Propulsion by an Oscillating Thin Airfoil at Low Reynolds Number

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Abstract. This paper describes an investigation of the mechanisms producing thrust for an airfoil performing a pitching or heaving motion in a low Reynolds-number flow ($Re = 1000$, based on chord length) by analysis of numerically obtained flow fields and forces on the airfoil. For heaving motion the dependence on reduced frequency and non-dimensional heaving amplitude are examined. For pitching motion the reduced frequency and the center of rotation are varied. The vortex generated by the leading edge is found to be determinant for thrust by heaving motion. Pitching propulsion is shown to be an effect of coupled acceleration and inclination of the airfoil.

Keywords: Flapping wing propulsion, Low Reynolds number, Heaving wing, Pitching wing.

1 Introduction

At low Reynolds numbers conventional wings produce relatively small lift and substantial drag. However, large insects and small birds realize high lift combined with flapping propulsion and great agility at the same low Reynolds numbers. These characteristics make flapping flight very attractive for micro air vehicles (MAVs), but equally so for aircraft designed for planetary research on Mars. Due to the low density of the Martian atmosphere, an aircraft of practical dimensions would encounter the same low Reynolds number.

The aerodynamics for flapping flight at these low Reynolds numbers is however not yet well understood and it is not clear how thrust is generated exactly [PJ06]. 3D Flapping flight of MAVs is described by many parameters (angular amplitudes, frequency, phase shifts) which make it difficult to determine which parameters govern the flow field.

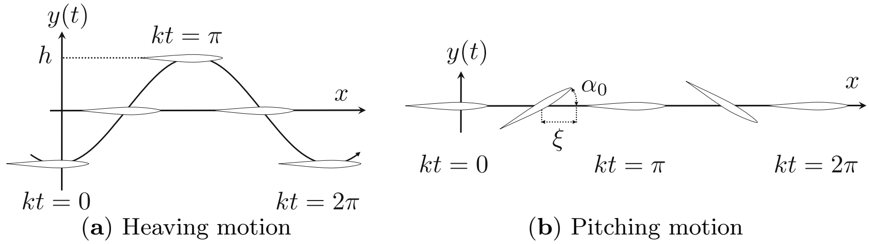


Fig. 1. Parameters for both oscillating motions

Therefore this research concerns analysis of basic motions. Thrust generation by a simple heaving airfoil (Fig. 1a) and a purely pitching airfoil (Fig. 1b) are examined, to detemine the variation with the parameters ξ, k and h independently. The results is helpful in obtaining insight in more complex cases.

For heaving motion the varied parameters are reduced frequency $k = \frac{2\pi f c}{U_\infty} \in (0.2, 4)$ and nondimensional amplitude h chordlength $h \in (0.125, 2.5)$. For pitching motion the reduced frequency $k \in (0.2, 6)$, the pitching amplitude $\alpha_0 \in (10°, 30°)$ and the center of rotation (between leading edge (LE) and trailing edge (TE), expressed by $\xi \in (0, 1)$) are varied.

2 Computational Method

Flow fields for these cases are obtained using a computational method based on one used for a variety of CFD studies, most recently [Oya07]. Besides the flow fields, the time history of thrust/drag of the airfoil, divided in a friction and pressure part, is used to analyze the results.

The governing equations are the Navier Stokes equations for incompressible flow. These were solved using a pseudo two-dimensional, pseudo-compressibility method. The convective terms are evaluated by Roe's scheme, while MUSCL interpolation based on the primitive variables is used to evaluate the fluxes at the grid interface. The viscous terms are discretisized by a second order central difference scheme. Time integration is carried out by means of a first-order lower-upper symmetric Gauss-Seidel (LU-SGS) implicit time integration scheme. Laminar flow of a Newtonian fluid is assumed.

3 Test Case

The computations were carried out using a C-shaped grid with 100 cells in radial and 268 in tangential direction. For every motion, 6000 time steps covering 3 cycles were simulated, the last cycle being used for analysis.

Accuracy was checked using a grid with doubled resolution. However, this showed better conservation of vortices and earlier flow separation. This caused only minor changes in far as thrust generating phenomena or the comparison of different cases are concerned. The absolute value of the thrust coefficient did however change up to 0.5 in some cases.

The range of design variables is representative for insects and some small birds and it is comparable with previous research focussing on insects, small birds and MAV development.

4 Heaving Motion

Figure 2 shows the dependance of $C_{T,av}$ on the parameters k and h. For $k > 1$ and $h < 2$, thrust increases strongly as the value of the parameters increase. In these cases thrust can be explained by one mechanism. For lower values of k, the airfoil does not shed the strong vortices needed to propell the wing. For higher values of h however, the structure of the flowfield is lost due to the the excessive motion of the airfoil.

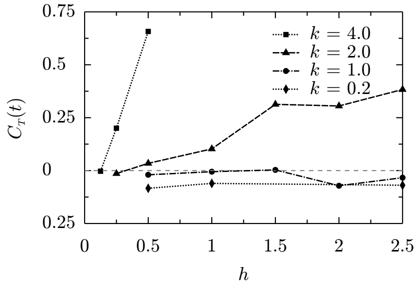


Fig. 2. Time-averaged thrust coefficient $C_{T,av}$ for different values of k and h

Heaving motion generates thrust when a vortex is generated at the LE and stays close to the airfoil, as shown in Fig. 3. Examination of the flow fields shows that such a vortex causes low pressure near the nose of the airfoil, generating thrust by suction. This vortex also induces a strong flow opposite to the free stream. This flow causes friction in upstream direction, which again is thrust. Both phenomena generate thrust of a similar order of magnitude. For comparison, the development with time of thrust due to pressure and friction is included in Fig. 3.

Figure 3a shows an airfoil simultaneously propelled by a LE vortex and hindered by a vortex shed at the TE. In Fig. 3b the effect of the LE vortex is maximal. Figure 3c–d show how the vortex travels along the airfoil. First the thrust by pressure decreases, as the vortex still induces a thrust-generating flow. Later the vortex travels around the TE and merges with the trailing edge vortex generated at that moment, which causes drag.

Vortices generated at the TE have the exact opposite effect of LE vortices, but since TE vortices travel away from the airfoil, their influence is smaller.

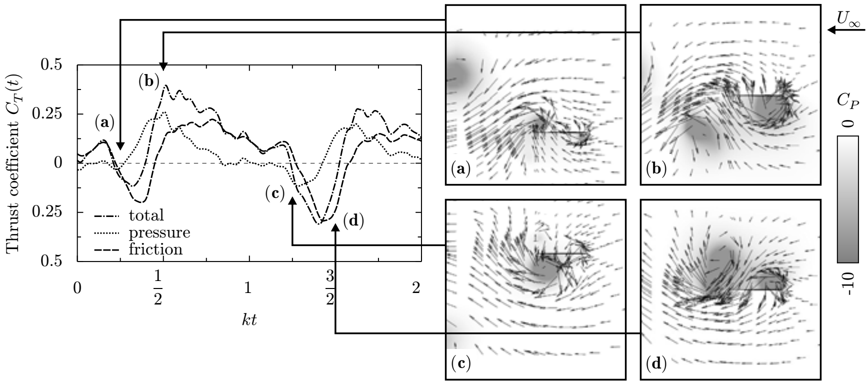


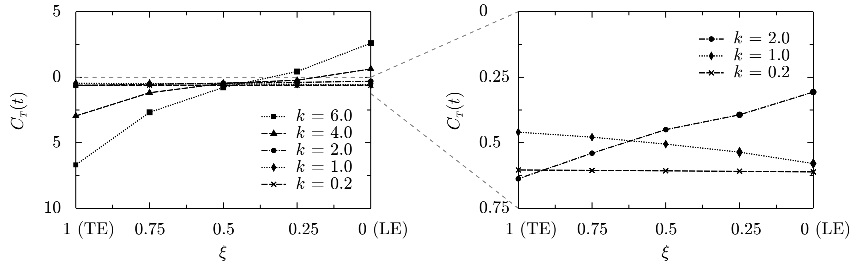
Fig. 3. Plunging airfoil propelled by a LE vortex ($k = 2$, $h = 1$)

5 Pitching Motion

Usually pitching around the LE is favorable for thrust, as seen in Fig. 4. For pitching around the LE ($\xi = 0$), as for the heaving motion, higher values of k give more thrust. $k = 4$ is the first value for which positive thrust is found. Similar to h, higher values of α_0 cause more thrust as well.

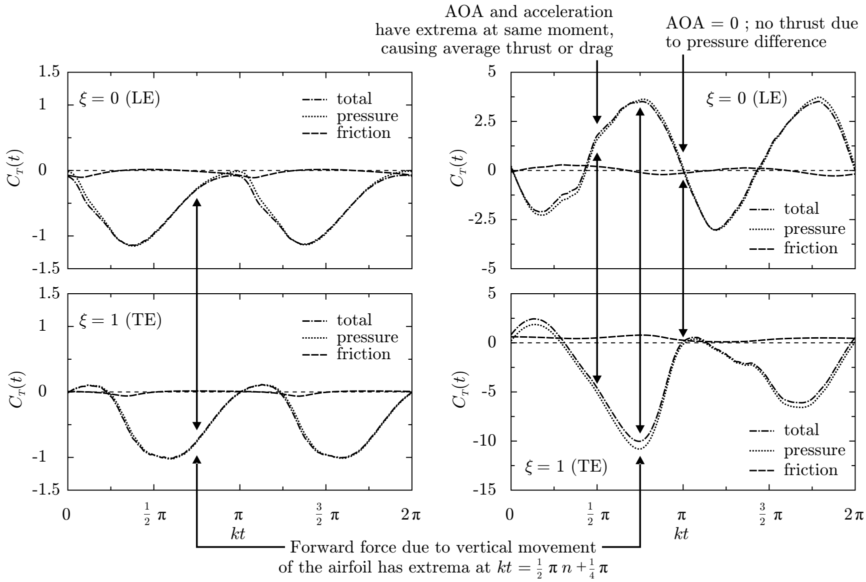
In the case of $k = 0.2$ and $k = 1$, pitching around the TE ($\xi = 1$) delivers more thrust. This seems to match the findings of heaving motion, for which thrust was generated by vortices at the moving LE. For higher values of k new mechanisms have to be found.

For pitching motion the time history of the thrust/drag shows relatively little influence of friction. At lowest frequencies, the airfoil shows a quasi-steady behavior, for which drag depends mostly on the momentary inclination of the airfoil, i.e. increasing inclination gives an increase in drag. As the frequency increases, the free stream velocity loses influence compared to the influence of the pressure difference over the airfoil opposing the pitching motion. When the



(**a**) All values of k (**b**) Lower values of k

Fig. 4. Time-averaged thrust coefficient $C_{T,av}$ for different values of ξ and k



(**a**) $k = 1$, $\alpha_0 = 30°$ (**b**) $k = 4$, $\alpha_0 = 30°$

Fig. 5. Time history of thrust for pitching around either LE or TE

airfoil is horizontal at $k = n\pi$, this does not cause any horizontal force. Since the airfoil does not move at $kt = n\pi + \frac{1}{2}\pi$, the influence of pressure on the airfoil due to the pitching motion is largest at $kt = \frac{1}{2}n\pi + \frac{1}{4}\pi$. This can already be seen at $k = 1$, as Fig. 5a shows. This effect gives thrust in a certain part of the cycle, but drag in another part of the cycle. Even though this effect stays dominant in the pressure thrust as a function of time, it does not give thrust on average, which however can be observed for higher values of k.

At even higher frequencies the average thrust for pitching around the LE is understood to be an effect of inertia of the fluid around the airfoil, as shown in Fig. 5b and schematically in Fig. 6.

When the airfoil rotates around the LE, it is accelerating upward when at maximum angle attack. Due to inertia of the fluid around the airfoil, the pressure on the top side of the airfoil in higher, which causes thrust. When the angle of attack is negative, the same effect still produces thrust. For pitching around the TE the effect is opposite however, and only drag is produced.

The effect of vortices on the pressure on a pitching airfoil is smaller than on a heaving airfoil. As seen in Fig. 7a, for pitching around the leading edge, this is because the leading edge is not moving, and therefore little vorticity is shed. Figure 7b shows how pitching around the trailing edge does generate a large LE vortex, but this vortex is relatively far away from the airfoil and has little influence on the pressure on the wing surface.

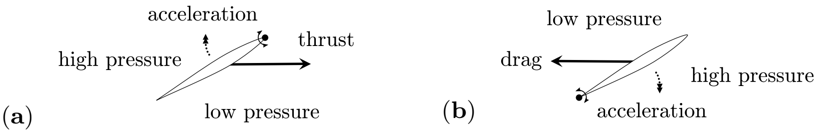
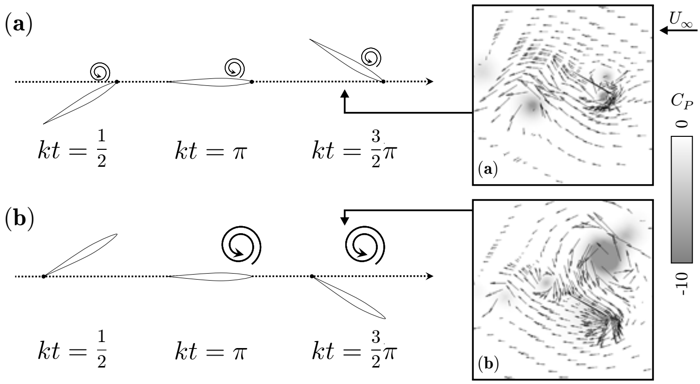


Fig. 6. At maximum angle of attack an airfoil is either: (**a**) propelled by positive vertical acceleration when pitching around the LE or (**b**) hindered by negative vertical acceleration when pitching around the TE



(**a**) $k = 1$, $\alpha_0 = 30°$ (**b**) $k = 4$, $\alpha_0 = 30°$

Fig. 7. In comparison with heaving, vortices play a smaller role for pitching motion

6 Summary and Further Research

The above identifies and explains the contributions of heaving and pitching to the thrust generated by an airfoil. It must however be realized that these phenomena are discussed on a qualitative basis. For engineering purposes quantitative analysis of more accurate simulations is required. These could include a wider range of parameters. The (symmetric) problems at hand did not allow an investigation of the effect of oscillation on the lift of the airfoil. For application in aviation this would be of great importance.

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