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A MECHANICAL FISH EMULATES THE C-SHAPE FAST-START MECHANISM

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ABSTRACT

We have built a simple mechanical system to emulate the fast-start performance of fish. The system consists of a thin metal beam covered by a urethane rubber, the fish body, and an appropriately shaped tail. The body form of the mechanical fish was modeled after a pike species, selected because it is a widely studied fast-start specialist.

The mechanical fish was held in curvature and hung in water by two restraining lines, which were simultaneously released by a pneumatic cutting mechanism. The potential energy in the beam was transferred into the fluid, thereby accelerating the fish. We measured the resulting acceleration, and calculated the efficiency of propulsion for the mechanical fish model, defined as the ratio of the final kinetic energy of the fish and the initially stored potential energy in the body beam. We also ran a series of flow visualization tests to observe the resulting flow patterns.

The maximum start-up acceleration was measured around 40 ms^{-2} , with the maximum final velocity around 1.2 ms^{-1} . The form of the measured acceleration signal as function of time is quite similar to that of Type I fast-start motions studied by Harper and Blake. The hydrodynamic efficiency of the fish was found to be around 10%. Flow visualization of the mechanical fast-start wake was also analyzed, showing that the acceleration peaks are associated with the shedding of two vortex rings in near-lateral directions.

INTRODUCTION

The diversity of fish and marine mammal locomotion has long captured the imagination and attention of scientists. In particular the unsteady nature of marine environments, and the evolutionary pressures it imposes, has produced fish that specialize according to a wide range of criteria. One impressive fact is that the accelerations produced by many fish can far exceed that of manmade vehicles. For example, Harper and Blake [1] reported northern pike peak instantaneous accelerations of 245 ms^{-2} . They have also reported the mean maximum start-up accelerations and velocities achieved by the northern pike as 96 ms^{-2} and 3.1 ms^{-1} for feeding and 150 ms^{-2} and 3.5 ms^{-1} for escape. Being able to accelerate ocean vehicles at this level, or even a fraction of it, could drastically improve turning ability, start-up/braking performance, and maneuvering in turbulent environments.

The fast-starts are quick bursts of energy from fish beginning in a resting or near resting position, to achieve very high accelerations [2]. Weihs [3] described each fast-start maneuver broken into three distinct stages. The first is the preparatory stage. It consists of a quick contraction of the fish to either a "C" or an "S" shape. The propulsive stage, stage two, is the aggressive uncoiling of the fish to produce the desired locomotion. This sends a traveling wave along the fish towards the tail [4]. The final stage is a variable phase that may include subsequent propulsive strokes or simply coasting [5].

Here, we attempt to emulate the fast-start performance of fish. A simple mechanical system was built to mimic the startle response of the most successfully studied fast-start specialist species, the pike. The body form of the mechanical fish in this work was modeled from a pike species. By using an

accelerometer, placed at the fish center of mass, we measured fast-start acceleration of the propulsion. We also calculated the propulsive efficiency of the mechanical fish and conducted a series of flow visualization tests using particle image velocimetry (PIV) techniques in order to study the flow pattern which accompanies the high acceleration start.

THE MECHANICAL FISH

The body form used to model the mechanical fish was the chain pickerel, *Esox niger*. A dead juvenile specimen was obtained from Harvard's Museum of Comparative Zoology (Cambridge, MA). The fish photographs were fit with polynomial curves of the body outlines, excluding the fins, and for symmetry, the profiles from the top and bottom curves were averaged. A CAD program was used to import the profiles and loft a nearly elliptical cross-section along the length of the fish, creating the 3-D model. Table 1 summarizes the physical properties of the mechanical fish. A photograph of the fish model is shown in Figure 1.

Table 1. Constant values used for equations and performance prediction

Hydrodynamic efficiency	η	0.2
Beam length	l_{beam}	0.368 m
Beam height	b	0.0330 m
Beam thickness	h	0.00127 m
Modulus of Elasticity	E	200 GPa
Beam natural frequency scale	c	1.8
Fish length	l_{fish}	0.508 m
Fish maximum height	b_{fish}	0.0635 m
Fish material mass	m_{fish}	0.804 kg
Water density	ρ	1000 kgm ⁻³

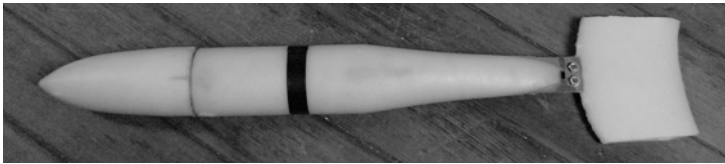


Figure 1. Completed fish model with cut tail.

Considering exclusively the propulsive stage of the C-shape fast-start, there is a quick and efficient transfer of energy from the fish to the water. The muscles of a live fish actively produce the energy to be transferred. To emulate this effect mechanically, a large amount of potential energy must be harnessed, stored, and quickly transferred into the water, producing forward thrust. In our device, a beam forced in curvature was the primary source of potential energy for this release. The beam was held in a deformed shape by a string that connected the two ends; the release was made by cutting the string. We used a pneumatic linear actuator with a razor blade to cut low-stretch fluorocarbon fishing line. The pneumatic

cylinder was powered by an off-fish air compressor and connected using flexible air tubing.

To meet the above-mentioned functional description, the mechanical fish was designed in three parts: a head, a body, and a tail. Beyond its biomimetic form, the head was designed specifically to allow easy access to the pneumatic cutting system. The body, comprising a soft rubber mass cast around a spring steel backbone, provided energy storage and connection points for the string and for the head and tail. The rubber used for the body and the head was VytaFlex 10 (Shore A Hardness 10, density 1000 kg/m³). This rubber provides the fish a realistic body without introducing significant energy into the system when bent.

The base tail fin used for testing was a NACA 0012 profile. The approximate surface area of a pike with comparable length is around 76 cm². Therefore, we have performed the majority of our tests with tails with an estimated surface area of 80 cm². Tail-fin materials were made of urethane rubbers Shore A Hardness 50, 60 and 94. In order to study the influence of the tail on fish performance, a series of experiments were conducted using a tail with a larger surface area: 187 cm², and another series with no tail.

PARAMETER SELECTION

The fish model uses a curved (deflected) beam to store mechanical potential energy (E_p). When the beam is released from curvature, it quickly transfers its energy into the surrounding fluid. A portion of this energy becomes useful kinetic energy (E_k) to propel the body forward, and the rest of it is lost into the fluid, and into the structure as heat. Here, we calculate the radius of curvature for the initial curved beam, which would result in the optimal kinetic energy of the fish after release.

A simple equation for the kinetic energy of the model after the fast-start is

$$E_k = \eta E_p, \quad (1)$$

where η is a hydrodynamic efficiency constant. Hydrodynamic efficiencies of pike fast-starts are reported between 0.16 and 0.39 using a ratio of useful power to total power [2]. McCutcheon [6] reports burst-and-coast swimming efficiency ranging from 0.18 to 0.7 [2]. A fast-start is, however, a violent unsteady propulsive mechanism, causing lower efficiency; we use a constant of 0.2 in our analysis.

The mechanical potential energy stored in a deflected beam is, in turn, dependent on the material properties, dimensions, and the degree of deflection, and can be calculated as

$$E_p = \frac{EI l_{beam}}{2R^2}, \quad (2)$$

where E is the modulus of elasticity of the beam, l_{beam} is its length, I is the bending moment of inertia, and R is the radius of curvature. The kinetic energy is given as

$$E_k = \frac{1}{2} m_{\text{forward}} U^2, \quad (3)$$

in which m_{forward} is the combination of the material mass of the fish (m_{fish}) and the added mass effect caused by accelerating the fluid around the fish. Webb [7] and Frith and Blake [2] estimated the added mass associated with forward fish acceleration as 20% of the material mass. The mass of the fish, m_{fish} , is approximated by half the mass of a cylinder with a diameter of b_{fish} , total fish length l_{fish} , and a rubber body with density ρ very close to that of water. Using (1) to (3) to solve for the fish velocity after the start, we obtain

$$U = \sqrt{\frac{\eta E I_{\text{beam}}}{m_{\text{forward}} R^2}}. \quad (4)$$

A scaling non-dimensional quantity, analogous to the Srouhal number for a fast-start fish is defined as

$$Q = \frac{A}{U \tau}, \quad (5)$$

where A is the wake width and τ is the characteristic time scale of the half stroke. For the northern pike, and based on information given by Schrieffer and Hale [8], the average length of the fish is 23.7 cm, the mean linear velocity for the escapes is 1.75 ms^{-1} and the propulsive stage duration is $\tau = 29.5 \text{ ms}$. Also, the amplitude of the tail excursion is approximately 0.4 of the fish length. Hence an estimated fast-start number is $Q = 1.84$. Using this number for fast-start, we can find a more general relation for the characteristic time scale in terms of fish length and velocity, and then using (4) we have

$$\tau = 0.22 l_{\text{fish}} R \sqrt{\frac{m_{\text{forward}}}{\eta E I_{\text{beam}}}}. \quad (6)$$

On the other hand, the first natural frequency of a uniform beam is given by

$$f_1 = \frac{c}{l_{\text{beam}}^2} \sqrt{\frac{EI}{M}}, \quad (7)$$

where, M is the mass per unit length, and we assume that the fish shape is a cylinder with a length equal to the beam length, and also we assume an added mass equal to the body mass. The coefficient c is 3.56 for a beam with free-free end conditions, and 1.57 for a simply-supported beam. In our fish, the flexural portion of the body is terminated by large head and tail sections, and a lower value of c is likely to be more accurate; we have chosen $c=1.8$.

Now we can equate characteristic time scale with the inverse of the beam first natural frequency, so as to link the resonant behavior of the model structure with the fluid, and to find an optimum radius of curvature as

$$R = \frac{l_{\text{beam}}^2}{0.22 c l_{\text{fish}}} \sqrt{\frac{\eta M l_{\text{beam}}}{m_{\text{forward}}}}. \quad (8)$$

For our mechanical fish with the physical properties of Table 1, we find $R \approx 0.23 \text{ m}$. This optimum radius of curvature

corresponds to approximately 90° of curvature. We have used this curvature in all of our experiments. Table 2 displays the resulting physical parameters based on the optimal radius of curvature.

Table 2. Estimated equation values using the design constants from Table 2.

Radius of curvature	R	0.234 m
Potential energy	E_p	3.79 J
Kinetic energy	E_k	0.76 J
Forward velocity	U	1.25 m/s
Characteristic time scale	τ	89 ms
Natural frequency	f_1	5.61 Hz

ACCELERATION MEASUREMENTS

The tests were carried out in a 350-gallon glass tank (240 cm \times 75 cm \times 75 cm) at the MIT Towing Tank laboratory. The fish was bent to the optimal radius of curvature and was held in a deformed shape by a string that connects the two ends. Another series of strings were used to hang the fish vertically in the tank. The two strings were cut simultaneously by a release mechanism, and the fish was released with no strings attached.

In the experiments, initially, the fish was bent to a mirror C-shape, with a radius of curvature of $R_{\text{opt}} \sim 23 \text{ cm}$. When the fish was released, two strokes of the tail were observed: in the first one, the fish was rapidly uncoiled and bent to a C-shape – opposite the initial figure – with a larger radius of curvature ($R_2 > R_{\text{opt}}$). The second stroke, which was slower compared to the first one, started from this larger-curvature C-shape and ended when the fish became almost straight.

A Vernier 3-Axis accelerometer was taped to the top of the fish at its center of mass using duct tape sealed at the edges. When the fish was released, the acceleration of the center of mass was recorded in three perpendicular directions: forward (x), transverse (y) and vertical (z). We conducted all the experiments with a sampling frequency of 2400 Hz.

Figure 2(a) shows acceleration signals in forward direction for a sample case. For the sample case shown here, the acceleration signal has two major peaks: the first one with a magnitude of 40 ms^{-2} at around $t=5 \text{ ms}$ and the second one with a magnitude of 42 ms^{-2} at around $t = 25 \text{ ms}$. This fast-start event lasts for about 100 ms.

Using the measured acceleration, the velocity and displacement of the fish in forward direction can be obtained – see Figure 2 (b,c). As indicated in Figure 2(b), the forward velocity of the center of mass increases rapidly from zero and after about 50 ms reaches a plateau of around 1.1 ms^{-1} . The total displacement of the fish during this period is around 8 cm.

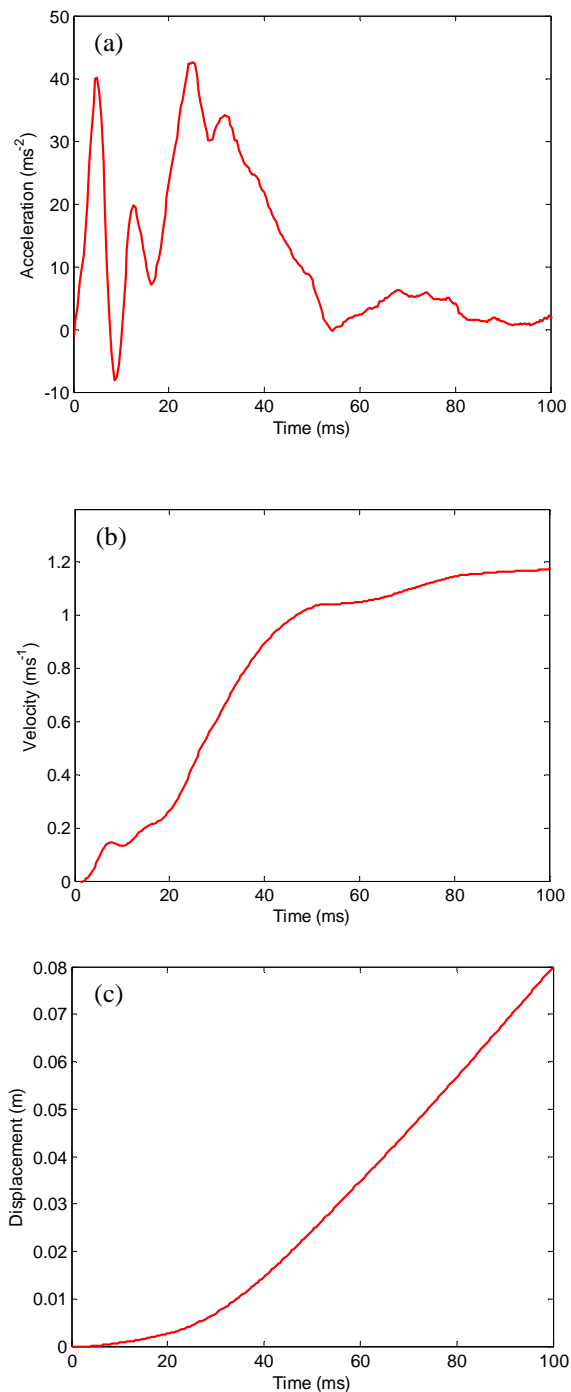


Figure 2. Forward (a) acceleration, (b) velocity, and (c) displacement calculated based on the acceleration signal measured with sampling frequency of 2400 Hz.

Figure 3 shows samples of acceleration signals both in the forward and the transverse directions, corresponding to the two strokes described above. For this particular example, the maximum forward and transverse accelerations are 42 ms^{-2} and 70 ms^{-2} , respectively. The first stroke occurs from $t=0$ to $t\sim 30$ ms, and the second stroke from $t\sim 30$ ms to $t\sim 120$ ms. In the transverse direction, each stroke corresponds to a peak in acceleration, followed by a peak with an opposite sign, and a second peak with the same sign as the first. During the first stroke (when the fish tail rotates about its center of mass in a counterclockwise direction) we observe two local maxima, and a local minimum, making an M-shape plot in the first 30 ms. During the second stroke (where the fish tail rotates in a clockwise direction about its center of mass) two local minima and a local maximum are observed in the last 90 ms of the plot, making a W-shape plot. The first stroke is due to a smaller initial radius of curvature of the beam, resulting in a larger transfer of momentum to the fluid and therefore occurs much faster (~ 30 ms), while the second stroke is due to a larger initial radius of curvature, and takes a longer time to complete (~ 90 ms). The acceleration in forward direction is positive and has its local maxima during the first stroke ($t < 30$ ms), but decreases toward zero during the second stroke.

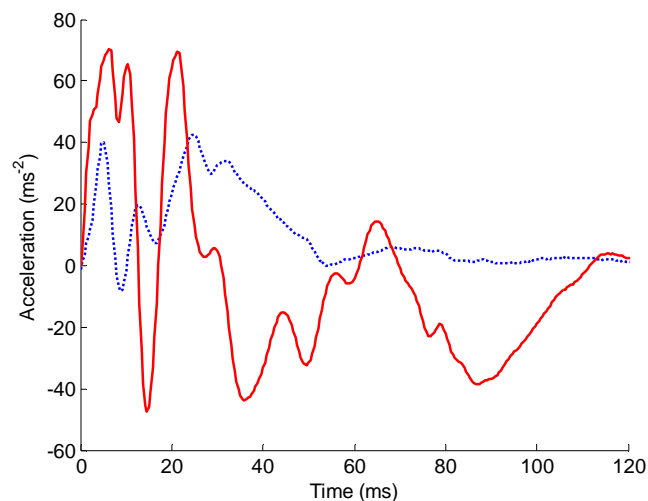


Figure 3. Sample acceleration plots measured in the forward (dotted blue) and transverse (solid red) directions.

Figure 4 shows measured values of acceleration, velocity, and displacement of the live fish (Harper and Blake, 1991), plotted on top of our measured accelerations. In all of these plots, normalized values are used, to make the qualitative comparison possible. Each plot is normalized by dividing each value by the maximum value of that plot. Our measured acceleration is with a sampling frequency of 2400 Hz. The two peaks that we have observed in the acceleration plot of our

mechanical fish exist in the acceleration plot of the live fish too, and the velocity and displacement plots are similar. The two peaks in the acceleration plot of the live fish in the particular case shown in Figure 4 are around 80 ms^{-2} and 90 ms^{-2} . The time gap between the two peaks is larger in our mechanical fish ($\sim 20 \text{ ms}$) than that for a live fish ($\sim 10 \text{ ms}$).

Overall, and based on the average values of at least 5 trials in each case, we have observed that all cases with a tail show a maximum acceleration of around 40 ms^{-2} and a maximum velocity of around 1.2 ms^{-1} (2.4 Ls^{-1}), while for the live fish, a maximum acceleration of 150 ms^{-2} and a maximum velocity of 3.5 ms^{-1} (8.7 Ls^{-1}) is observed, where Ls^{-1} stands for body length per second.

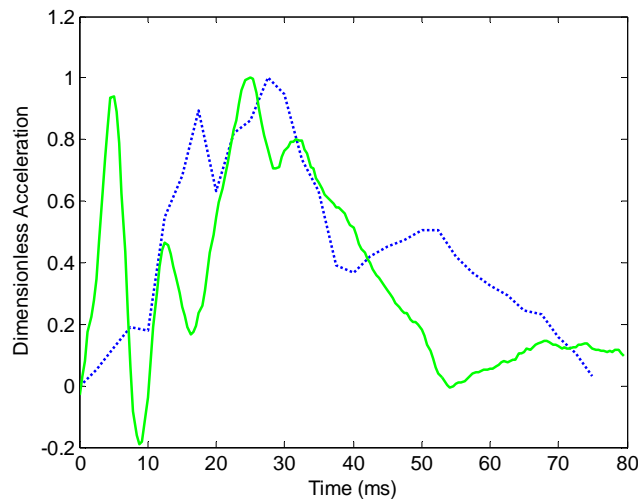


Figure 4. Sample forward acceleration signals of the mechanical fish (solid green) and of the live fish, from Harper and Blake's experiments [9] (dotted blue).

The case with no tail shows a much smaller final velocity, while its maximum acceleration is not very different from the other cases. The reason for this low final velocity, and therefore small displacement, is that a peak of almost the same size as the maximum acceleration, but with a negative sign – deceleration – exists immediately after the positive peak, canceling the effect of the initial acceleration.

Efficiency is estimated based on the transfer of energy from elastic potential to kinetic swimming energy. The fish beam placed in 23-cm curvature has about 3.8 Joules of energy, and an error of 1 cm in either direction produces 3.5-4.2 Joules of stored energy. When released, the model accelerates to a mean velocity of around 1.2 ms^{-1} . The energy transferred to kinetic energy is thus approximately 0.4 Joules, and the efficiency is approximately 10%. The fast-start efficiency for live fish, as noted previously, is in the range of 16-39%.

FLOW VISUALIZATION

The fact that the acceleration signals of our mechanical fish and those of a live fish are qualitatively similar suggests that our mechanical fish captures the essential physics of the fast-start, and can be used to understand the corresponding details. We conducted a series of flow visualization tests using particle image velocimetry (PIV) to observe the flow behavior when the fast start occurs. The fish was suspended in the PIV tank by using two series of strings, which were cut simultaneously to release the fish, as discussed in the previous section. The high speed camera was located above the tank, so that the flow around the tail or body was observed.

The camera used for the PIV tests was an Imager Pro HS, high speed digital camera, capable of taking pictures at 638 Hz at the full resolution of 1280×1024 pixels. The laser used in these experiments was a Quantronix Darwin 527 Series diode-pumped, Q-switched, Nd:YLF laser and the laser pulse frequency was at 600 Hz. The software used for PIV processing was DaVis version 7.

Each experiment was conducted in a pair: Once such that a side-view of the fish was visible in the camera, and then such that a top-view was visible. This leads to having a three-dimensional image of flow behavior.

Figure 5 shows a series of images taken from the top view of the fish tail, immediately after it was released. Each figure is accompanied by plots of the forward and transverse accelerations. It is observed that after releasing the fish, a vortex is generated and shed in the first 10 ms, resulting in a first peak in both acceleration plots (Figure 5a). As this vortex moves downstream, the two accelerations experience their first local minima at $t \sim 20 \text{ ms}$. This is then followed by the shedding of a second vortex at around 30 ms, resulting in a second local maximum in each acceleration plot (Figure 5b). These two vortices make a vortex pair, which can be configured as a vortex ring; the side-view run of the same test (not shown here) shows that a vortex pair is shed with an angle of around 180 degrees with respect to the direction of motion. During the second stroke (which starts at $t \sim 30 \text{ ms}$), first a vortex is shed at $t \sim 40 \text{ ms}$, in an opposite direction of the previous vortices resulting in a local minimum in the transverse acceleration signal, instead of a local maximum (Figure 5c). A local maximum in the transverse acceleration is observed when the shed vortex is far enough from the tail, and a second local minimum is observed at $t \sim 90 \text{ ms}$, when a second vortex is shed (Figure 5d). These two vortices, also, make a vortex pair which similarly to the first vortex pair can be configured as a vortex ring.

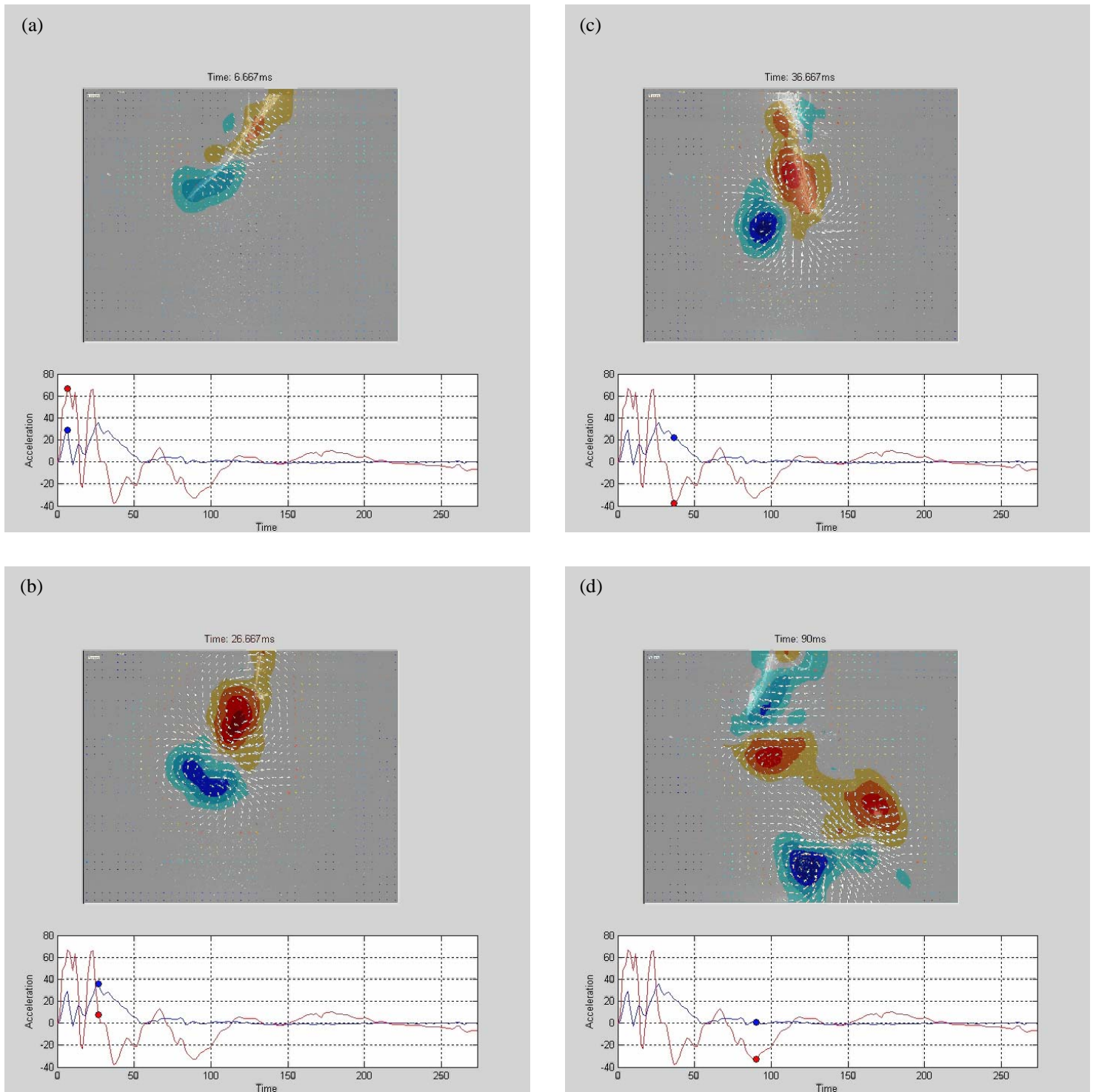


Figure 5. PIV images of the flow pattern around the tail during the fast-start together with the acceleration plots in forward (blue) and transverse (red) directions.

Overall, we can see that two vortex rings are shed during these two strokes: The first vortex ring with an angle of around 150 degrees with respect to the direction of fish motion, measuring clockwise, and the second vortex ring with an angle of about 260 degrees (almost perpendicular to the direction of fish motion). Epps and Techet [10] have observed the shedding of two distinct vortex rings for a Giant Danio (*Danio aequipinnatus*) performing a C-start. In our mechanical fish, the shedding of the first vortex ring results in a transfer of momentum from the fish to the flow, and a resulting reaction force on the fish with an angle of approximately 30 degrees with respect to the direction of motion. Therefore, this reaction force has a non-negligible component both in the forward and in the transverse direction, resulting in non-zero values for accelerations in both directions. The second vortex, however, is almost perpendicular to the direction of motion, resulting in a reaction force from the fluid mainly in the transverse direction, with almost no contribution in the forward direction. This corresponds to the period in the acceleration plot where we observe almost zero acceleration in the forward direction.

CONCLUSIONS

A simple mechanical system was built to emulate the startle response that is used by a fast-start specialist fish, the northern pike. The system consisted of a thin metal beam covered by a urethane rubber fish body. The mechanical fish was held in curvature by a restraining line and released by a pneumatic cutting mechanism. Using some acceleration measurements and PIV tests, we observed that two almost lateral vortex rings are shed during the fast-start, resulting in large accelerations both in the transverse and forward direction. Maximum forward acceleration was calculated at around 40 ms^{-2} , with a maximum velocity of about 1.2 ms^{-1} . The hydrodynamic efficiency of the fish, calculated by the transfer of energy, was around 10%.

The velocity, acceleration and displacement plots are qualitatively similar to what was previously observed for live fish. The maximum values, however, are by far lower than those for a live fish, which is not surprising. It was found that the tail material and size (at least the ones used in this work) do not have a crucial influence on the observed acceleration maxima and final velocities. However, a fish with no tail experiences a much lower final velocity.

In our model, we neglect the preparatory stage, which is known to have a significant influence on the fast-start. In this regard, Ahlborn et al. [5] describe a fast-start propulsion mechanism called the reversal of momentum in which during the preparatory stage, an initial angular momentum is imparted to the fluid by the fish coiling, producing a shed vortex. The direction of this vortex is then reversed in the propulsive stage, resulting in production of a second vortex. According to the model developed therein, the existence of an equal and opposite initial vortex created in the propulsive stroke could improve thrust performance by 50%.

During the propulsive stage, a live fish produces a traveling wave from the head toward the tail [4], while this is not the case in our model. The release mechanism is designed in a way that the head and the tail are released at the same time, and therefore, no traveling wave is induced. This means that our model does not include the influence of this traveling wave on the resulting accelerations and flow pattern.

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