# PASSIVE ENERGY EXTRACTION IN THE WAKE OF BLUFF OBJECTS BY FISH

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## Abstract

The design issues associated with underwater vehicles operating in the surf zone or other high-energy environments are likely to have viable biomimetic solutions. Fish, combining awesome maneuverability with the flow-sensing lateral line, can reduce energy expenditure through interaction with environmental vorticity.

Rainbow trout (*Oncorhynchus mykiss*) swimming within a flow channel voluntarily positioned themselves 4D downstream from a 2" D-section cylinder, and synchronized with the cylinder wake in both frequency and phase. An electromyographic study of the axial muscle illustrated a significant reduction in activity while the trout was entraining behind the cylinder, as opposed to swimming within the free stream. A euthanized trout passively synchronized with the wake and accelerated forward towards the cylinder, through fluid-excited motion only, proving that trout benefit not only from drafting in the velocity deficit behind the cylinder, but also through interaction with the vortices in the wake.

## Introduction

Foils passively flapping in heave and pitch are capable of recovering energy from surface waves [Isshiki, 1984]. Similarly, the tail-flukes of whales have been shown to receive significant energy benefit through synchronicity with waves [Bose, 1990]. More generally, there is the potential for energy extraction from oscillating flows like those seen while moving through waves or eddies [Wu, 1974]. Although it is possible to extract energy from an incoming flow while incurring a drag on the energy extracting body - like a windmill - due to momentum conservation it is not possible to both extract energy and produce positive net thrust from a uniform and steady flow. However, with the addition of vorticity in the incoming flow, it is possible to extract net positive energy and produce net thrust completely passively.

Fish swimming in currents will reduce energy expenditure by refuging behind obstacles, as has been shown for salmonids positioning themselves within turbulent streams in order to maximize energy gain [Fausch, 1984]. Rainbow trout, *Oncorhynchus mykiss*, were placed in flow channels containing a vertically mounted D-section cylinder. The trout were found to voluntarily entrain behind the cylinder while synchronizing their tail-beats to the shedding frequency of the cylinder in what has been dubbed the Kármán gait [Liao, 2003]. Therefore, in addition to the obvious benefit of drafting behind the cylinder, it appears that the trout may be using the vortex wake for an additional advantage.

While it is clear that stream-dwelling fish, like rainbow trout studied here, would be expected to take advantage of the velocity deficit behind a cylinder, it is desired to investigate whether they also benefit from the vortices and oscillating lateral flows in the wake through the

creation of beneficial angles-of-attack across the trout's body and tail. If trout do not synchronize their tail-beat frequency to the shedding frequency of the wake then there is little chance that they utilize the vorticity in any special way, other than for the lower downstream velocities present in a cylinder wake. As such, initial experiments compared the kinematics of the trout swimming in the presence of cylinders to the kinematics of trout swimming in uniform flow, and showed that the trout voluntarily synchronize to the vortex wake in frequency. Subsequent tests using particle image velocimetry (PIV) quantitatively illustrated the interaction between the trout and the incoming Kármán wake, showing that trout synchronize with the wake in phase as well as frequency. Additionally, these tests demonstrate that the interaction with the wake varies along the body and tail.

Synchronization with the wake in frequency and phase does not necessarily mean that the fish are capable of taking advantage of those oscillating flows, as the fish could still be simply drafting in the velocity deficit with motion forced upon them by the strong lateral flows in the wake. In order to prove that the fish were entraining not just to take advantage of the wake's velocity deficit, but to gain further energy benefit from the unsteady flows and large-scale vorticity, a euthanized fish was shown to be able to passively hold station in the wake, against its own drag, using only the oscillating flows in the wake as energy input.

**Review of Literature**

Fishes commonly reside in high-energy environments such as rivers, streams, and coastal surf zones. It seems reasonable that fish may adopt behaviors to reduce energy expenditure. Indeed, salmon and trout have been found to entrain behind obstacles to optimize their net energy gain [Fausch, 1984], a function of local currents and the availability of food. The lateral line, an array of mechanosensory cells distributed along the body of fishes, enables fish to detect pressure discontinuities to select favorable hydrodynamic conditions in the flow [Sutterlin, 1975 and Coombs, 1998].

Fishes use their various fins to propel themselves through the water, [Videler, 1993], producing thrust through the formation of a staggered array of vortex rings, where the mean flow within the ring forms a jet away from the fin [Lauder, 1999].

Thunniform swimmers, such as tuna, create the majority of thrust with their caudal fins. As the body undulates with a wave passing from the head to tail, body-bound vortices are formed and pass down the body with the wave. The tail, rather than cutting through a uniform incoming flow, interacts with this body-bound vorticity [Anderson, 1996]. Additionally, the tail has been found to interact with vortices shed by the anal and dorsal fins in a beneficial way [Wolfgang, 1999 and Lauder, 2001].

In addition to interaction with self-induced vorticity, there are many cases in which fin-based swimmers can benefit from interacting with environmental vorticity. For instance, it has been hypothesized that schooling can serve a hydrodynamic benefit, with fish in the second rank, swimming between the thrust wakes created by those in the first rank, seeing a 40-50% reduction in incoming velocity [Fish, 1999]. Dolphins have been observed to surf in the bow wakes of ships [Fejer, 1960], and whales can see significant thrust benefits from swimming near surface waves, due to the oscillating flow over the tail fluke [Bose, 1990].

Webb (1998) studied how river chub and smallmouth bass align themselves with obstacles in a flow channel. Using cylinders mounted both vertically and horizontally, he found that the fish tended to hold position with their nose or head up against the obstacle, without showing any synchronization with the cylinder wake.

The following describes a set of experiments performed with rainbow trout (*Oncorhynchus mykiss*) within a flow channel containing a vertically-mounted cylinder. The experiments differ from previous work, other than the species of fish, in that the ratio in sizes between the cylinder and the fish are considerably larger than those studied by Webb.

Being a lotic (stream-dwelling) fish, it is expected that rainbow trout should be well-evolved to take advantage of the obstacles presented to it in an optimal way. The following studies how rainbow trout located themselves, voluntarily, at a relatively constant distance downstream from the cylinder, and synchronized with the cylinder wake for energy benefit.

# Kinematics of Trout Synchronizing with Cylinder Wakes

## Kinematics: Experimental Setup

We performed a set of experiments studying the strategies and motions of rainbow trout, a fish well adapted to turbulent stream environments, swimming in the presence of a vertically-mounted D-section cylinder in a water channel located in the Lauder Laboratory at Harvard University. The experimental setup and results are discussed in detail in [Liao, 2003], and are summarized here with a different emphasis.

Rainbow trout were purchased from a commercial hatchery and kept in a temperature-controlled recirculating tank. Eight fish were used in the experiments, averaging 10.3±0.3cm in length, and 10.0±0.5g in mass, where ranges given are standard error. One fish was run through all of the tests, and then euthanized with MS-222 and stored in a freezer for posterity, before testing began with the next fish.

The flow channel's test section was 80cm long with a 28x28cm cross-section. A variable-speed pump was used to set the flow velocity in the channel, and the pump speeds were calibrated to flow speed using PIV. A baffle of flow-straighteners was placed at the upstream end of the test section in order to reduce the turbulence of the incoming flow.

A high-speed digital video camera (the RedLake Motionscope PCI-500) was set up to record the silhouette of the fish within the flow channel at 250 frames per second, with a backlit ventral view, as seen in Figure 1. Throughout an experiment, fish were found to maintain a fairly constant position within the cylinder wakes.

The cylinders were clamped into place, with the lower end of the cylinder abutting the bottom of the flow channel. PVC round cylinders were machined to form a D-shaped cross-section, which was found by Anderson to produce a robust 2-S wake despite the presence of other objects in the flow nearby [Anderson, 1996].
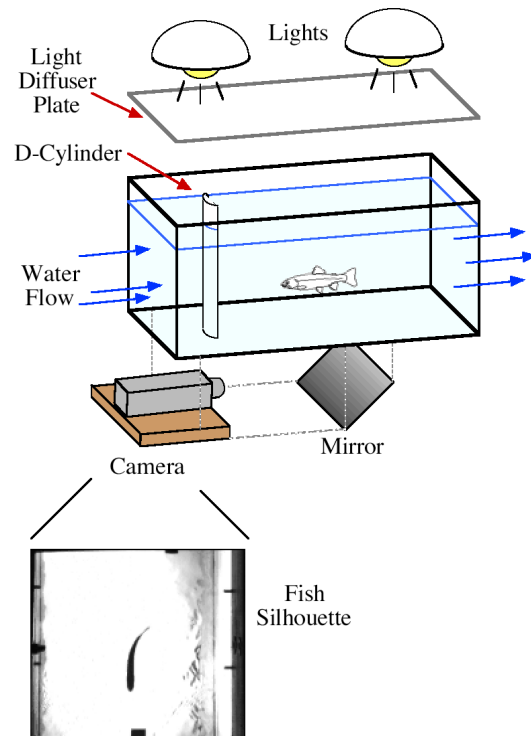


Fig. 1. The silhouette of the swimming trout was recorded with a high-speed video camera

The video was passed through a digitizing program, which returns the outlines and mid-lines of the fish at each time step, with a discrete number of body-points along the mid-line (30, in this case). This information was then analyzed to give the tail-beat frequency, amplitude, and wavelength, as follows. The analysis software followed the lateral position of each body-point with time. The times of maxima and minima in the lateral motion were recorded for each body-point. The amplitude at each body-point was then calculated using the average of the absolute value of those extreme positions around the mean, while the frequency was calculated by averaging the measured period between extrema for each body point. Similarly, the phase-speed of the body wave was calculated by following the motion of the extrema down the body, as shown in Figures 2 and 3, and the wavelength was calculated by simply multiplying the average phase-speed by the average period, as described in [Videler, 1993]. Since amplitudes of lateral motion were very small over the front half of the body for free-stream swimming, only extrema from the back half of the body were used for these calculations.
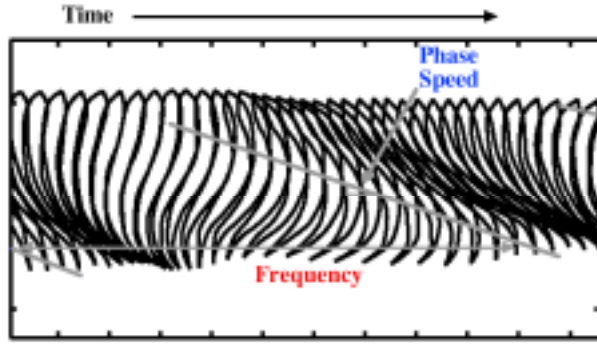
Fig. 2. The body waves were followed in order to measure phase speed and frequency
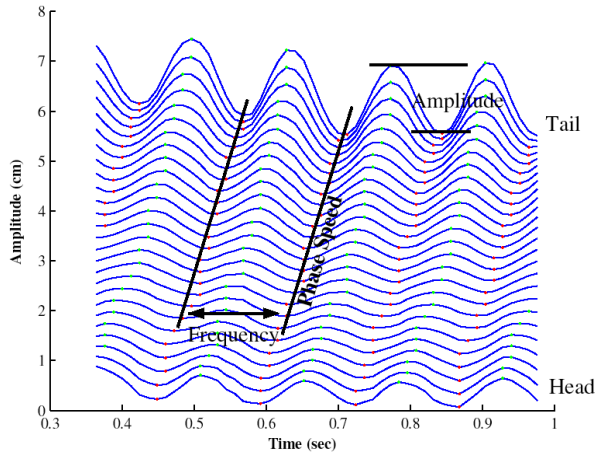


Fig. 3. The extrema of the body waves, shown from the head (at bottom) to the tail (at top), were used to measure frequency, phase-speed, amplitude, and wavelength. The curves are artificially separated on the y-axis for clarity.

The frequency and wavelength of the trout tail-beats were then compared to what was expected for the cylinder wake. However, the constriction effects from the cylinders in the flow channel were non-negligible, at 9% and 18% for the 1" and 2" cylinders, respectively. Hence, the expected shedding frequency was adjusted using

$$U_c = U \cdot \left( \frac{W}{W - D} \right)$$
$$St_c = \frac{f_c \cdot D}{U_c}$$

where $W$ is the width of the flow channel, $D$ is the cylinder diameter, $U_c$ is the constricted velocity, $St_c$ is the cylinder Strouhal number (0.2 for this Reynolds number range [Blevins, 1993]), and $f_c$ is the shedding frequency.

The wake wavelength was then estimated as $\lambda_w = U/f_c$ because although the cylinder shedding would be determined by the constricted flow, the vortices would then be carried downstream by the unconstricted flow. Using PIV, these estimates were found to be reasonable.

As the control case, fish swam within the flow channel at 4.5 $L_f$/sec without a cylinder present. Tests were then performed at 4.5 $L_f$/sec with 2.5 cm and 5cm cylinders, corresponding to Reynolds numbers (based on diameter) of approximately 12,500 and 25,000, respectively. Additionally, tests were performed using the 1" cylinder at 2.5 $L_f$/sec, giving the same wake wavelength as the 1" case at higher speed, but also the same frequency as the 2" cylinder at higher speed, after taking into account the constriction effects. This way, it would be possible to see if the fish preferentially matched frequency and/or wavelength to that of the wake.

Experiments were performed with 8 different trout, and 4 tail-beats from each treatment were analyzed for each fish. Every 3 frames of the video was digitized, giving a sample frequency of 83.3 Hz.

The fish were allowed to position themselves voluntarily within the test section of the flow channel. They were given more than 10 minutes to acclimate themselves to the their new surroundings and recover from the stress of being moved from the holding tank before the recirculating pump was turned on. Fish discovered the cylinder wake within several minutes of starting an experiment.

**Kinematics: Results and Discussion**

These results are also presented in [Liao, 2003], and are shown here with a different emphasis: the 2" cylinder case compared to swimming in a uniform stream. All ranges given are in standard error.

The trout adapted to the presence of the cylinder quickly. Once the flow was turned up to full speed trout quickly entrained behind the cylinder, usually near the downstream baffles, and then slowly moved upstream until they held position at a spot approximately 4.0±0.1D downstream from the cylinder. Once they found the chosen position, they would rarely leave it, only then in the pursuit of a particle of food, and would always return. This implies, although it does not prove, that the fish are positioning themselves in a hydrodynamic 'sweet spot' where conditions are optimal. In addition, some fish also rested in the bow-wake of the cylinder, as discussed in [Liao, 2003] further.

Once entrained behind the cylinder, the fish exhibited large-amplitude whole-body lateral oscillations of 0.32±0.01D (peak-to-peak), with a frequency within 1% of the cylinder shedding frequency. These oscillations were interspersed with small corrective

motions with the tail and pectoral fins. Clearly, the fish were doing something different from the free-stream case, as illustrated in Figure 4.
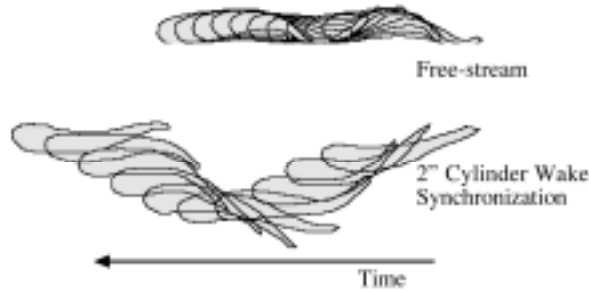


Fig. 4. Outlines of fish within the free-stream (top) and behind the cylinder (bottom). Steps forward are with time, both for clarity of the diagram and to illustrate the difference in frequency between the two cases.

Table 1 shows the difference in amplitudes between entraining and free-stream swimming. Not only is the lateral amplitude for the front half of the body very different between the two cases, but the tail-beat amplitude increases by a factor of 3 over the free-stream case. The frequency not only matches the shedding frequency, but also differs from that of the free-stream by a factor of 3. Although the mean flow speed seen by the fish within the wake is considerably less than that in the free-stream, the frequency of tail-beat changes linearly with velocity [Webb, 1984], which still would not explain a factor of 3 difference between the cases.

|  | Behind Cylinder | Cylinder Wake | In Free-stream |
|---|---|---|---|
| Head Amplitude ($L_f$) | $0.160 \pm 0.008$ | N/A | $0.020 \pm 0.001$ |
| C.O.M. Amplitude ($L_f$) | $0.153 \pm 0.007$ | N/A | $0.018 \pm 0.001$ |
| Mid-body Amplitude ($L_f$) | $0.165 \pm 0.006$ | N/A | $0.024 \pm 0.001$ |
| Tail Amplitude ($L_f$) | $0.322 \pm 0.009$ | N/A | $0.107 \pm 0.003$ |
| Frequency ($Hz$) | $2.18 \pm 0.05$ | $2.22 \pm 0.01$ | $6.62 \pm 0.11$ |
| Wavelength ($L_f$) | $4.05 \pm 0.22$ | $2.03 \pm 0.01$ | $1.15 \pm 0.02$ |

Table 1. A comparison between free-swimming and entrained trout, also showing the synchronization between the trout and the expected frequency and wavelength of the wake. The amplitudes of the body points are relative to the mid-line.

The wavelength of the entraining trout was 1.99 times that of the expected values for the wake, and 3.5 times that of the free-stream case. So although the trout apparently synchronizes in frequency, it does not do so in wavelength. This implies that the trout is interacting with the wake differently with its head than with its tail.

## Flow Visualization of Wake Interaction

In order to quantify the interaction strategy of the trout within the wake, we used Digital Particle Image Velocimetry (DPIV) to illustrate the flow around the fish. This would give an accurate and complete assessment of the interaction between the trout and its environment, as well as to proof the estimated wake characteristics used above. In addition, if a trout were using the incoming vorticity, as well as drafting within the velocity deficit, it is necessary that it would be synchronizing not just in frequency but in phase as well.

### Flow Visualization: Setup

In order to ensure a strong and regular wake, an apparatus was used to sway the 2" diameter D-section cylinder laterally in the flow channel. A Pitmann GM9236S013 5.9:1 geared servo-motor was attached to a Scotch-yoke apparatus, as in [Gopalkrishnan, 1994]. The 500 cpr encoder was read using a Simpson S664 digital counter, enabling an open-loop control of the sway frequency, which was recorded for each test, although the actual shedding value would be later calculated using PIV. For all tests, the cylinder was set to heave at 0.33D peak-to-peak amplitude and the frequency was set just above the cylinder's natural shedding frequency, so that the wake was seen to be regular and strong.

The flow channel was seeded with 12μm silver-coated glass spheres. An 8W argon-ion Coherent laser was used to create a thin horizontal light sheet 15cm wide across the flow tank, as seen in Figure 5. The light sheet was set up at the approximate distance downstream from the cylinder that the fish were seen to position themselves in the previous experiments, 9cm above the bottom of the channel.

We desired to record both the kinematics of the fish and the flow characteristics around it, simultaneously. Optimally, the flow view would be in the same plane as the centerline of the fish, in the dorsal-to-ventral sense. However, not only were the trout averse to swimming in the light sheet, with a powerful laser in the eye, but having the fish within the particle view makes the PIV considerably more difficult, with shadows from the fish blocking much of the flow, as well as the need to mask the trout from the PIV analysis software. Since the fish appeared to prefer to swim just beneath the light sheet, we decided to film the flow using a dorsal camera, and, simultaneously, film the fish silhouette (against the light sheet) using a ventral camera, as shown in Figure 5. This gave a clean, unbroken view of the flow ---

which was then analyzed for the entire field around the fish --- as well as a clear view of the fish outlines.
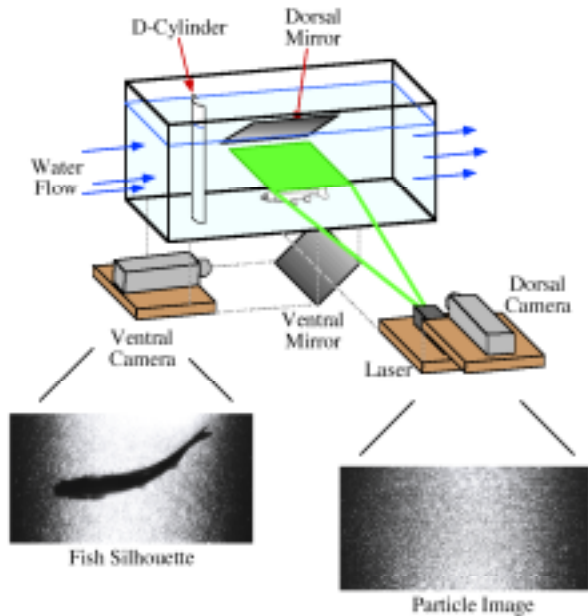


Fig. 5. The dorsal camera shot an unadulterated view of the particle field, for PIV, while a synchronized ventral camera recorded a silhouette of the fish.

Whatever information was lost due to illuminating a plane just above, rather than through, the fish was more than compensated for by the fact that the data taken was considerably cleaner, and consists of the full plane. For instance, the trout used were nearly the length of the light sheet and when they were within the sheet, they would block more than half of the view of the flow. Indeed, when at the laser-side extreme of their lateral motion, the fish blocked the view of most of the particles, which would make analysis difficult and more prone to error.

In a sense, the plane measured is that of the unadulterated flow seen by the fish, without any effect of the fish upon it. The vorticity created by the fish is expected to be considerably smaller in strength and size from the wake vorticity anyway. In fact, any local effect of the fish on the incoming wake is likely completely washed out a few diameters downstream, due to the size of the large, two-dimensional columnar vortices relative to the span of the fish tail.

We desired to overlay the outlines of the fish, digitized using the video from the ventral camera, upon the vorticity flood-plots obtained from the particle data on the dorsal video. In order to do this, the cameras had to be correlated so that a point on one could be properly placed on the video from the other. A wire probe with

4 discrete points in one plane was placed within the light sheet, and video from both cameras were recorded. The 4 points could then be translated from one camera to the other, requiring scale, rotation, translation, and mirroring the image so that the 4 points matched up optimally in a least-squares sense. This calibration was recorded so that it could be used to overlay any object in the ventral view onto the field from the dorsal camera.

The particle image from the dorsal camera was analyzed using Insight 3.0 from TSI Inc., which ran a cross-correlation of consecutive frames (at 4ms apart) in a 17x26 matrix of 442 vectors. The velocity vectors were smoothed first by a standard deviation filter, which removed vectors over 1.5 deviations from the mean, second by a mean filter, with a tolerance of 2 and a 5x5 neighborhood, and finally by running a smoothing filter thrice, with a 3x3 neighborhood and a Gaussian radius of 1.1, to give a clear view of the large vortex structures in the wake. Once the ventral view of the trout was digitized to give the mid-lines and outlines at each point in time, the smoothed velocity vectors were read into a MATLAB script, which overlaid the outlines onto a vorticity map produced using the velocity vectors from PIV. This could then be used to compare the positioning of the trout with the instantaneous and unadulterated flow around it.

All of the analyses performed in the kinematics experiments were performed again, including the comparison of the tail-beat frequency and body-wave to those of the flow, but using actual values of the flow frequency and wavelength given by the PIV. In addition, we desired to find whether or not the fish were synchronizing with the wake in phase as well as frequency. In order to do this, the phase of the wake needed to be defined. An example of a desirable signal from the wake, as a means for finding its phase, would be periodic with the wake period, reach a maximum when a positive vortex passes the position in question, and reach a minimum when a negative vortex passes. A signal like this, dubbed the wake function $W(x,t)$, was obtained by taking the sum of vorticity passing a given line downstream from the cylinder, as shown in Figure 6. The phase of this signal was then compared to the phase of lateral position, with time, for the fish at the same downstream location. Since the fish is not guaranteed to remain in place, although it does not move much in the upstream-downstream direction, the wake function was calculated for the x-position of each body point with time, and then compared with the y-position of those same body points.
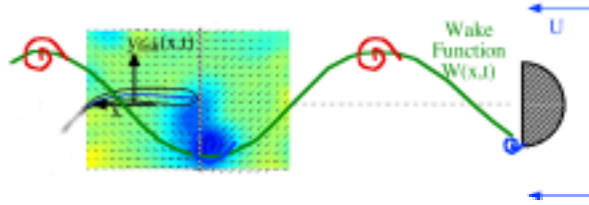
Fig. 6. The wake function W(x,t) is the sum of vorticity lateral to a given body point on the fish (in this case, the nose). This defines a phase for the oscillating wake.

For a cylinder drag wake, if a trout's lateral position was in-phase with the wake function, its lateral motion would carry it into the vortices as they pass by. Similarly, if it was 180° out-of-phase with the wake function, its lateral motion would carry it through the wake in such a way that it would avoid contact with the vortex centers. In essence, this is a comparison of the trout's side-to-side position with the relative upstream-downstream position of the vortex wake.

Additionally, we wished to know whether or not the trout's lateral motion moves with or in opposition to the instantaneous lateral flow in the wake. Hence, for each body point, the lateral velocity was compared, in both amplitude and phase, with the instantaneous lateral velocity of the flow local to that body point, as shown in Figure 7. Although the phase of the lateral velocities in the flow is intrinsically related to the phase of the wake function described above, by 90° (as it is related to the integral of the wake function), we felt that analysis would be easiest to compare similar quantities with each other, position with position, and velocity with velocity, in a way that in-phase and anti-phase are meaningful.
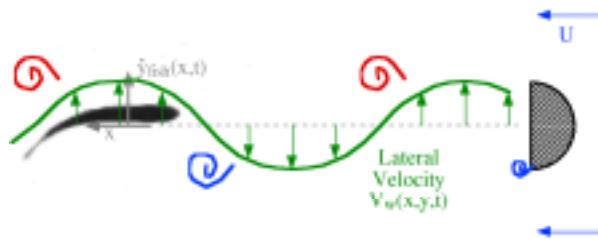


Fig. 7. The lateral velocities of each body point were compared to the local lateral velocities in the flow.

Experiments were performed with 7 different trout, and 4 tail-beats were analyzed from each fish. A new batch of fish was purchased for these experiments, averaging 12.9±0.31cm in length, and 19.5±0.6g in mass. Every 10 frames of the video was analyzed, giving a sample frequency of 25Hz.

## Flow Visualization: Results and Discussion

Using PIV to measure the flow, while simultaneously filming the trout swimming just beneath the laser light sheet, confirmed the frequency and wavelength synchronization results from the kinematics experiments. The frequency of the fish motion normalized by the frequency measured in the wake was 1.00±0.01, which clearly shows that the fish tail-beat frequency was locked-in to the wake. The wavelength of the trout body-wave, however, was 1.94±0.05 times the wake wavelength, implying that the trout were not interacting with the individual vortices in the same way for the head as for the tail.

The trout avoided areas of strong vorticity in the wake of the cylinder, as seen in Figure 8. It should also be noted that the direction of the trout's lateral motion appeared to generally move with the lateral component of the flow velocity arrows.
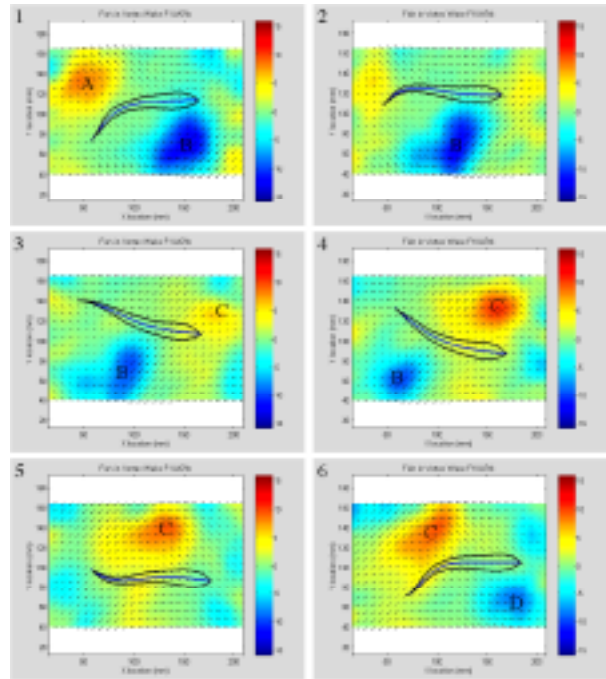


Fig. 8. Select frames from one cycle of fish motion within the wake. The flood color represents vorticity, in 1/seconds

A possible strategy for a trout in a cylinder wake would be to always locate itself laterally in the wake so that its location always corresponds to the location with the instantaneous minimum downstream flow. Plotting the fish outlines on a flood plot of U-velocity show that the trout generally remain near regions of low downstream flow, but not in such a way as to suggest that this is the

overall strategy, as the body and tail can each be seen to leave low-flow areas during parts of a single tail-beat period in Figure 9.
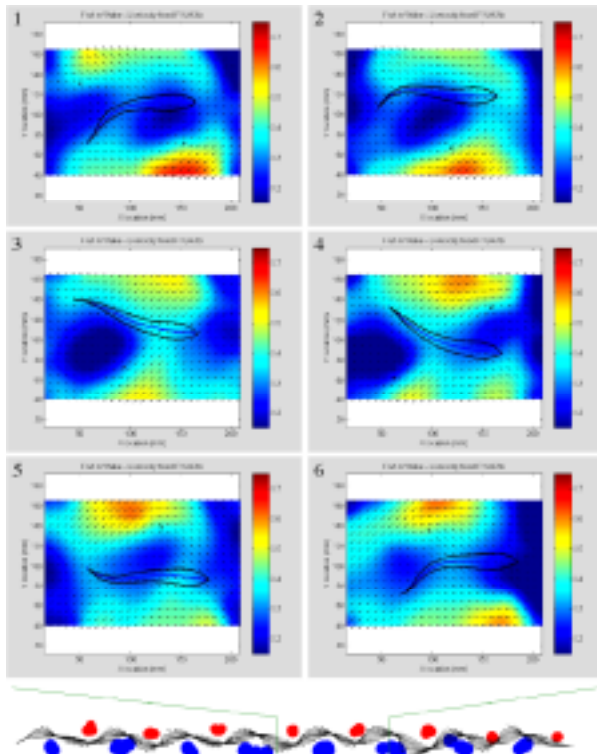


Fig. 9. Select frames from one cycle of fish motion within the wake, where the color represents instantaneous velocity in the downstream direction, in m/sec.

The phase of the wake was represented through a 'wake function', defined as the lateral sum of the vorticity passing by a given body-point. This function results in a sinusoidal-looking signal, with the signal high when a positive vortex passes the point, and low when a negative vortex passes the point.

The phase between the body lateral position and the wake function, measured at each body-point, is shown in Figure 10. The low scatter (standard error) implies that the phasing relation is fairly strong, and shows that the fish are generally out-of-phase with the wake function, although the head follows a different trajectory through the wake than the tail (100° for the head vs. 160° for the center-of-mass vs. 240° for the tail).
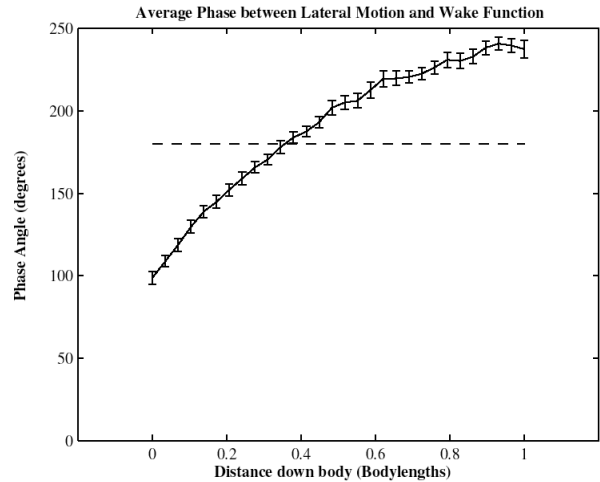


Fig. 10. The phase difference between the lateral motion of the fish body to the wake function, from head to tail. The dashed line demarks positions 180° out-of-phase with the wake function

The strong and consistent phase relation between lateral motion and the wake function shows that the fish are indeed synchronizing to the wake in both frequency and phase.

The trout are not opposing the oscillating lateral flow on a large order, as the body points each move laterally back and forth at nearly the same peak velocity as that of the local flow, as shown in Figure 11. The exception for this would be the tail, which moves considerably faster than the flow across it. Additionally, the lateral velocity of the trout is very similar in phase to the wake lateral velocity, as seen in Figure 12, with deviation from that at the head and tail. This would imply that the oscillating lateral motion seen in the fish is the result of the fish merely allowing itself to be buffeted back and forth by the flow, at the same time that the fish is producing thrust in order to maintain its position behind the cylinder.

As the fish voluntarily chose the location behind the cylinder, it is likely that there is an advantage to doing so. Indeed, fish entraining behind the cylinder never reached the point of exhaustion during the experiments, as was sometimes seen during free-stream swimming. Some benefit is to be expected as the fish take advantage of the lower mean downstream flow speed in the cylinder wake. However, some contrast needs to be made between a fish merely drafting in the velocity defect, and a fish utilizing the vortex street for energy benefit as well.
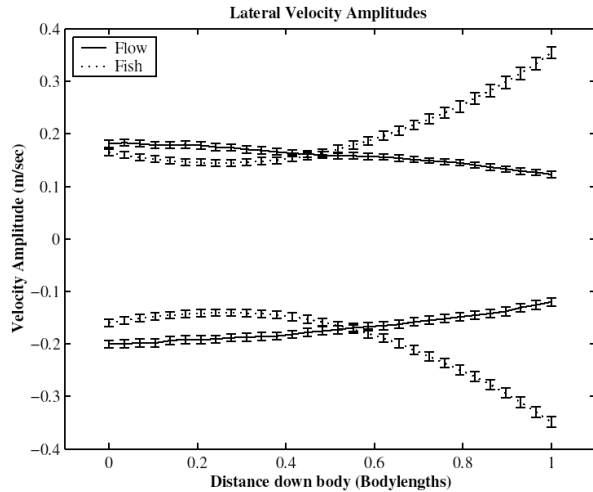
Fig. 11. Amplitude of the lateral velocity for the trout body points and the instantaneous lateral component of the flow local to those body points, from head to tail.
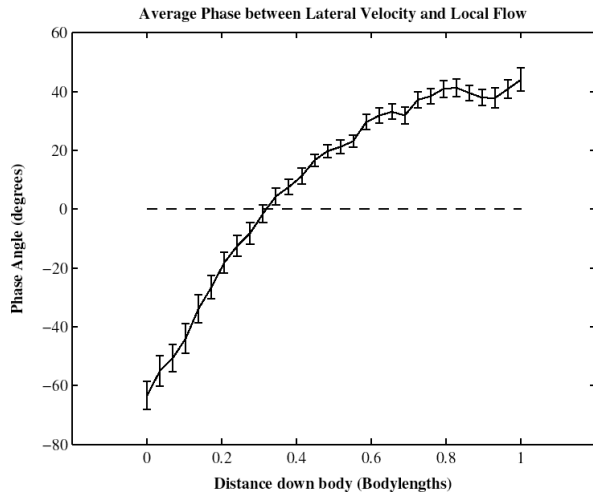


Fig. 12. The phase between the trout lateral velocity and the oscillating lateral component of the flow local to the trout's body points, from head to tail.

## Flow Visualization: Summary

As all the fish synchronized with the wake in both frequency and phase, it is clear that the motion is not just a function of the fish swimming normally within a reduced flow. However, it is less easy to distinguish whether or not the trout were synchronizing to a particular phase for thrust or energy benefit, or whether they located themselves in the wake to take advantage of the velocity deficit, and were compelled to follow the strong lateral flows rather than to fight them.

## Muscle Activity During Synchronization

We used electromyography to measure axial muscle activity for trout holding station in a vortex street. Our results show that trout swimming in the free stream flow displayed a stereotypical pattern of sequential red muscle activation down the body (Fig. 13a). In contrast, trout behind the cylinder (Fig. 13b) exhibited a fundamentally different, and substantially decreased, muscle activity pattern. Although there was some spatial and temporal variability in axial muscle activity during the Kármán gait, two general patterns emerged. More than half of the time, only the anterior-most red muscles were active, while at other times, when the pectoral fins were active, there was no appreciable red muscle activity at all. Thus, although the entire body of a trout behind the cylinder participates in a mechanical wave, only the anterior-most axial muscles, if any, are regularly active. Activation of pectoral fins and anterior axial muscles likely provides a redundant mechanism for fine-scale adjustment of head angle to facilitate vortex energy capture. In addition, isolated pattern of anterior red muscle differs from the pattern of posterior red muscle activation seen in trout swimming steady at a uniform flow that approximates the velocity found behind a cylinder, conclusively demonstrating that trout are not just drafting behind the cylinder. The little amount of axial muscle activity during the Kármán gait, despite large amplitude oscillations of the body, reveals that whole body movements are dictated by vortices rather than muscle activity.
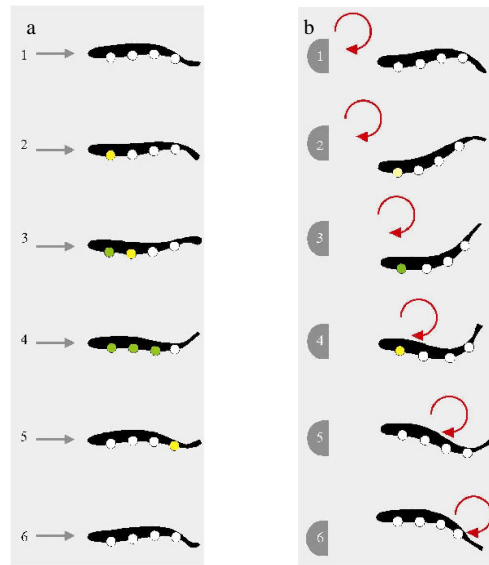


Fig. 13. Schematic diagram of a time series illustrating muscle activity for trout swimming in the free stream flow and in a vortex street. Four electrodes were inserted into the superficial red muscle along the left side of the fish (white circles), where yellow fill indicates weak muscle activity and green fill indicates strong muscle activity. Trout swimming in the free stream display a sequential wave of muscle activity (a), while trout holding station in a vortex street often only exhibit muscle activity near the head (b).

## Dead Fish within Wakes

The PIV experiments showed that trout synchronized their motions to the incoming vortex wake in both frequency and phase, but could not prove that the trout were gleaning additional energy benefit from this synchronization, beyond that of drafting alone. The trout generally moved back-and-forth with the lateral flow, as if they were flags in the breeze. Since electromyograms exhibited little or no muscle activity in the rear two-thirds of the body when the trout were swimming within the wake, the motion of the fish within the wake appeared to be passive.

Wu (1972) found that a foil placed in an oscillating flow was capable of producing thrust and extracting energy in a fluid-excited motion, where no power input from the foil was required. This was supported experimentally by Isshiki (1984), and applied to whales near the surface by Bose (1990), who found that they could extract more than 25% of their propulsive power through the oscillating wake. These all imply that it may be possible for trout to passively produce thrust through fluid-induced motion in a Kármán wake.

In order to test the hypothesis that the fish were swimming passively in the wake, a euthanized trout was tied to a string attached to the cylinder (all tests were performed prior to rigor mortis). The string, when taut, positioned the dead trout at the downstream location that live fish were seen to choose, approximately 20cm behind the cylinder. The oscillating flow of the wake was found to excite the trout body in lateral oscillations, which could be expected, but also to entice the trout to move forwards towards the cylinder, against its own drag.

### Passive Swimming: Methods

A fish was euthanized using MS-222, a general anesthetic which shuts down nerve cells, both in the brain and the body [Alpharma, 2001]. In small doses, this effect is temporary, and it is used to anesthetize fish for surgeries. In large doses, however, its effects are fatal and permanent, and a bath of highly concentrated MS-222 for one hour is the standard method to euthanize the fish. The dead fish (17.8 cm) was an individual used previously in the EMG experiments.

A line was hooked to the fish and tied to the cylinder, which was held stationary as in the kinematics experiments. The line was not significantly compliant and, when taut, held the fish 20cm downstream of the trailing edge of the 2" D-cylinder in the range in which live fish were seen to hold station. The flow speed was set to $3.20L_f$/sec, similar to the relative flow speed used in previous tests. The ventral view was videotaped as in the kinematics tests.

The suction region behind the cylinder was conservatively estimated at 2.0D [Gerrard, 1966], and the mean and minimum downstream flows at the location of the fish were measured with PIV, which showed that the fish was not in the suction region, and that at no time during the cycle was there even instantaneous upstream flow near the fish, as seen in Figure 14.
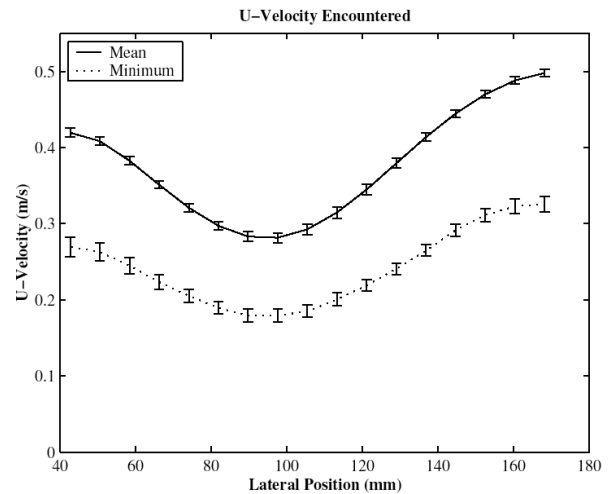


Fig. 14. The mean and minimum downstream velocities encountered by the fish in its default location 20cm back from the cylinder. The flow at the two sides does not match perfectly due to the dorsal mirror in the flow during the flow visualization tests.

Six tail-beats during forward motion were digitized, where the line was no longer taut but the fish had not yet entered the suction region. Every 4 frames of the video was analyzed, giving a sample frequency of 62.5Hz.

### Passive Swimming: Results and Discussion

When in the Kármán wake, the dead fish regularly synchronized with the wake and moved upstream until it entered the suction region behind the cylinder and ran into the cylinder itself, before tumbling back downstream, as seen in Figure 15. Since PIV showed that the mean downstream flow at the location of the fish, as well as the minimum downstream flow at that location, was not upstream at any time, this motion implies that the dead fish was passively moving forward against its own drag due to the oscillating vortex wake.

t = 3.75 s

t = 3.83 s
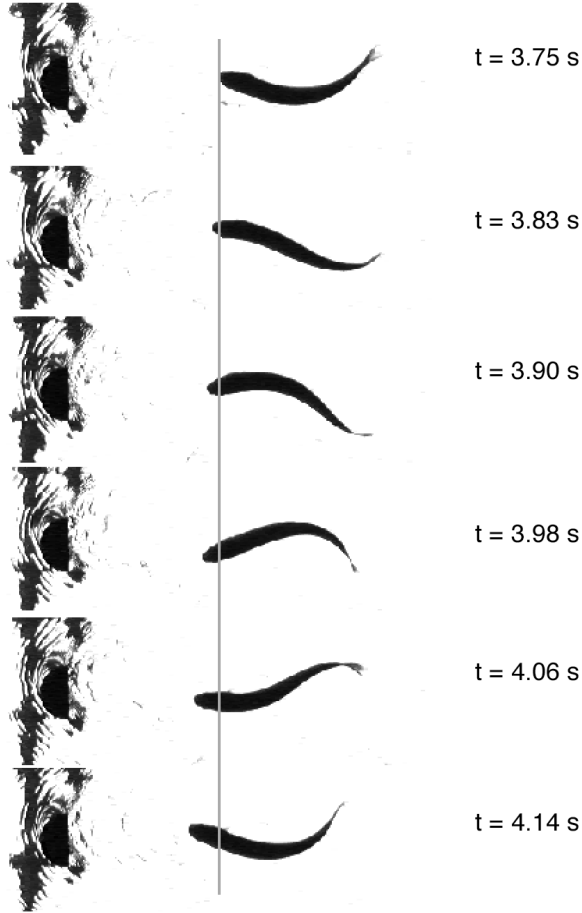
t = 3.90 s

t = 3.98 s

t = 4.06 s

t = 4.14 s

Fig. 15. The oscillating fluid induces lateral motion on the dead trout's body as well as thrust on the tail, accelerating this dead trout forward against its own drag. The times given correspond to times in Figure 16. The vertical line represents a fixed location behind the cylinder.

In order to test and make certain that it was not 'snap' of the line or some other mechanism pulling the fish forward, the video was digitized and analyzed. Figure 16 shows a typical approach. Initially, the fish is being buffeted back and forth by the flow, and its frequency does not even match that of the wake. At around 3.7 seconds, in this run, the fish begins to move forward. At this point the line cannot be taut. However, the fish continues accelerating forward, despite the fact that there are no forces on it other than those from the fluid itself. Once the suction region is reached, the oscillatory motion begins to fall apart as the fish gets pulled into the cylinder. The x-velocity oscillations seen in the figure are perturbations from the lateral motion, at a frequency twice that of the lateral oscillations, as the body points move in a figure-8.
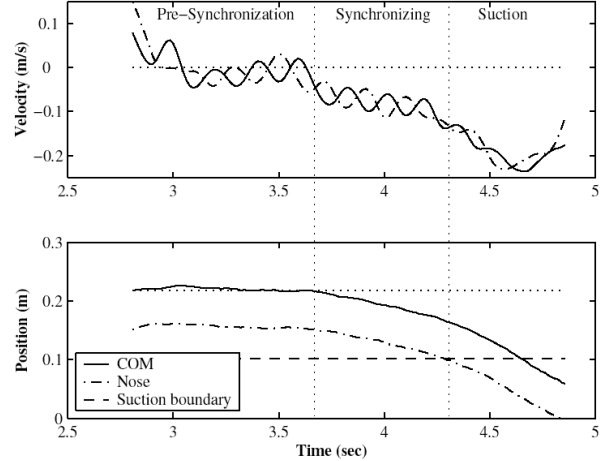


Fig. 16. Downstream velocity and position of the center-of-mass and nose of the dead trout. The cylinder back is located at position zero, and a negative velocity is upstream.

Table 2 compares the kinematics of the dead fish with that of the trout used in the flow visualization experiments previously described. The amplitude of the dead fish motion is 58% to 75% of the live fish (center-of-mass and tail, respectively), although it is uncertain as to whether that is a function of life or death, or just a function of the size and mass difference. In both cases, the frequencies were closely matched to that of the wake. However, the dead trout's wavelength was considerably shorter than that of the live trout, only 1.25 times that of the wake, rather than 1.94 times.

In addition, the average head angle amplitude for the dead fish was 3.4 times that of the live fish. Given that muscle activity has been shown only near the head in live fish while synchronizing with the cylinder wake, it appears that they are decreasing their head angle. Apart from hydrodynamic considerations, lower head angles may also serve to stabilize their visual field.

|  | Live Trout | Dead Trout |
|---|---|---|
| Head Amplitude ($D$) | $0.338 \pm 0.015$ | $0.239 \pm 0.017$ |
| C.O.M. Amplitude ($D$) | $0.317 \pm 0.017$ | $0.184 \pm 0.015$ |
| Mid-body Amplitude ($D$) | $0.340 \pm 0.017$ | $0.194 \pm 0.018$ |
| Tail Amplitude ($D$) | $0.648 \pm 0.025$ | $0.484 \pm 0.066$ |
| $\omega_f/\omega_w$ | $1.00 \pm 0.01$ | $1.01 \pm 0.01$ |
| $\lambda_f/\lambda_w$ | $1.94 \pm 0.05$ | $1.25 \pm 0.06$ |
| Head Angle Amplitude | $5.4° \pm 0.5°$ | $18.5° \pm 1.3°$ |

Table 2. Comparisons between live fish from the PIV tests and the dead fish, where all amplitudes are relative to the mid-line.

The only mechanism available to the dead fish to allow it to accelerate upstream, against its own drag, is if the wake works to move the fish in such a manner as to set up a beneficial flow across the body and tail. Although seemingly remarkable, there are other comparable and well-known situations that are similar in a basic level.

A sailboat can easily 'tack' upwind by taking advantage of the difference in flow velocities across its sail and hull, where the hull and keel 'anchor' the boat so that it can take advantage of the beneficial lift created by the sail. Similarly, dead whales have been found to move approximately one knot in surface waves. This is due to the surface waves creating an oscillating current across the whale's fluke; far more energy can be extracted if the fluke is allowed to move synchronously with the wave frequency [Bose, 1990].

This last situation appears to be very similar. In both cases, an oscillating flow is induced across a foil --- using the body as a flow-anchor --- which subsequently moves the entire body through the water. In one case, the flow is set up by surface waves. In the other, it is set up by a vortex street. In fact, this from Bose could very easily apply to either situation:

> In smaller waves, ranging down from wave lengths several times the length of the whale, the whale's body is either steady or oscillates in such a fashion that the flukes are in water oscillating vertically at a different phase and amplitude to the motion of the body. The differential vertical velocity of the flukes can be used to extract energy from the waves.

Consider that each part of the trout body is being acted upon by the local flow as well as the neighboring body sections, which may pull the part in question across the local flow, to some extent, rather than with it. This may explain why the center-of-mass appears to move with the flow, in Figure 12, while the rest of the body moves against it to a certain extent. In the end, each part of the body is being pulled against the local flow, to some degree, because its being pulled by the center-of-mass, which is itself synchronized with its own local flow. Hence, it is expected that, when the wake wavelengths are very long, there will be less differential flow across the body sections, resulting in lesser effects, as seen by Bose.

This is not to say that the motion of the live fish is always entirely passive. The live fish must not only make certain that it stays within the wake but also cannot let itself drift too far forward or backwards. Essentially, the 'sweet spot' in the wake is a saddle point, where if the fish drifts too far forward it will be sucked into the back of the cylinder, and if it drifts too far back it would likely have to spend some energy producing thrust. The preference for positioning themselves in the saddle point may explain the frequent, small-amplitude, corrective beats employed, as well as the considerable amount pectoral fin activity. Lending support to this interpretation, fish appear to improve at synchrony the longer that they are behind the cylinder.

## Passive Swimming: Summary

Taken together, these experiments conclusively prove that fish are not just positioning themselves behind the cylinder in order to draft within the velocity deficit, but are also extracting energy from the vorticity for additional energy benefit to the point where the trout are essentially resting behind the cylinder. This could help to explain the ability of salmon to sustain long migrations upstream without food, and motivates further research using mechanical foils, where the actual performances can be measured directly.

# Conclusion

Rainbow trout within a vortex wake will synchronize their swimming motions to the oscillating flows in both frequency and phase. Through studies with electromyography and dead fish, proper interaction with the wake was shown to significantly reduce the energy required to hold station within a current.

### Acknowledgment

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