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Vorticity Control in Fish-like Propulsion and Maneuvering[1]

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SYNOPSIS. Vorticity control is employed by marine animals to enhance performance in maneuvering and propulsion. Studies on fish-like robots and experimental apparatus modelling rigid and flexible fins provide some of the basic mechanisms employed for controlling vorticity.

INTRODUCTION

Systematic observations of the kinematics of swimming fish and marine mammals have revealed a new paradigm of locomotion, distinctly different from conventional propulsion used in man-made vehicles (Gray, 1969; Aleyev, 1973; Videler, 1993). Relatively large amplitude, rhythmic, unsteady body motions are used by fast-swimming animals to achieve remarkable agility underwater. Such large amplitude motions must be accompanied by optimized flow control mechanisms, otherwise these same motions may lead to uncontrolled flow separation and the generation of large adverse pressure forces and hence considerable degradation of performance. Recent work with live animals has provided important information on the resulting flow, structures (Stamhuis and Videler, 1995; Anderson, 1996; Mueller *et al.*, 1997; Wolfgang *et al.*, 1999; Drucker and Lauder, 1999; Lauder, 2000).

Vorticity control, therefore, is of considerable interest, because it is the only known way to control flow in an effective way, requiring only a finite amount of sensors and actuators. Indeed, the presence of a few large scale vortices renders flow sensing and control manageable. The basic rules of vorticity control are understood at least for some basic flows, such as controlling the vortex shedding process behind a bluff body through rotational oscillation of the cylinder (Taneda, 1977; Tokomaru and Dimotakis, 1991), and controlling oncoming vortices using a flapping foil (Gopalkrishnan *et al.*, 1994). Taneda (1977) and Tokomaru and Dimotakis (1991) imposed a rotational oscillation on a two-dimensional cylinder in cross-flow, reducing the width of the wake and hence the drag coefficient significantly, for properly selected parametric values. Injection of unsteady vorticity is the mechanism through which the flow control was implemented.

A flat plate undergoing transverse oscillations in the form of a traveling wave, placed within an oncoming steady flow, was found to exhibit reduced turbulence intensity and separation as the phase speed of the traveling wave is increased to reach values comparable to the free stream velocity (Taneda, 1977). The same mechanism of unsteady vorticity injection appears to control separation and turbulence production.

The possibility of extracting energy from oncoming vortices through an oscillating foil was investigated experimentally by Gopalkrishnan *et al.*, (1994), and Anderson (1996); and theoretically by Streitlien and Triantafyllou (1995, 1996). It was shown that energy contained in large scale eddies can be retrieved hence enhancing propulsive efficiency, or amplifying thrust production.

We review evidence of flow control achieved in fish like swimming, including separation elimination and turbulence reduction, up to Reynolds numbers of 1.5×10^6; as well as energy extraction from oncoming vortical flows.

WAKE CONTROL

As in man-made systems, steady forward motion by fish is achieved through the generation of a jet which provides the thrust needed to overcome the body drag. Unsteady motion of the body of the fish means that the flow left in the wake is also unsteady; time averaging of the flow, however, must have the form of a jet. The free shear layers of a jet flow are known to be unstable, *i.e.*, small perturbations are amplified, initially exponentially—until nonlinear terms saturate the growth of these instabilities. The continuous flapping of the tail and the body provides for a harmonic excitation of the flow and hence unsteady patterns are expected to form, in addition to any organized vortical patterns shed by the tail, the body or the fins of the animal.

Minimization of the energy expended in propulsion is contingent on satisfying a number of conditions, principally that: (a) the flow does not separate from the body to generate adverse pressure losses; (b) the energy put in the fluid by the fish is the minimal needed for the given thrust generation. The first condition requires that the body motion is well synchronized to avoid the uncontrolled separation and vortex shedding encountered, for example, in a flapping flag. The second condition requires that the flow patterns contain minimal energy for a given generated thrust.

Hence the concept of a minimum energy wake has been developed on the basis that the vortical patterns developing through body motion must be compatible with the instability properties of the average wake flow. This concept is not so simple to apply, because

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the average flow is affected by the unsteady vortical patterns through the Reynolds stresses. It is coincidental that the average jet flow in an actual wake behind a flapping foil, has qualitatively the same bell-shape expected for a jet: Still, the quantitative values vary as function of the amplitude and frequency of oscillation.

As a result of these considerations, it was proposed that a wake-based non-dimensional frequency, or Strouhal number, St, should be the controlling parameter (Triantafyllou *et al.*, 1991, 1993):

$$St = fA/U,$$

where f is the frequency of oscillation, A the peak-to-peak motion of the tail of the fish or trailing edge of the foil, and U the speed of forward motion. The Strouhal number, as defined above, is an indicative quantity, since there are major simplifications introduced: A should be the width of the wake, which is unknown beforehand, although it is reasonable to assume that it approximately equal to the amplitude of oscillation; U should be an average jet velocity, which is also unknown. For moderately loaded foils, the average speed of the jet should be close to the speed of locomotion; for heavily loaded foils this speed may be significantly different.

For the streamlined body of the fish, one may expect the load to be light to moderate; hence the approximations used in the definition of the Strouhal number are reasonable. Indeed, observations from fish show that it is very likely that the Strouhal number of fish will fall within the theoretically predicted range, *i.e.*, between 0.25 and 0.35 (Fish, 1997; Rohr *et al.*, 1998).

The theoretical prediction is based on the experimentally observed fact that thrust develops optimally when two counter-rotating vortices develop within a cycle, resulting in a reverse Karman street, and, when time-averaged, in a bell-shaped average velocity profile. Also, on the fact that such a jet flow has a convective instability with a preferred frequency and wavelength of maximum spatial amplification: Excitation of the wake at this preferred frequency results in the development of a reverse Karman street with minimum excitation energy; the vortical patterns form partially through rearrangement of the shed vorticity.

Similar arguments have been used by Gharib *et al.* (1994, 1998) in studying the development of a single vortex ring through the ramped up motion of a piston with diameter D, moving at constant velocity U for a time period t. In this case, a non-dimensional formation time is formed, tU/D, which is qualitatively the inverse of the Strouhal number, expressed for an unsteady, single-event flow. It is found that the circulation of the ring grows optimally, *i.e.*, with minimum energy until a value of tU/D roughly equal to 4, when a maximum is found; after this parasitic vorticity is generated, wasting energy.

The arguments above are based on two-dimensional flow considerations. In three-dimensions, the vortical patterns must connect with each other and with the foil or body producing them. The idea of a chain of alternately inclined—with respect to the direction of motion—interconnected vorticity rings, as sketched by Lighthill (1975), provides a consistent qualitative picture for the flow structure behind oscillating foils. Recent work by Drucker and Lauder (1999) and Lauder (2000) shows the formation of ring-like vortices by fish fins.

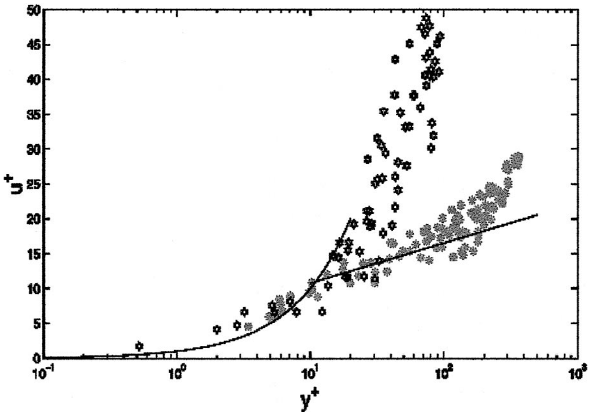

FIG. 1. The average velocity profiles for swimming and non-swimming cases. The solid lines show the ''law of the wall.''

Detailed flow visualization in flapping foils provides a more complex picture: The vortical patterns close partially on themselves to form apparent ring loops, but the vorticity of each loop connects all the way back to the foil (Freymuth, 1989, Hart *et al.*, 1992). This is similar to the way Karman vortices interconnect with themselves and to the body, in the wake of a finite length bluff cylinder, or—in a more simplistic description—to the way helical vortices in the propeller go all the way back to the propeller blade. The only difference here is that the connecting vortices to the foil are entangled in a ''spaghetti'' like structure, resembling the hub vortex of the propeller but with the difference that the constituent vortices do not have the same rotational sign. This picture has a significant effect on induced drag.

SEPARATION AND TURBULENCE REDUCTION THROUGH VORTICITY CONTROL

Flow visualization with a 1.20 m long robotic mechanism, the RoboTuna, whose external shape has the form of a bluefin tuna (Triantafyllou and Triantafyllou, 1995), capable of emulating the swimming motion of a live tuna, exhibited lack of separation effects along its body, even when the motion amplitude reached values 10% of the body length. Also, measurement of the flow characteristics of the boundary layer showed apparent re-laminarization of the flow when the traveling wave phase speed was close in value to the stream velocity (Techet *et al.*, 1999; Anderson *et al.*, 1999; Techet and Triantafyllou, 1999, 2000; Techet, 2001). Under conditions of towing the mechanism without transverse motion, the boundary layer was characterized by a turbulent velocity profile. Figure 1 demon-

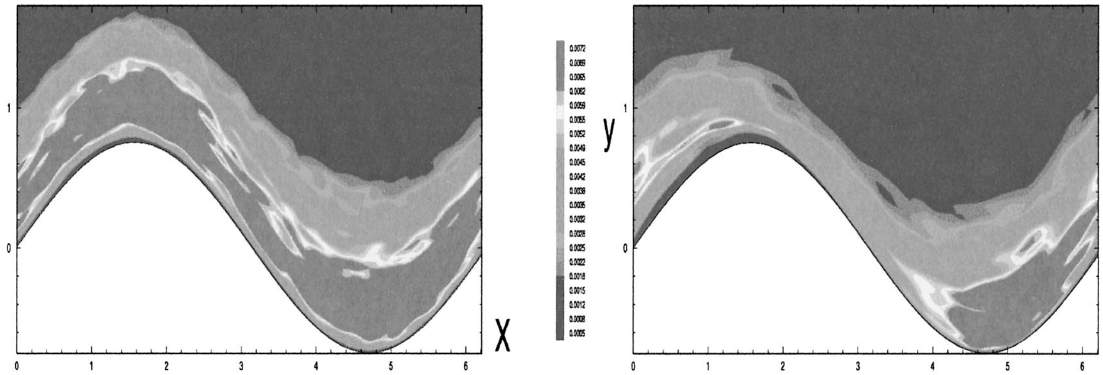

FIG. 2. The turbulence intensity along the length of a flapping plate for c/U = 0.40 (left) and c/U = 1.2 (right).

strates the difference between the two measured average velocity profiles: The form of the velocity curve has the characteristic law of the wall shape when there is no transverse motion, while a laminarized shape appears when there is active swimming motion with c/U = 1.14, where c is the speed of traveling wave and U the speed of the external stream.

Computational studies on a flat plate undergoing traveling wave oscillations within an oncoming stream, show reduction of separation as the phase speed c increases, with complete elimination of separation at c/U close to 1 (Zhang, 2001). Similarly, turbulence intensity is found to decrease non-uniformly across the length of the plate, with increasing c/U, up to a value of about 1.5. The study was conducted at Reynolds number, based on plate length, of 6,000 and then 18,000. Although the flow features around the plate change with Reynolds number for a non-vibrating plate, the flow remains qualitatively similar at the Reynolds numbers studied when c/U is near 1, with a preferred value of c/U = 1.2. The energy to propel the flapping plate, defined as the energy to tow the plate (which can be negative if the plate produces thrust) plus the energy to oscillate the plate, is minimal at a value of c/U = 1.2 (Zhang, 2001; Zhang *et al.*, 2001). Observations with live fish show that the preferred value of c/U is about 1.2 as well. Figure 2 shows the turbulence intensity along the length of a flapping plate, for two values of c/U, 0.4 and 1.2. There is non-uniform, but substantial reduction of turbulence intensity in the case of c/U = 1.2.

Experimental work with an 1-meter flapping plate in a water tunnel at Reynolds numbers up to 2,000,000 shows reduction or even elimination of separation, and significant reduction of turbulence intensity as c/U approaches 1.2 (Techet, 2001). Figure 3 shows a sketch of the experimental apparatus, which allows for a traveling wave motion using a series of scotch yokes driven by a single motor, activating 8 pistons. Figure 4 shows a comparison between DPIV data at Reynolds numbers 10^6 (left) and direct numerical simulations at Reynolds number 6,000 (right), demonstrating the qualitative similarity between the two cases, despite the large difference in Reynolds number. Figure 5 shows the intensity of the horizontal (streamwise) and vertical components of the velocity, normalized with respect to U^2, calculated from ensemble averaged LDV records obtained 4 mm under the plate surface at piston #5. The inflow velocity is U = 1.0 m/sec and the phase speed varies from c/U = 0.3 to 2.0. As shown, the local turbulence intensity is reduced for c/U up to 1.5, but increases for phase speeds beyond this value.

Red denotes points taken at the crest of motion, while blue the corresponding data in a trough, showing that turbulence reduction varies during the cycle.

Recent studies with a three-dimensional body, in the form of a water snake, undergoing traveling wave oscillations, shows non-uniform turbulence reduction along the body, but the clear trends observed with a two-dimensional plate could not be established (Michel *et al.*, 2001).

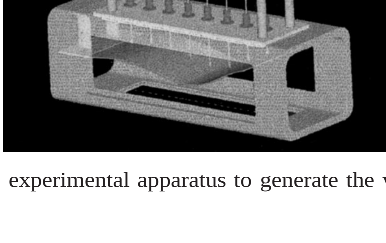

FIG. 3. The experimental apparatus to generate the wave motion.

ENERGY EXTRACTION FROM ONCOMING VORTICAL FLOWS

Anecdotal evidence of energy recovery by live fish in turbulent flow containing large scale eddies is substantiated by experimental work with live fish (Beal *et al.*, 2002); and with simpler experiments using the controlled motion of a flapping foil within the wake of a bluff body, such as a D-section cylinder. The foil is used to extract energy from the flow by properly timing its motion relative to the arrival of large eddies (Gopalkrishnan *et al.*, 1994; Beal *et al.*, 2001; Beal, 2002).

Gopalkrishnan *et al.* (1994) placed a two-dimensional foil in the wake of a cylinder within an oncoming stream to measure the forces and torque needed to

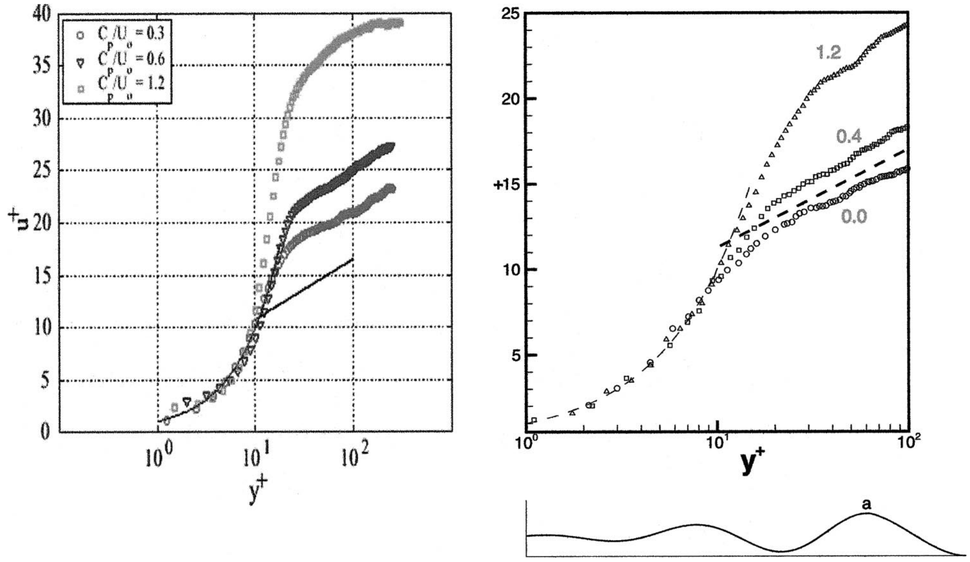

FIG. 4. Comparison between DPIV data at *Re* = 10^6 (left) and direct numerical simulations at *Re* = 6,000 (right).

oscillate the foil so as to produce thrust; and to observe the flow patterns around the oscillating foil. The foil would undergo a flapping motion, *i.e.*, harmonic, controlled heave (transverse) and pitch (angular) motions with adjustable amplitude and relative phase. They found that depending on the timing of the motion of the foil relative to the arrival of oncoming vortices, three distinct patterns could be observed:

- A destructive interference pattern, where vortices shed by the foil would first pair and then coalesce with opposite-sign vortices shed by the upstream cylinder to form a wake consisting of weak vortices aligned near the centerline of the wake. The efficiency of thrust production was found to be increased compared to other conditions.
- A constructive interference pattern, where vortices shed by the foil would coalesce with same-signed cylinder vortices forming strong vortices arranged in a Karman street or reverse Karman street, depending on the parametric conditions. Efficiency was found to be minimal under such conditions.
- An intermediate condition, where foil vortices would pair with opposite signed cylinder vortices forming ‘‘mushroom’’-like structures, expanding the wake width.

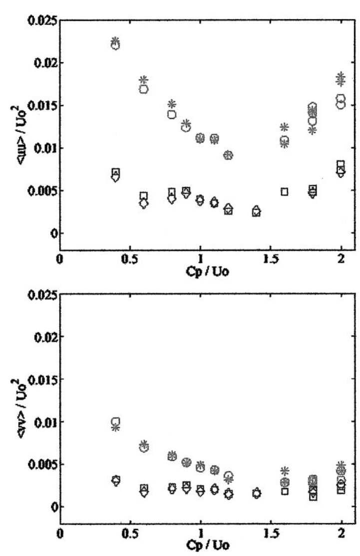

FIG. 5. The intensity of the horizontal (upper figure) and the vertical (lower figure) component of the velocity calculated from ensemble averaged LDV records obtained 4 mm under the mat boundary at piston #5.

Theoretical studies by Streitlien and Triantafyllou (1995, 1996) showed that energy extraction is possible when a foil operates in the wake of a bluff body, in an ‘‘intercepting’’ mode, where the foil would intercept with its leading edge oncoming vortices. Efficiency, defined as the ratio of the useful energy (thrust times free stream velocity) over expended energy, could exceed 100% under conditions of energy extraction. The flow patterns associated with the intercepting mode consist of opposite-signed vortices, one from the cylinder and the other from the foil, which are pushed close together, resulting in an effective mutual elimination (the inviscid code could not predict destructive vortex interference, since two inviscid vortices of the opposite sign do not coalesce). A different mode, named ‘‘slaloming mode,’’ is associated with a path that keeps away from the core of the oncoming vortices (slaloming around them): Energy was not recovered and the resulting wake consisted of vigorous vortices resulting from coalescence of same signed vortices, one form the cylinder and the other from the foil.

Figure 6 shows the thrust coefficient C_t and efficiency η of a flapping foil within the wake of a vortex-shedding cylinder. The cylinder has diameter D = 7.5

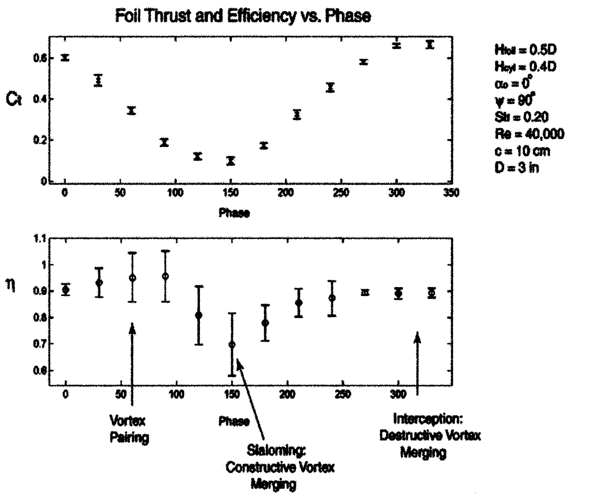

FIG. 6. The thrust coefficient C_t and efficiency η of a flapping foil within the wake of a vortex-shedding cylinder, plotted here as functions of the phase angle between the foil motion and the cylinder motion.

cm and is placed upstream of an oscillating foil; both the cylinder and the foil translate at constant velocity U in a towing tank. The cylinder oscillates transversely with amplitude 0.4D, while the foil moves transversely both in a linear and angular motion. The linear motion is equal to 0.5D, while the nominal angle of attack is ao = 0 degrees. The Reynolds number, based on the foil chord c = 10 cm, is Re = 40,000 (Beal 2002). The horizontal axis is the phase angle between the foil motion and the cylinder motion, which affects the relative phase between the arrival of the cylinder-generated vortices and the position of the foil. As shown, thrust and efficiency are affected significantly by the timing of vortex arrival. The relative timing between the arrival of cylinder-generated eddies and eddies shed by the trailing edge of the foil is crucial in determining the type of vortex interaction that will prevail. Visualization of the flow shows that the three principal patterns identified in Gopalkrishnan *et al.* (1994) can be associated with the efficiency peaks (destructive interference mode), efficiency troughs (constructive interference mode), and efficiency nodes (vortex pairing). Efficiency can even exceed 100% due to energy recovery by the foil (Beal *et al.*, 2001).

CONCLUSIONS

Experimental and numerical studies show that fish-like locomotion employs mechanisms of separation elimination, turbulence reduction and energy extraction from oncoming flow, to minimize the energy needed for locomotion.

A two-dimensional plate undergoing traveling wave motion captures the essence of the phenomena involved in turbulence reduction and separation elimination, showing that over a wide range of Reynolds numbers qualitatively similar mechanisms are at work, providing flow without separation and non-uniformly reducing turbulence when the phase speed is close to 1.2 times the free stream velocity.

Energy extraction is seen to be feasible both by flapping two-dimensional foils and by actively swimming live fish, or fish-like, three-dimensional bodies.

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