FLOW PAST AN OSCILLATING BI-CONVEX AEROFOIL

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ABSTRACT

This preliminary study aims to investigate the flow structure of an impulsively started bi-convex aerofoil, both at fixed incidences as well as in oscillation, using a digital cross correlation particle image velocimetry (PIV) technique. The experiments are conducted in a recirculating, piston (water) tunnel and the angular amplitude as well as the reduced frequency are varied for a given Reynolds number and linear acceleration.

The results of the experiments show that for the static case, an increase in the angle of attack intensifies the instabilities within the flow whilst for the oscillating cases, the reduced frequency, rather than the angular amplitude, is the key parameter which influences the fundamental characteristics of the flow.

The lower reduced frequency cases display characteristics that are remarkedly similar to that of the static stall cases, with the main distinction being a chronological delay in the flow evolution characteristics that exists between the former and the latter at any particular angle of attack.

The higher reduced frequency cases, on the contrary, are set apart from the other cases in both leading edge and wake development. The leading edge activity seems to be out of phase with what would normally be predicted in a quasi-steady condition whilst the wake vortex generation is predominantly due to the rotation of the aerofoil rather than the effect of the translating flow, as in the lower reduced frequency cases.

INTRODUCTION

In the domain of the study of unsteady aerofoils, one of the most fundamental problems investigated is the case where the effective incidence, or angle of attack of the aerofoil oscillates periodically with time. Such studies, which date back to the early 1930s, were originally motivated by their potential applications in engineering situations such as the performance of rotorcraft, wind turbines as well as aircraft manoeuvreability.

In the late 1970s, these studies gradually found extensive use in bio-fluid-dynamics, since the propulsion of certain species of birds; insects and fish were observed to be characterized by a heaving and oscillating motion of a high aspect ratio wing or fin. (Wu, 1971)

In more recent times, with the advent of Micro Electro Mechanical Systems (MEMS) such as Micro Aviation Vehicles (MAV), the employment of dynamic or "flapping" wings in such applications has become more and more of a distinct possibility. This has generated a surge in in-depth studies into the motion of airborne creatures, especially those of a smaller nature such as insects, so as to have a better understanding of their flight dynamics.

Studies by Dickinson (1994) and Ellington (1984) have shown that insect wing motion, contrary to common perception, is not merely pure flapping motion, but rather a complicated three dimensional affair which combines flapping, premotion and remotion as well as twisting, analogous to the pitching, coning and lagging motion of the main rotor of a helicopter.

The current study investigates the flow structure of an impulsively started sharp edged aerofoil, both at fixed incidences as well as in oscillation, using particle image velocimetry (PIV). The Reynolds number is maintained at a constant value of 1000 and the axis of oscillation is also fixed at half chord throughout the course of the experiments, whilst varying the angular amplitude as well as the reduced frequency.

Though the resultant motion does not mimic the flight kinematics of an insect in its entirety, the aim of this study is to gain an insight into insect flight dynamics by broadly exploring the characteristics of the flow field of such a motion rather than to reproduce and analyse the exact trajectory of a typical insect wing.

EXPERIMENTAL SETUP

The experiments were carried out in a recirculating, piston tunnel facility shown in figure 1. The water tunnel

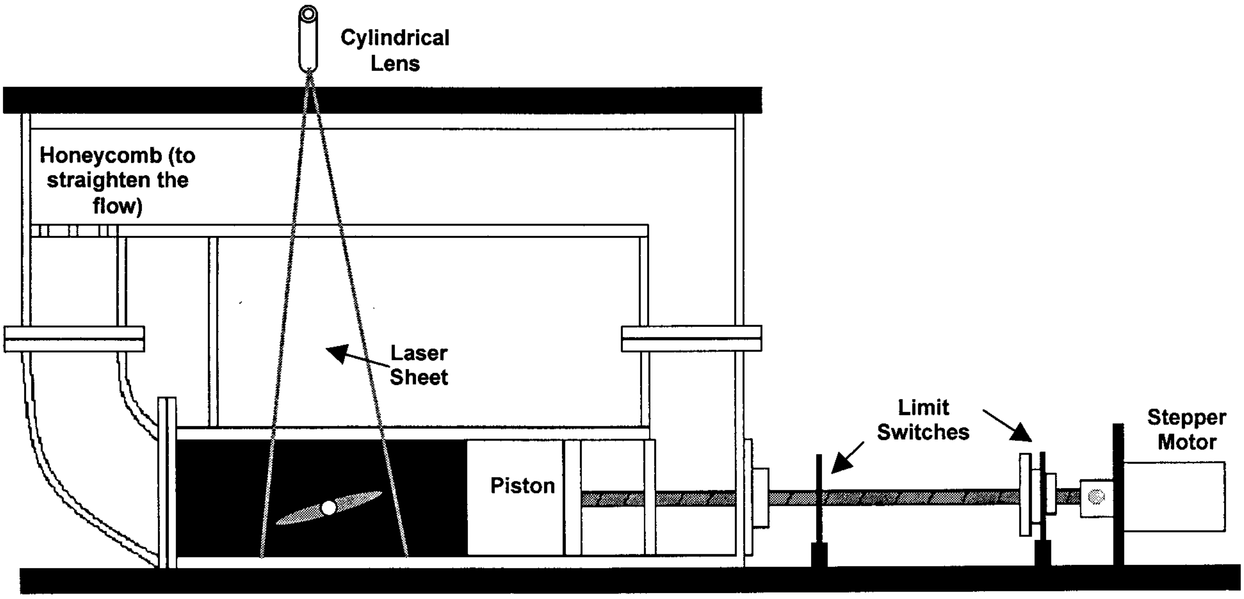

Figure 1: Schematic of Recirculating Piston Tunnel Facility.

consists of a square piston, measuring 198mm by 198mm, used to generate the impulsively started flow. A stepper motor, connected via a coupling to a ball and screw mechanism, is used to drive the piston. This allows the rotational motion of the motor to be converted into linear motion. The motion of the piston is restricted to a maximum horizontal displacement of 400mm.

A two dimensional, bi-convex aerofoil of chord 60mm, aspect ratio of 3.25 and radius of curvature 122mm, is used throughout the experiments and spans the entire width of the water tunnel.

For the oscillating cases, another stepper motor is connected to the aerofoil to generate the required sinusoidal oscillating motion. In all cases, the axis of oscillation is fixed at half chord.

The stepper motors and the PIV camera and laser are all computer controlled and are linked via an Ethernet interface. TTL signals are used to synchronize all the devices and ensure that they are triggered at the same time.

A multigrid cross correlation digital PIV (MCCDPIV) algorithm by Soria (2001) is used to analyse and process the raw data.

EXPERIMENTAL CONDITIONS

For all experiments conducted, the flow is impulsively started from rest (zero flow condition within tunnel facility) with the aerofoil in a horizontal position (i.e. zero angle of attack). In theory, one would require that the acceleration is of an infinite nature, (i.e. zero acceleration time) but this is not possible experimentally. Instead, the initial acceleration, a_o, is of a linear nature, and is fixed at 100mm/s^2 throughout. The Reynolds number, Re, defined as

$$Re = {}^{U_\infty c}\!/_{\upsilon} \qquad (1)$$

where

U_∞ = Constant, post acceleration, freestream velocity
c = Aerofoil chord
υ = Kinematic viscosity of water

is assigned a constant value of 1000 with reference to the flight of a typical drosophila.

For the oscillating cases, the chosen mode of oscillation is that of a sinusoidal nature, given by the equation:

$$\theta = \theta_o \sin \omega t \qquad (2)$$

where

θ = Angular displacement
θ_o = Angular amplitude
ω = Angular frequency
t = Time elapsed

The varied parameters are the angular amplitude, θ_o, and the oscillation frequency, which is represented by the dimensionless reduced frequency, κ. The reduced frequency is defined as,

$$\kappa = {}^{fc}\!/_{2U_\infty} \qquad (3)$$

where

f = Oscillation frequency

The time elapsed is also non-dimensionalized by the freestream velocity and aerofoil chord to give,

$$t^* = {}^{tU_\infty}\!/_{c} \qquad (4)$$

RESULTS AND DISCUSSION

Fixed Incidence Cases

The general flow pattern (figures 2 and 3) is characterized by the formation of a starting vortex and concurrent thickening of the boundary layer that promotes the development of a primary, (clockwise) leading edge vortex. The low-pressure core of the leading edge vortex subsequently induces the formation of a counter rotating vortex at about quarter chord. This is then followed by the growth of a secondary, trailing edge vortex and finally, shedding of the primary, leading edge vortex which is accompanied by the simultaneous growth of a secondary, trailing edge vortex.

However, an increase in the angle of attack does seem to demonstrate a positive relationship with the instabilities within the flow and this in turn results in a chronological difference in the evolution of the fundamental characteristics mentioned above.

Oscillatory Cases

The reduced frequency rather than the angular amplitude appears to be the dominant parameter in determining the fundamental characteristics of the flow.

For the lower reduced frequency of $\kappa=0.1$ (figure 4), the starting flows seem to preserve the general flow pattern typical of the static cases. After the detachment of the starting vortex and its subsequent translation out of the visual field, the initial separation bubble aids in the growth of a primary, leading edge vortex that traverses the top surface of the aerofoil.

Having said that, this does not imply that the quasi-steady state assumption can be applied to such a flow response. A distinct feature between this particular reduced frequency and the static cases is that a discernible chronological delay in the flow characteristics exists between the latter and the former. Similar observations have been reported by Ohmi et al (1990), and Visbal (1989).

Apart from the above, it is also evident from the results that the ascent of the leading edge seems to promote leading edge separation and growth of the leading edge vortex, whilst the descent of the leading edge, on the other hand, inhibits the leading edge separation, promotes the shedding of the leading edge vortex and in addition, gives rise to a counter rotating vortex (at about quarter chord) which reinforces the shedding of the primary vortex.

The flow response at the higher reduced frequency of $\kappa=0.5$ (figure 5) is drastically different from that of the previous case. The starting flows also indicate the presence of a starting vortex but the subsequent flow pattern is characterized by cyclic, alternating wake vortices, with each vortex having a rotational sense opposite to that of the aerofoil. It also appears that the generation of wake vortices at this higher reduced frequency is mainly due to the rotation of the aerofoil whereas the wake development at the lower reduced frequency is much less prominent and more typical of a static-stall regime response.

It is postulated that the aerofoil oscillation has the effect of imparting an additional velocity component to the flow which alters the effective angle of attack. The magnitude of this velocity component is directly proportional to the oscillation frequency whilst its direction is dependent on whether the aerofoil is in a pitch-up or pitch-down motion.

During the pitch-up motion of the aerofoil, the additional velocity component imparted by the oscillatory motion to the fluid has the effect of reducing the angle of attack of the aerofoil. By the same token, when the aerofoil pitches downwards, this same component of velocity increases the effective angle of attack.

In the lower reduced frequency cases, this velocity component is relatively small. Hence, it has less of an influence on the effective angle of attack and only serves to 'retard' the flow evolution characteristics. However, in the higher reduced frequency cases, this velocity component is large enough to actually reduce the effective angle of attack such that separation above the leading edge is almost totally suppressed.

CONCLUSION

A preliminary study of an impulsively started bi-convex aerofoil at fixed incidences as well as in oscillatory motion has been conducted. The effect of an increase in the angle of attack seems to amplify the instabilities within the flow, especially as manifested in the repeated shedding of the leading edge vortex for the high incidence case of $\alpha=60^\circ$.

For the oscillatory motion, the dominant parameter influencing the fundamental flow characteristics is the reduced frequency, rather than the angular amplitude, which affects secondary considerations such as the strength and alignment of vortices.

The lower reduced frequency cases exhibit a flow pattern akin to that of the static cases except for the existence of a chronological delay in the flow characteristics between the oscillating case and the static case. Broadly speaking, the flow generally seems to adapt well to the sinusoidal incidence variation and displays features reminiscent of an aerofoil in static stall.

The higher reduced frequency cases, on the other hand, show a distinct dissimilarity from the other experiments. Unlike the former case, flows in this regime are dominated by the effect of the fluid inertia against the motions of the two edges of the aerofoil. This leads to the formation of cyclic, alternating vortices with opposing rotational sense to that of the aerofoil and leading edge activity which appears much different from that of the lower reduced frequency cases.

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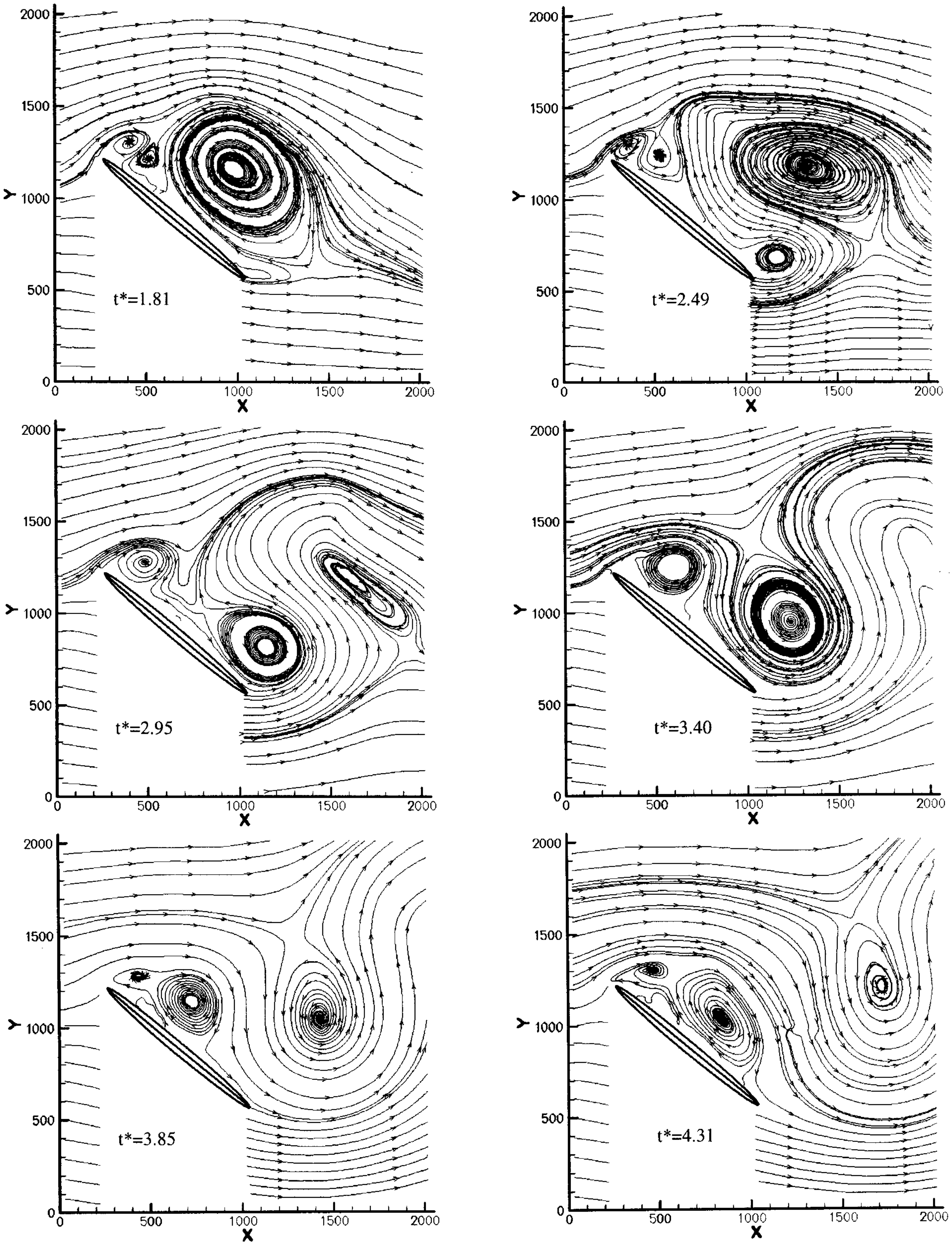

Figure 2: Streamline plots of an impulsively started, bi-convex aerofoil at an angle of attack of 40° and Reynolds number of 1000. The flow is from left to right. The loss of data (white region) is due to the lack of illumination beneath the aerofoil.

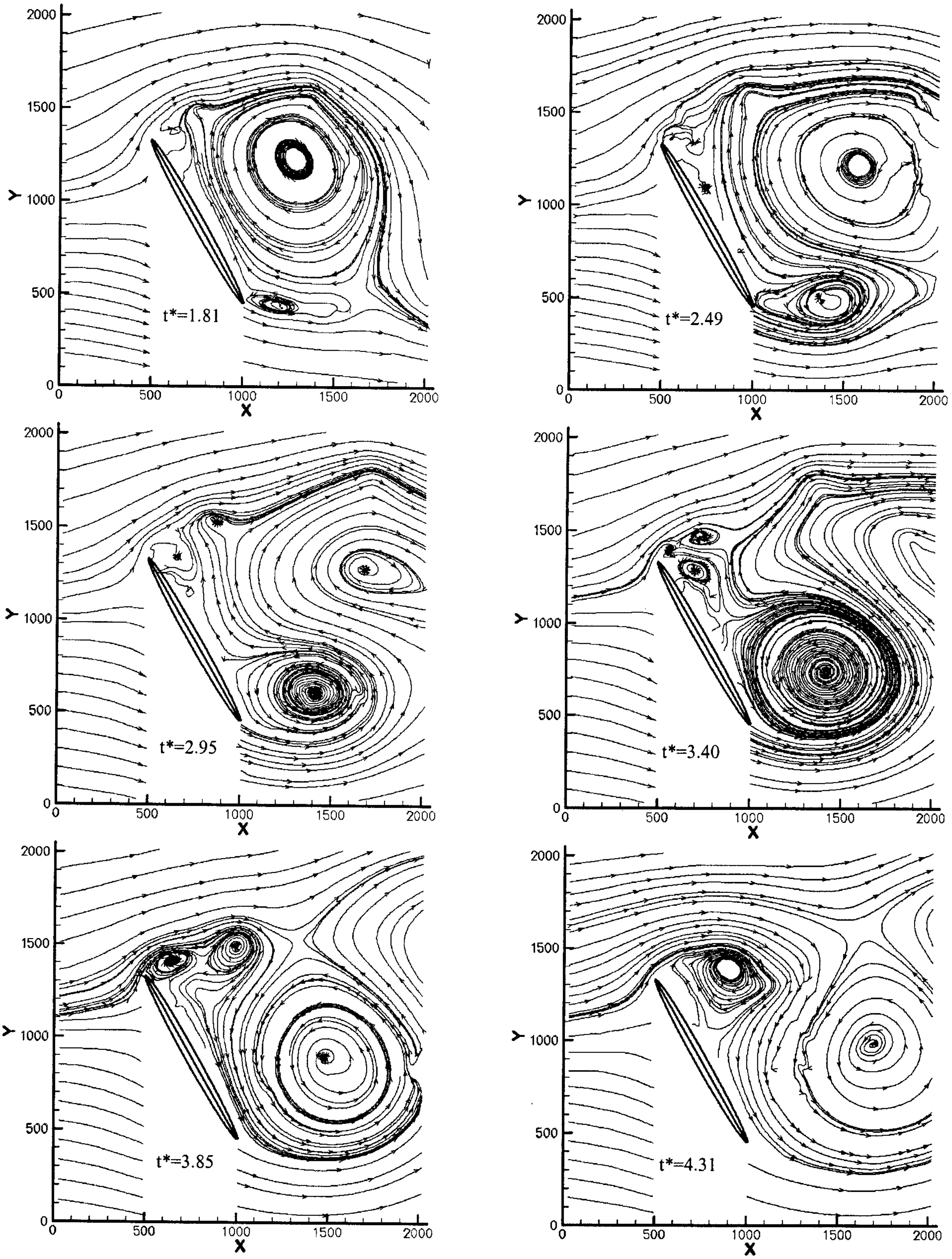

Figure 3: Streamline plots of an impulsively started, bi-convex aerofoil at an angle of attack of 60° and Reynolds number of 1000. The flow is from left to right.

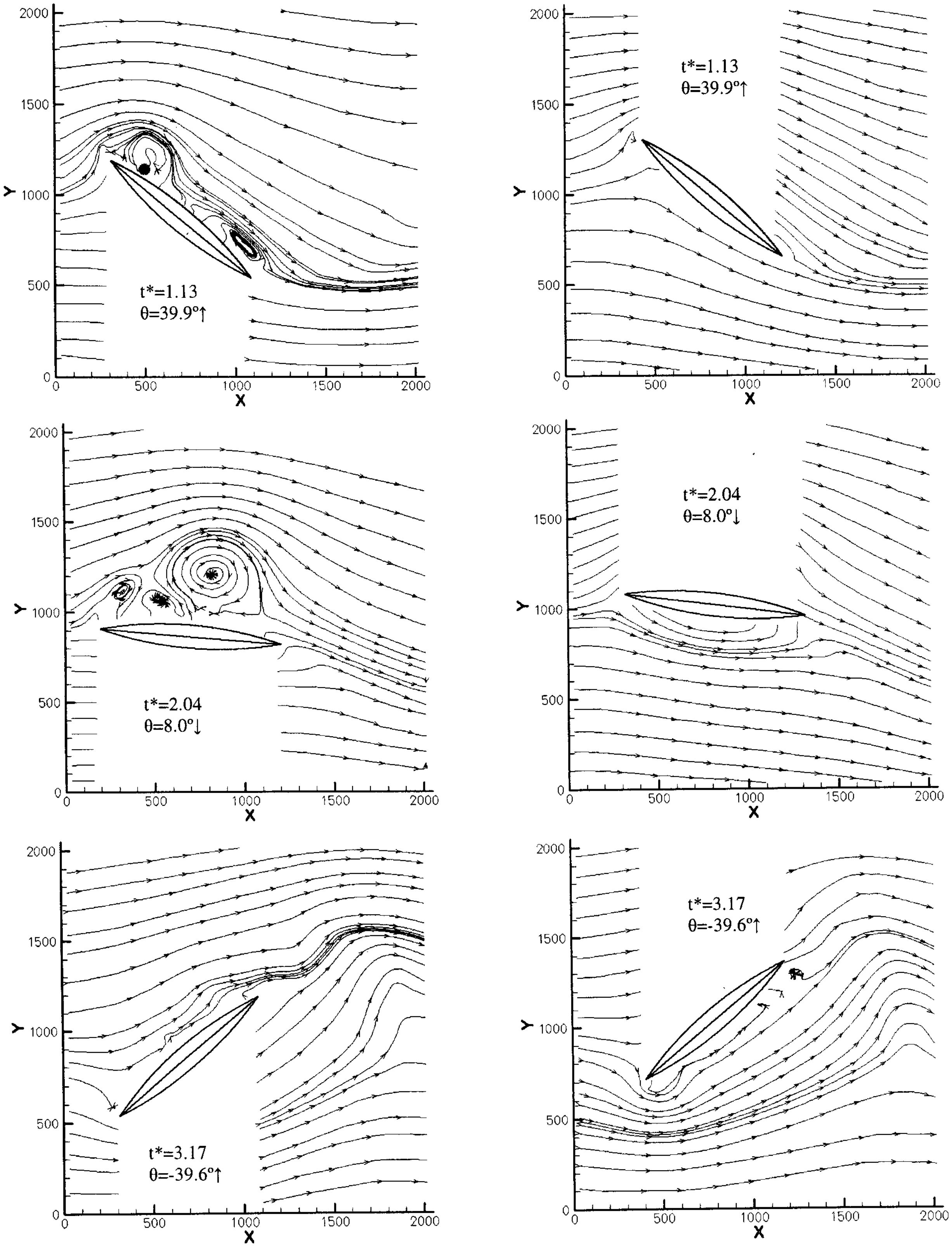

Figure 4: Streamline plots of an impulsively started, oscillating bi-convex aerofoil with an angular amplitude of 40°, reduced frequency of 0.1 and Reynolds number of 1000. The flow is from left to right. The symbols ↑ and ↓ refer to nose-up and nose-down motion of the aerofoil respectively.