VISUALIZATION AND ANALYSIS OF BOUNDARY LAYER FLOW IN LIVE AND ROBOTIC FISH

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ABSTRACT

Near wall flow over both live and robotic fish was visualized using a pulsed laser sheet and a high-resolution digital video camera. Velocities of particles illuminated by the laser sheet were determined by particle tracking, PTV. Particles very close to the fish surface, $y < 1$ mm were tracked semi-automatically, while those further away were tracked automatically using a particle finding and matching algorithm. Standard cross-correlation DPIV (digital particle imaging velocimetry) was also used as a crosscheck. The outline of the fish surface was fit with an appropriate spine so that u and v velocity profiles could be constructed with respect to the curved fish surface. The technique allowed for the resolution of the viscous sublayer. The boundary layer flow over live and robotic fish was not always easily categorized as laminar or turbulent when compared to accepted flat plate profiles. Deviations from flat plate theory are not surprising, however, considering the waving motion of the fish surface. Resolution of the fish boundary layer is an essential part of examining possible drag reducing techniques involving the manipulation of near wall flow.

INTRODUCTION

The analysis of fish boundary layer flow, especially in the viscous sublayer, is essentially non-existent. This can be attributed to the difficulties of filming a free-swimming fish while using the extremely small field of view necessary to resolve the boundary layer. The construction of robotic fish (Barrett and Triantafyllou, 1995) allows investigators to surmount these difficulties, but it is still necessary to make measurements of the boundary layers of real fish. There may be locomotory modes and fluid phenomena occurring in live fish swimming which robotic fish fail to mimic.

In contrast, much is known about the large-scale flow around swimming fish and the nature of fish wakes (Anderson, 1996; Mueller, *et al.*, 1997). There is a considerable volume of material concerning the optimization of thrust and efficiency in propulsion by flapping foils (Triantafyllou, *et al.*, 1993). Furthermore, investigators have been looking to fish for hints on drag reducing techniques (Barrett, *et al.*, 1999) due to observation of remarkable swimming performance in fish and other marine organisms (Gray, 1936). Resolution of boundary layer flow is an important step in this process, both for nailing down the shear experienced by swimming fish and determining whether the fish are manipulating near wall flow to their advantage.

Boundary layer flow over oscillating and compliant surfaces has been the subject of much research (Kobashi and Hayakawa, 1981; Cary, *et al.*, 1979; Choi and Graham, 1998). Taneda and Tomonari (1974) suggested that boundary layer manipulation by the waving movement of the fish surface is a mechanism for significant drag reduction. They found that the stability of the flow over a waving plate depends on the ratio of wave speed to the free-stream velocity. For speeds greater than the oncoming flow, separation is prevented and turbulent boundary layer flow is re-laminarized over part of the plate. Whether these

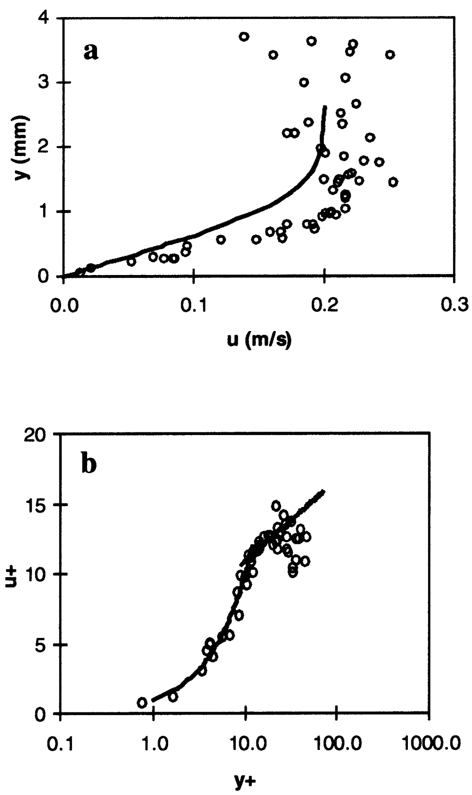

Figure 1. a. The *u* velocity profile over a live swimming scup, $U = 0.2$ m/s, compared to the laminar boundary layer profile for a flat plate according to Blasius. b. The *u* velocity profile in wall coordinates over a live swimming scup, $U = 0.2$ m/s, compared to the law of the wall profile.

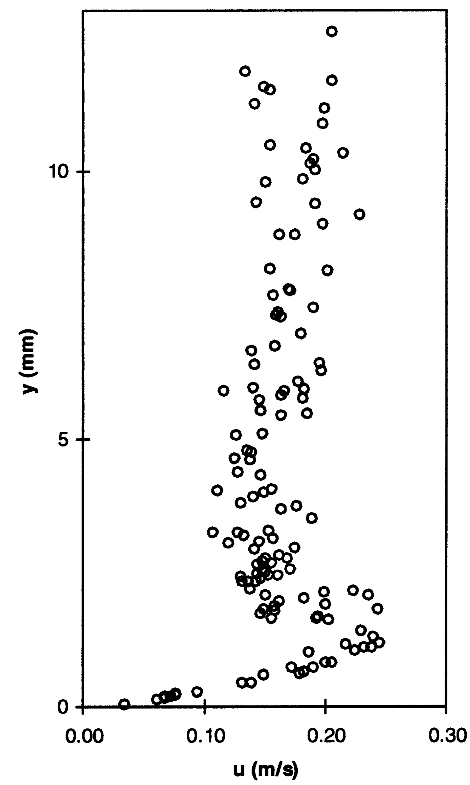

Figure 2. The *u* velocity profile at a different location, $U = 0.2$ m/s, showing a larger range of distance from the wall. Note the high-speed event close to the wall. This may be caused by tangential blowing due to the gill or pectoral fin.

phenomena are occurring in live swimming fish is as of yet unconfirmed.

MATERIALS AND METHODS

Scup, *Stenotomus chysops*, approximately 0.18-0.22 m in length were allowed to swim in an open channel tank of calm seawater. The water depth was 0.23 m and the channel width, 0.20 m. Scup swam at speeds ranging from 0.10-0.25 m/s, $Re \approx 10^4$-10^5. Water temperature ranged from 10-12 C.

Scup were video recorded from above as they swam through the 20 x 20 mm field of view of a Kodak Megaplus camera. The camera resolution is 1008 x 1022 pixels. The flow was visualized by illuminating 20-40 μm fluorescent particles with 4 nsec pulses from a New Wave Research Gemini PIV Nd:YAG Laser. Dual laser pulses 2 msec apart were triggered off every other vertical drive signal from the camera and made to straddle the break between every other pair of video frames using a Stanford Research Systems, Inc. digital delay/pulse generator DG535. The fish were simultaneously video recorded with a second camera from the side. The field of view of this second camera was set large enough to capture the entire side view of the fish as it swam through the experimental section of the channel. These recordings were used to determine fish forward velocity and the position of the laser sheet on the fish surface. Thus, the precise location of particular boundary layer profiles could be determined.

The MIT robotic tuna, 1.2 m in length, was towed at various speeds in swimming and non-swimming trials, $Re \approx 10^5$-10^6. The towtank depth was 1.5 m and the tank width, 2 m. The tank was filled with freshwater at 20 C.

The robotic fish was video recorded from above using a TI-Multicam CCD camera fixed to the towing carriage. Therefore the images obtained in a particular video sequence are taken at a fixed location along the fish. The camera was moved to a number of positions downstream of the position of maximum chord in the

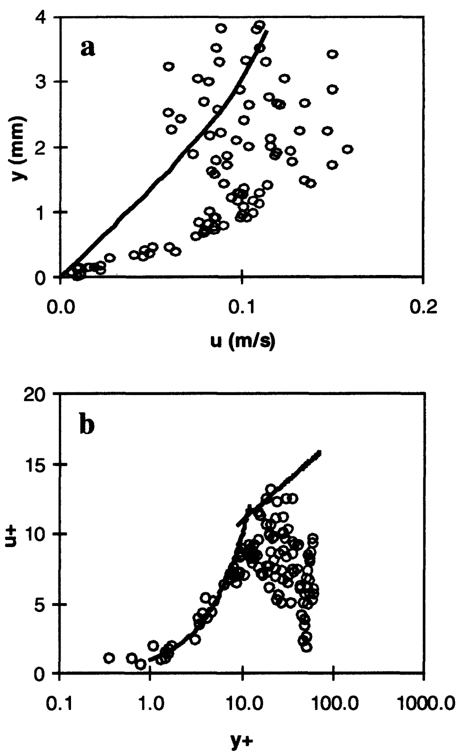

Figure 3. a. The *u* velocity profile over a live swimming scup, $U = 0.10$ m/s, compared to the laminar boundary layer profile over a flat plate according to Blasius. b. The *u* velocity profile in wall coordinates over a live swimming scup, $U = 0.10$ m/s, compared to the law of the wall profile.

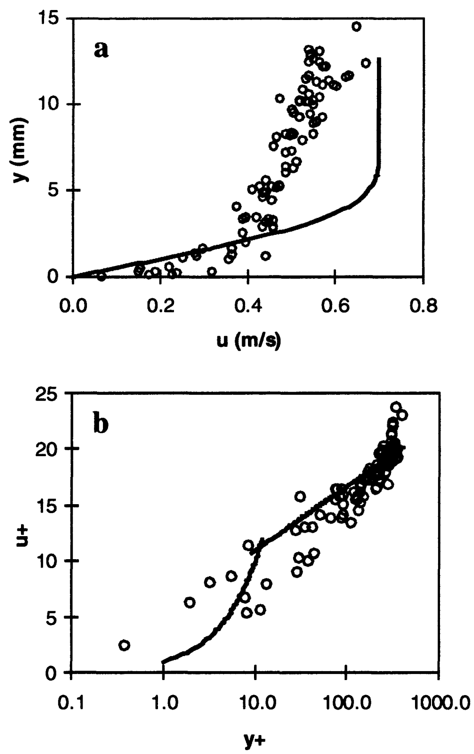

Figure 4. a. The *u* velocity profile over a swimming robotic tuna, $U = 0.7$ m/s, compared to the laminar boundary layer profile over a flat plate according to Blasius. b. The *u* velocity profile in wall coordinates over a swimming robotic tuna, $U = 0.7$ m/s, compared to the law of the wall profile.

fish horizontal cross-section. The camera has a resolution of 752 x 480 pixels. The field of view used was approximately 20 x 15 mm. The flow was visualized as in the live fish experiments. The system was arranged so that visualizations were made at the midline of the robotic tuna.

Particle velocities at distances greater than about 1 mm from the fish surface were determined using an automated PTV routine. For particles closer to the wall, a semi-automatic PTV routine was implemented. The outline of the fish surface was fit with an appropriate spline so that *u* and *v* velocity profiles could be constructed with respect to the fish surface. Particle positions were determined with sub-pixel resolution using an intensity centroiding algorithm developed by the first author.

RESULTS

Profiles of live swimming scup are shown in Figures 1-3. Figure 1a shows an example of a live fish boundary layer in comparison with the Blasius laminar profile that would be expected if the fish were treated as a flat plate. The flow at the outer edge of the boundary layer appears to be turbulent, while the flow throughout the majority of the boundary layer is suggestive of laminar flow. Figure 1b shows the same profile represented in wall coordinates compared to the law of the wall. Note that a number of points fall well within the viscous sublayer. An expanded view of the flow over the fish, extending further from the wall, reveals a complex structure with high shear regions and downstream flows far exceeding the forward speed of the fish (Fig. 2). This observation may be the result of a large eddy near the wall or tangential blowing in the boundary layer. For some time now, tangential blowing in boundary layer flow has been known to delay separation (Carriere and Eichelbrenner, 1961). It is possible that this blowing is caused by fluid ejected from the fish's gills and/or pectoral fins.

Boundary layer profiles did not always follow the pattern displayed in Figure 1. Figure 3 shows the *u* velocity profiles in comparison with Blasius and law of the wall. The fish boundary layer does not appear to follow either of the theoretical curves very well, suggesting that the fish cannot be treated simply as a flat plate. Shape, three-dimensionality, unsteady phenomena, and a complicated pressure distribution over the swimming fish (Dubois, *et al.*, 1974) are the likely sources of the departures from flat plate theory.

Figure 4 shows an example of boundary layer flow in the robotic fish compared to flat plate laminar and turbulent curves. Note that in the robotic fish we do not observe the blowing effect pointed out earlier in the scup boundary layer. This supports the possibility that this effect results from gill or fin action since the robotic tuna has neither gills nor pectoral fins.

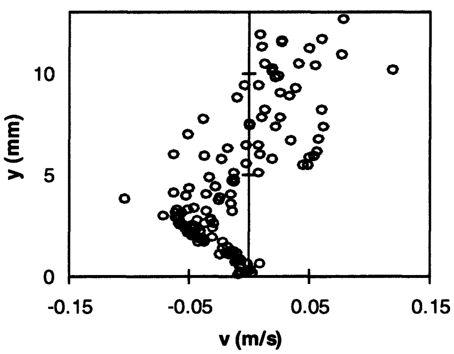

Figure 5. The v velocity profile over a live swimming scup, $U = 0.2$ m/s. Note the strong downwash near $y = 3$ mm. Motion of the fish surface was in the negative y-direction and decelerating.

Figure 5 shows the vertical velocity v plotted versus the distance from the wall. Note the region of high-speed fluid moving toward the fish surface. This was perhaps an unsteady effect related to the fact that the fish surface was moving in the negative y-direction and decelerating for this profile. The region of high-speed downwash may be fluid swept toward the fish by its undulatory motion. Fluid closer to the fish reduces in speed to that of the surface satisfying the well-known boundary condition.

DISCUSSION

These first glimpses of the boundary layer flow in live and robotic fish demonstrate a complexity which, as mentioned earlier, comes as no surprise. The 3-D nature of fish boundary layers, the unsteadiness due to the waving fish motion, the exterior pressure gradient and external body structures all serve to differentiate the fish from a flat plate and complicate the analysis of the boundary layer. Several investigators are studying the structure and evolution of near wall flow over moving surfaces, and considerable effort is being made to understand 3-D boundary layer flow, as well (Littell and Eaton, 1994; Webster and Eaton, 1995). At this time, we are continuing to compile large quantities of fish boundary layer data toward statistical treatment of boundary layer development, Reynolds stresses and turbulence intensities.

Taneda and Tomonari (1974) observed a reduction in turbulence, even re-laminarization, over a waving plate. With our boundary layer data, we intend to determine the validity of the assumption that this phenomenon is occurring in live fish. Such manipulation of flow stability, if it could be mimicked, would enhance the performance of submerged vehicles.

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