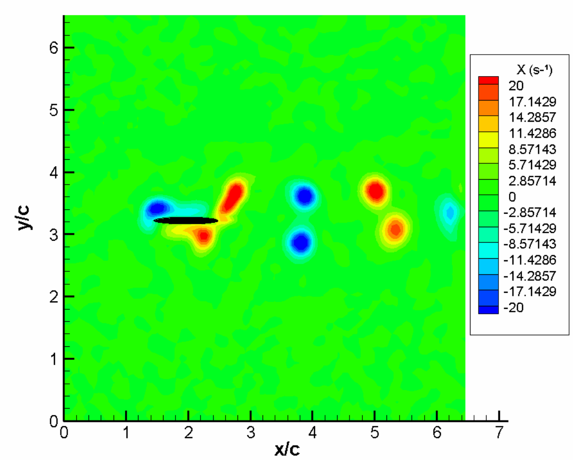

Figure 2b. Vorticity plot Sta=0.16, Stc=0.5, t = 5.125T, airfoil descending.

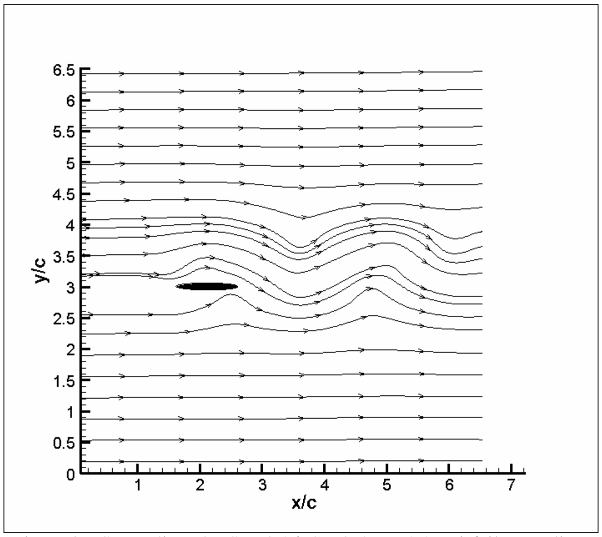

Figure 3a. Streamline plot Sta=0.16, Stc 0.5, t = 5.5T, airfoil ascending.

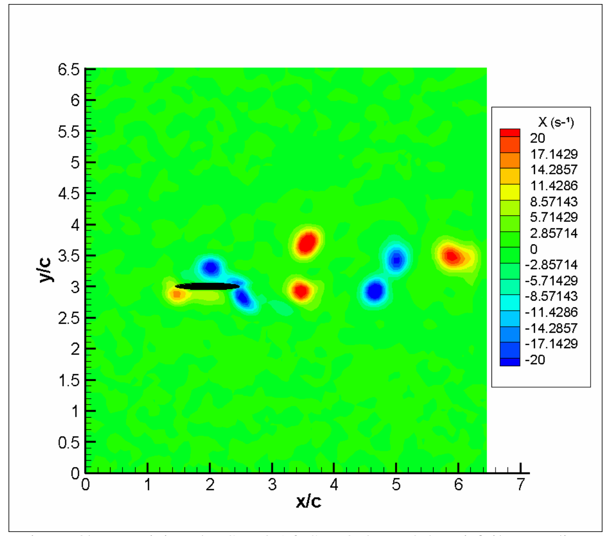

Figure 3b. Vorticity plot Sta=0.16, Stc=0.5, t = 5.5T, airfoil ascending.

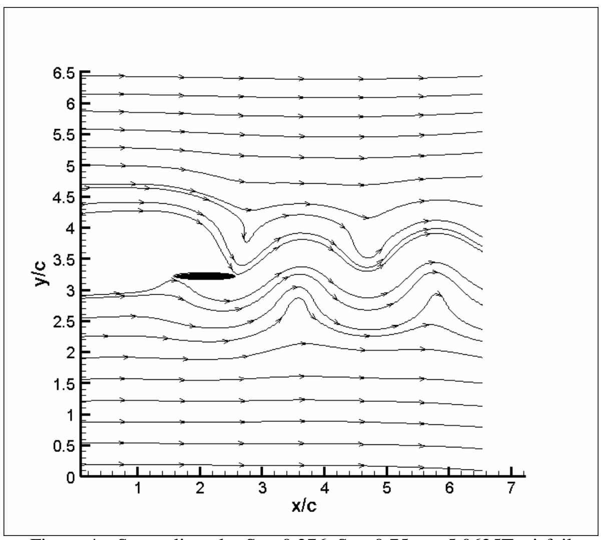

Figure 4a. Streamline plot Sta=0.276, Stc=0.75, t = 5.0625T, airfoil descending.

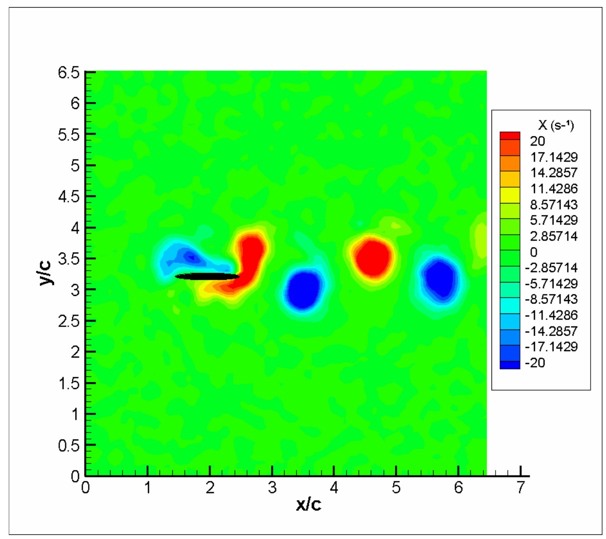

Figure 4b. Vorticity plot Sta=0.276, Stc=0.75, t = 5.0625T, airfoil descending.

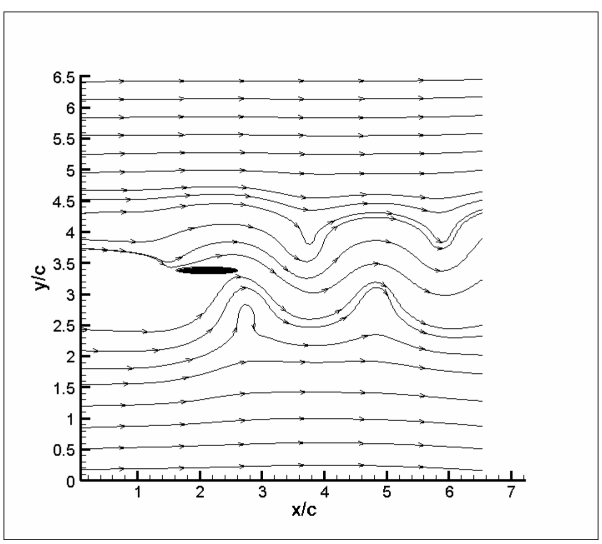

Figure 5a. Streamline plot Sta=0.276, Stc=0.75, t = 5.625T, airfoil ascending.

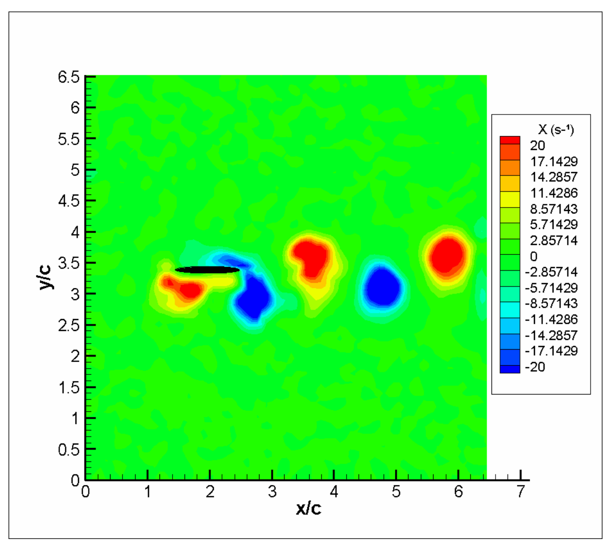

Figure 5b. Vorticity plot Sta=0.276, Stc=0.75, t = 5.625T, airfoil ascending.