Hydrodynamics of a Fusiform Shape

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Introduction:

Fishes are the most abundant vertebrate on the planet, with over 30,000 species in number. One of the fastest types of these animals is the Tuna, in the family Scombridae (MIT, 1996). These fishes are highly muscular and capable of quick bursts of speed. It is for this reason that I chose this animal as a model for the ideal shape for dealing with the stresses of fluid flow. This is due to the fact that the Tuna swims miles each day in search of food, and has many adaptations to reduce drag in water such as flattened eyeballs and grooves for its fins to rest in (Morris, 2003). Natural selection has driven fast swimming fishes to have a fusiform body shape such as that of the Tuna and other Scombridae. In this experiment, I attempted to model the body plan of a Tuna to test the hydrodynamic properties of such a body shape. Their body shape is roughly teardrop-shaped, slightly more bulbous at the front end and tapering off towards the rear. Compared to this shape, I used the same model, but turned sideways to mimic an un-ideal hydrodynamic form. My hypothesis was that the fusiform shape of the Tuna model would be much more hydrodynamic than the other form, and I tested this by comparison of forces exerted on the towing system.

Materials:

The device used for measuring the force exerted by the model was two fishing poles, tied together. The pole holding the model was one that was 6 feet long, suitable for line tested for 6-15 lbs, and the line was 8 lb test.

The model itself was made by shaping wire 1/8th of an inch thick into a fusiform shape such as the one used in the model of the Robotuna. More wire, much more thin, was used to surround this skeleton. Tinfoil was then used to surround this, and wax was used to fill it. A Bunsen burner was used to melt the wax, and a scalpel was scrape off excess wax. Pieces of 1/8th inch wire were used to make the model heavier so it would sink in water. Smaller pieces of wire were used to create fastening points to which the fishing line was attached.

A digital video camera was used to videotape the model being towed by the fishing pole, which was towed in a large pool free of waves. A protractor was then used to measure the angle of bend of the pole.

Methods:

The two fishing poles were tied together in such a way that un-stressed, their poles were parallel to one another. The top pole was unattached to the line holding the model, and thus free from any stresses put on the other pole. This way the angle of bend of the first pole could be measured using the second as a starting point.

The model was made by bending 1/8th inch diameter wire into a rough fusiform shape, and then surrounding this main structure with more wire which was thinner and thus more flexible. This metal skeleton was then surrounded by tinfoil, with an opening left at the top. Into this hole, paraffin wax tablets were poured until the model was full, and then into this, molten was poured to solidify the structure. A Bunsen burner heated a Pyrex dish of water that held a beaker full of wax tablets, which slowly melted and were poured out as needed. Wax was poured into the model until it was completely full, and then it was left to solidify. After this, the tinfoil was torn away, and more wax, semi-solid so as to be easy malleable was added to the model to make it streamlined and as close to a true fusiform shape as possible. A scalpel was used to shave away any areas that were not streamlined or were not streamlined.

When this shape was achieved, the model was submerged in water to establish its buoyancy. In order for the experiment to work ideally, the model would have to be neutrally buoyant, and float upright. Once the buoyancy properties of the model were found, pieces of wire 1/8th an inch in diameter were added in the bottom of the model so that it would float upright as well as to make it heavier, as the model at this point was too buoyant. Eventually enough wire was added to make the model have the desired properties. Again, a scalpel was used to shave any wax off that did not conform to the fusiform shape. Wire was attached to the inner wire frame and bent into hooks which could be used to attach the model to the line; one on the anterior end, and one on the right side of the model, both centered. The first hook was set into the model in such a way that when the model was dragged, it would present a fusiform profile to the water, pulled by its anterior end. The second hook was set in such a way as to pull the model through the water in a way which presented a non-fusiform profile to the water. The model was then brought to the Wheaton College aquatics center, and attached to the fishing line by the first hook. The model was then pulled through the water at a constant rate, three times, and each trial was videotaped from the same position and magnification. The line was then attached to the second hook and pulled through the water and videotaped in the same manner. The video trials were paused at the point of the most bend in the pole, and the angle created between the straight pole and the bent was measured in all six trials, with the end of each pole as a reference point.

Results:

In the trials, the model pulled through the water in a relatively straight manner, although it shifted somewhat side to side when pulled through the water by the anterior end.

First Hook/ Angle
Trial 1/ 24º
Trial 2 /26º
Trial 3 /27.5º
Average: 25.83º

In the previous table, the results are those of the model being pulled through the water with the fusiform profile exposed. The model, when pulled, sank lower in the water, perhaps due to the shape of the profile exposed to the forces. The angles listed are those created by the distance between the two fishing pole ends. The angles of this trial are much smaller than those seen in the next series of trials, and the average of the angles is 25.83º, much smaller than that of the second series of trials.

Second Hook/ Angle
Trial 1/ 34.5º
Trial 2 /34º
Trial 3 /33.8º
Average: 34.1º

In the previous table, the results are those of the model being pulled through the water from the second hook, the profile presented to the water that of a non-fusiform shape. These angles are much larger than those yielded by pulling the fusiform shape, and the average of the angles is 34.1º. This average of these angles is over 24% larger than the average of the fusiform shape.

Discussion:

From the results, we can clearly see a marked difference between the two trials. Trial one exerted much less force on the pole and thus caused it to bend less. As the only difference between the two trials was the profile presented to the water, this means that indeed, the fusiform shape is much more hydrodynamic than the second shape. So much so in fact, that the second set of trials exerted 25% more resistance than the first. Considering the fact that it was the exact same model, just in different positions, this is quite remarkable. A few angles of degree difference would most likely to be expected, but to see the angles differ by as much as 10.5º is quite extraordinary. This supports my hypothesis that a fusiform body shape is ideal in respect to dealing with the stresses of fluid flow.

There were many sources of error in my experiment that could have contributed to the angles being more or less than they were found to be, however, the large angle difference between the two trials is more than what could be explained as experimental error. Firstly, the model was obviously not a perfect fusiform shape and this probably accounted for a little more drag, but the imperfections in the shape, were also present when the other profile of the model was pulled through the water. Also, the side to side motion in the first trial, and the dragging down of the model in the second trial both probably affected the drag and the angle of the poles bend. However, these two things are constructive in the sense that both would be adding more drag to their respective trials and thus the two trials still remained experimentally sound. Other sources of error included the rate at which the models were pulled, which could have varied to some degree purely out of human error. Also, the angles measured (by pausing the video) could have been affected by the moment in which they were measured; perhaps this angle was a bit smaller or a bit larger than the average of the whole trial. Overall, the experiment had many sources of error that could have changed slightly the actual measurements of the angles, but due to the difference between the two trials, these differences would have been insignificant.

If I were able to do this experiment again, I would test different body shapes of other fish, which would have produced more interesting results that weren't so obvious before the experiment began. Fish body plans I would have liked to test are that of a long, thin fish, such as a Barracuda, and also that of a wider fish, such as a Grouper, although the second trial was shaped somewhat the same as the profile a grouper would present to the water. Overall, I think this experiment does indeed show that a fusiform body plan is one that is quite good at reducing stresses created by water.

Bibliography:

Professor Bob Morris, lectures from March-April of 2003, and for his help with working out the specifics of the experiment.
MIT Robotuna site, http://web.mit.edu/towtank/www/tuna/robotuna.html