Flapping Membranes for Thrust Production

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It has been known for some time (for example, Gray (1936), Triantafyllou and Triantafyllou (1995)) that the efficiency and agility of flying and swimming species far exceeds that of man-made vehicles. To understand the physical mechanisms involved in such locomotion, researchers have investigated a variety of unsteady devices and analytical models for the production of thrust and lift (reviews are presented in Triantafyllou et al. (2000) and Wu (2001)). The present study is an experimental investigation of the thrust generation and flow field characteristics of a quasi two-dimensional flapping flexible membrane, fixed at its leading edge. Preliminary experiments have been conducted using flow visualization and digital particle image velocimetry (DPIV), which indicate that thrust is produced when the membrane is actuated to generate a transverse wave traveling in the downstream direction. In this study, we wish to identify the relevant parameters governing the production of thrust, and identify the physical mechanisms responsible for optimal operation.

Triantafyllou et al. (1991 and 1993) identified the Strouhal number as the primary parameter governing the efficiency of thrust production in various oscillating rigid airfoil experiments, and in a survey of a variety of fish and cetaceans. The optimal Strouhal number was found to predominantly lie between 0.25 and 0.35, and is defined as:

$$St = \frac{fA}{V}, \qquad (1)$$

where f is the frequency of oscillation, A is the full width of the wake, often approximated by the maximum excursion of the trailing edge (peak to peak), and V is the average swimming speed or relative free-stream velocity. However, this does not appear to be universal. In a computational study of a swimming tadpole – a geometry more representative of the present work but at a much lower Reynolds number – Liu et al. (1999) report maximum efficiency at a Strouhal number of 0.72. This is attributed to the larger excursion of the tadpole's tail; perhaps Reynolds number is also a factor. Ohmi et al. (1990, 1991) propose a similar parameter, the reduced frequency, as an important parameter governing the structure of the wake generated by a flapping foil:

$$f^* = \frac{fc}{V}, \qquad (2)$$

where the wake width A has been replaced by the chord length c of the foil.

The present experiment consists of a thin flexible plastic membrane extending downstream from the trailing edge of a stationary symmetric two-dimensional airfoil section. A schematic of the experiment is given in Figure 1. The assembly is placed in a water channel with a free-stream velocity of order 0.1 m/s, giving a Reynolds number based on membrane chord of approximately 25000. A streamwise traveling wave is imposed on the membrane by periodically exciting two buckling modes through the displacement of four cables attached to the membrane at various points. The cables serve as actuators. The two modes are separated by a 90° phase difference and are depicted separately in Figures 2 and 3. The chord of the membrane c is 24.5 cm. Experiments have been conducted with a span s of 6.5cm and 11cm for aspect ratios of 0.27 and 0.45.

Figure 4 shows a dye visualization of the flow field downstream of the membrane (aspect ratio s/c=0.45, $St \cong 0.6$) in the near wake. Dye injection along the mid-span reveals a net streamwise momentum addition, indicated by the sense of the vorticity in the alternating vortex street. The traditional von Kármán vortex street, resulting in a mean momentum deficit would have vorticity of the opposite sign.

Figures 5 and 6 show wake velocity fields determined using DPIV for an aspect ratio of 0.27 and St=0.58, calculated according to Equation 1. The wake contains a complex collection of vortices of which the origin is not fully understood. Each shedding event results in vorticity of both signs. This could be characteristic of forcing at a suboptimal Strouhal number and the boundary layer separation indicated by the arrow labeled 'A' in Figure 5 hints at a mechanism for the inferred thrust deterioration. Wake experiments of an oscillating airfoil by Ohashi et al.

(1972) support this: for higher frequencies, the flow separates from the leading edge resulting in loss of thrust. Highly three-dimensional flow near the edge of the membrane was revealed by

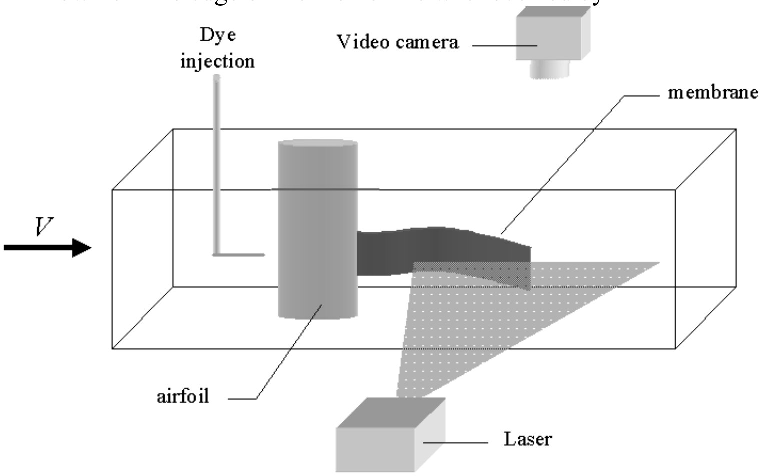

Figure 1. Experimental setup.

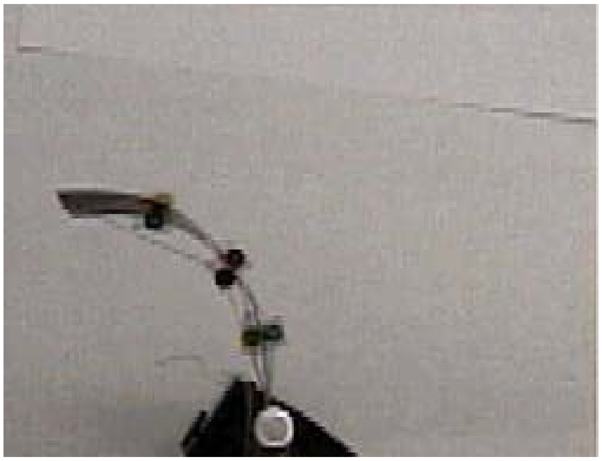

Figure 2. Flexible membrane actuated by first buckling mode.

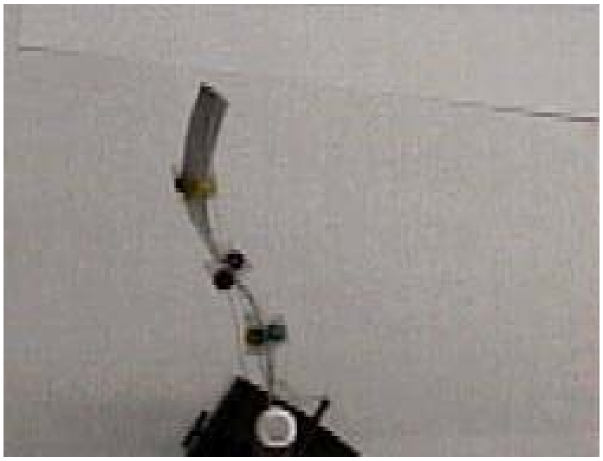

Figure 3. Flexible membrane actuated by second buckling mode.

Figure 4. Dye visualization of near wake of the flapping flexible membrane. Flow is from right to left. Aspect ratio *s/c*=0.22, $St \cong 0.6$.

surface-mounted tufts, suggesting also the importance of aspect ratio for the production of thrust. It should be noted that in general, flow visualization experiments at the higher aspect ratio have generated simpler wakes such as that shown in Figure 4; whereas the lower aspect ratio typically yields a more complicated dye pattern, consistent with the vectors in Figures 5 and 6.

Further work is in progress. The conference submission will focus on the relevance of Strouhal number, reduced frequency, aspect ratio, and amplitude in characterizing the flow field behavior, using DPIV data to study the three-dimensional vortex structure of the wake and near-body flow field.

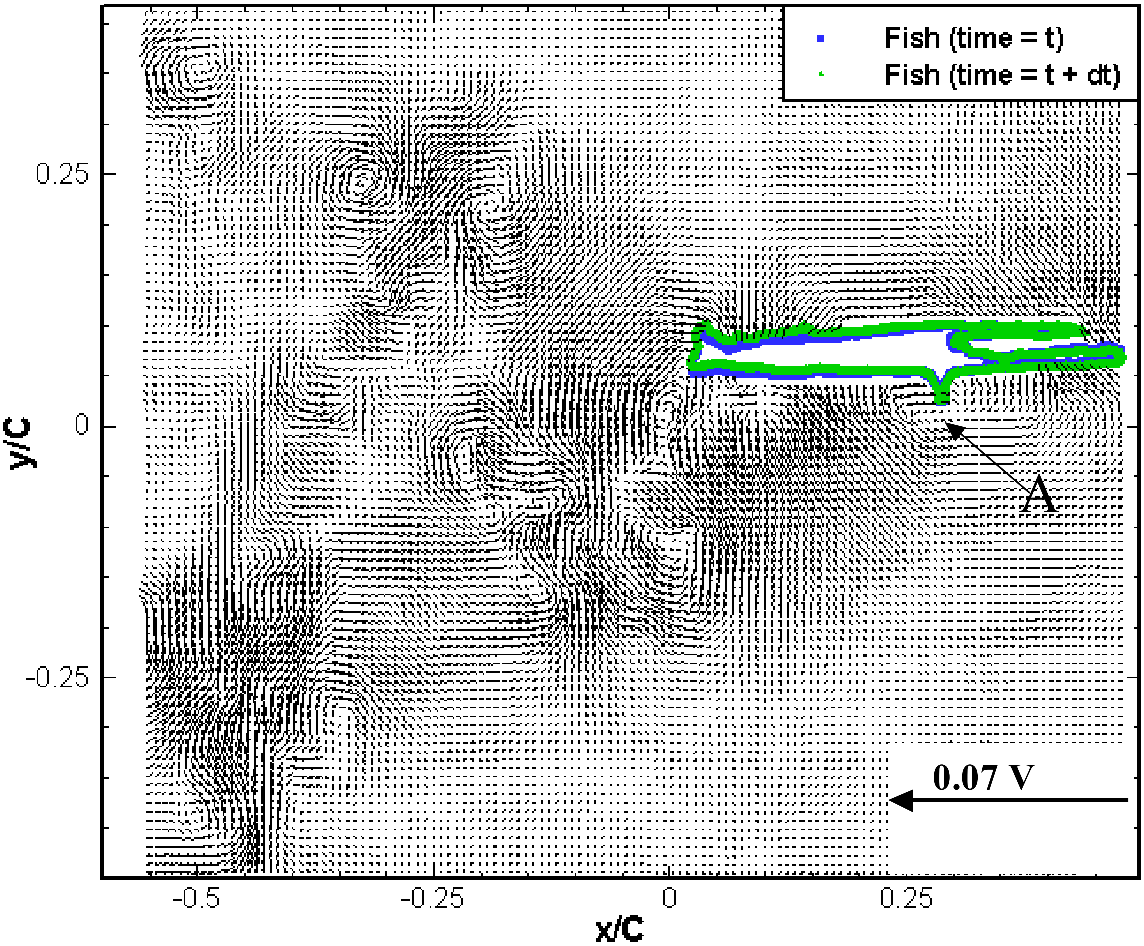

Figure 5. Instantaneous velocity field of near wake of the flapping flexible membrane viewed in a Galilean reference frame equal to $U_c = 0.07\ U_\infty$. Aspect ratio s/c=0.27, St=0.58. The arrow labeled 'A' indicates a flow separation region along the flapping flexible membrane surface.

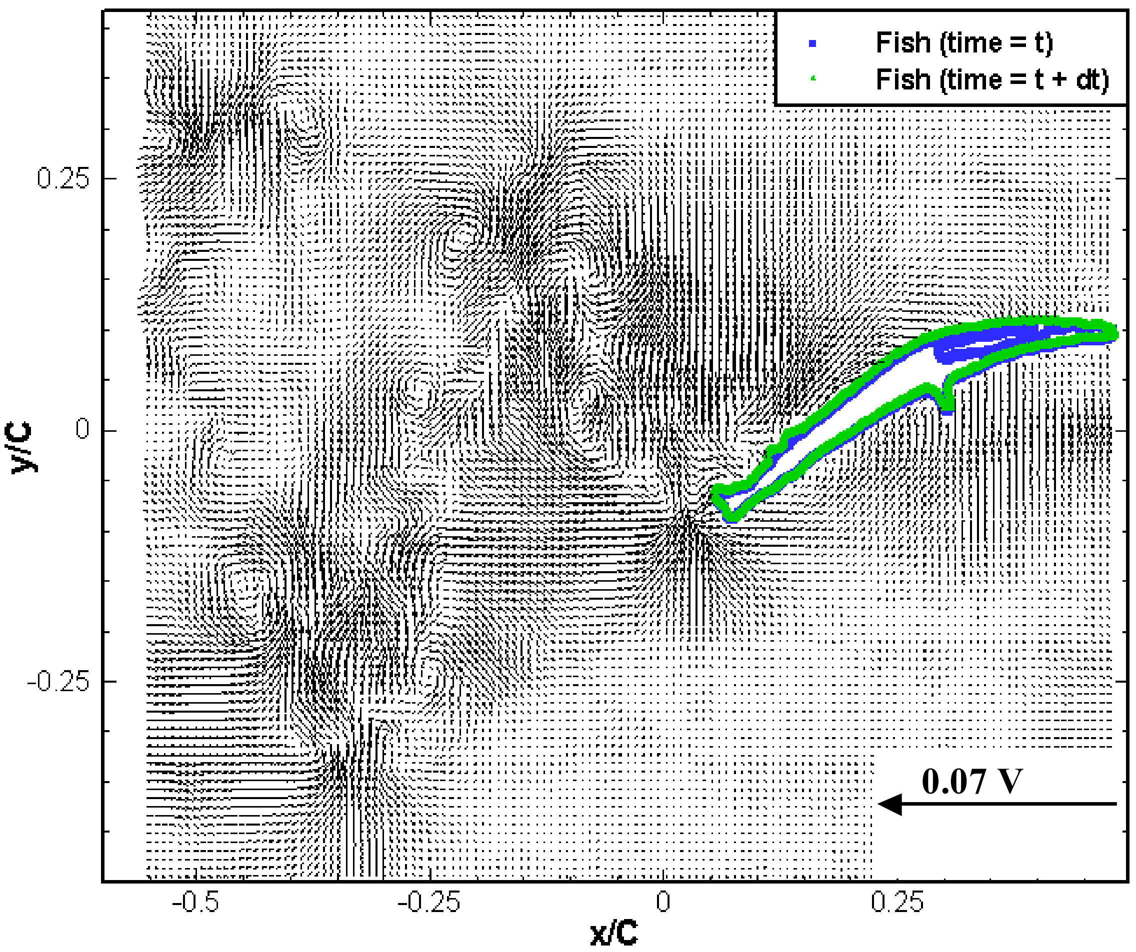

Figure 6. Instantaneous velocity field of near wake of the flapping flexible membrane viewed in a Galilean reference frame equal to $U_c = 0.07\ U_\infty$. Aspect ratio s/c=0.27, St=0.58.

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