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Technical Memorandum



# THE RELATIONSHIP BETWEEN FISH LOCOMOTION AND MORPHOLOGY

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## ABSTRACT

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## 1. INTRODUCTION

Human interest in swimming and flight in nature is age-old. Such forms of locomotion have been perfected over millions of years of practice, and no wonder they have been the inspiration of many inventions that surround our life today. A flying aircraft is the most vivid example. Since the historical flight of the Wright brothers, the bio-kinetics of swimming and flight has been studied in a systematic way, and some of the progress has been summarized in Azuma (1992) and Wu, Brokaw, and Brennen (1975).

Much has been learned about the bio-kinetics of basic locomotion like cruise swimming and flight (Grillner and Kashin, 1976, for example). However, far less is known about the hydrodynamics of brisk maneuvers like sudden acceleration (burst of speed) or deceleration, or abrupt change in the direction of locomotion, and even fewer attempts have been made to apply the knowledge gained from such studies to engineering vehicles.

Due to the reduction in procurement volume and increase in unit cost, self-defense of undersea vehicles has assumed an increased importance. Brisk maneuverability can provide such a defense mechanism (Nadolink, 1994). The subject is clearly important to vehicles in motion both in water and in air. However, the hydrodynamics of brisk maneuverability of undersea vehicles is largely an uncharted territory.

One approach to the study of brisk maneuver is to learn from aquatic locomotion and then apply that knowledge to engineering vehicles. This approach has been tried many times in the past and, in fact, several examples can be cited where nature and engineering bear a remarkable morphological similarity (Azuma, 1992). The profile of a tuna is close to that of NACA profile 67-021, which offers maximum volume as well as a long laminar flow length (70%). The profile of a trout is similar to that of NACA profile 63A016 and the laminar profile LB N-0016 given by Tani (1943) and Kármán (1954). The dolphin profile is also very close to that of NACA profile 66018, which was invented artificially. The viscous drag-reducing riblets are similar to the scales of sharks (Bechert et al., 1985). The induced drag-reducing winglets of Gates Learjet 557, Fairchild 300, Canadair Challenger 601, and Boeing 777 are similar to the winglets of a condor. The leading edge flap in aircraft wings, developed by Handley Page, is deployed during takeoff and landing, and was originally inspired by feather configurations in bird wings.

In the same vein, the present study assumes that much can be learned by studying fish families that are efficient in brisk maneuvers. The study was motivated by a long term effort to make a vehicle capable of undertaking a brisk maneuver. As a starting point, the morphology of various fish families was examined to determine what makes some families more maneuverable than others. Three families of fish were examined: (1) those that are maneuverable and are generally regarded as low speed fish, (2) those that are known to cruise at a relatively high speed, and (3) those that can both cruise at high speed and yet are maneuverable. The length scales of the body and the fins have been examined. The relationship between the fin morphology and the characteristics of locomotion are discussed, the emphasis being on maneuverability.

## 2. RESULTS AND DISCUSSION

Morphology describes the shape and size of an animal. It has evolved in a way that allows an animal to lead a certain way of life, called ecology (the activities of feeding, reproduction etc.), in a certain environment, called a habitat. Locomotion is the bio-mechanics of moving from point to point that makes the ecology possible. Due to interdependence, it is reasonable to assume that even the static morphology of a fish can provide clues to its locomotion, habitat, and ecology (Aleev, 1969).

### 2.1 Definition of Length Scales

The morphological length scales of a fish are shown schematically in figure 1. Three kinds of scales are shown. The overall axial length of the main body is L, and the maximum height is T. The caudal fin is defined by width $W_C$ and by axial length in the mid-plane $L_C$, measured from the middle of the caudal peduncle. The combined axial length of the first and second dorsal fins at the roots is defined by $L_D$, and its maximum span in the normal direction is given by $S_D$. The second dorsal fin is practically nonexistent in some families , for example, in salmon and dace. The axial distance of the leading edge of the second dorsal fin (also known as soft fin) at the root is given by $L_2$ , while its axial length is given by $D_2$. Finally, the axial length of the anal fin at the root is given by A, and its leading edge is situated at an axial distance of $L_A$. Unlike the dorsal and anal fins, the ventral fin is hinged (or rooted) practically at a point, and not over its entire length. For this reason, the ventral fin is not compared with the dorsal and anal fins. The roughly elliptical cross-section of the main body of the fish is also not considered.

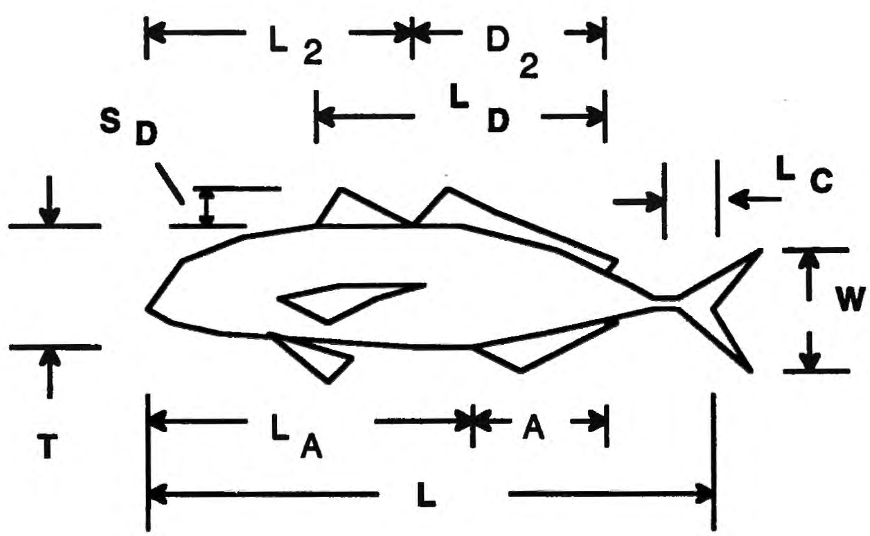


Figure 1. Definition sketch of the length scales of a fish.

The scales shown in figure 1 were quantified from photographs of three categories of fish: (1) highly maneuverable but low speed, (2) high speed but not highly maneuverable, and (3) both highly maneuverable and high speed. This qualitative categorization is based on Azuma (1992) and Wu (1994). There is a factor of 2 to 10 between the absolute speeds of families of types (2) and (1). However, representation of speed in terms of body length per second, rather than in absolute units, may be more meaningful.

The maneuverable fish families tend to live in crowded areas like reefs, rocky shores, and at the bottom of the sea. On the other hand, those endowed with speed, tend to live in swift streams or open seas.

## 2.2 Caudal Fins

The results for the overall morphology are shown in figure 2. (In the legends of figures 2 to 5, the common names of the fish families are given, followed by abbreviations of the Latin genus and species names, which are given in the appendixes). It is interesting to see that the first and second categories defined in section 2.1 indeed follow two different trends, while the third category falls in both of these clusters. It is suggested that, while the first two categories of data fall roughly in families of circular arcs (approximated by a straight line in the figure) centered at the origin, the third category follows a radial trend. For the same overall aspect ratio ($L/T$), the caudal fin is fuller (large $L_C/W_C$) in maneuverable, low speed fishes compared to those that are fast swimmers.

## 2.3 Dorsal Fins

The results for the dorsal fins are shown in figure 3, which shows that those families that maneuver well have a high value of $L_D/L$ ($0.4 < L_D/L < 0.6$), the mean being 0.5. Figure 3 suggests that, in general, high-speed fishes have short dorsal fins and maneuverable fishes have long dorsal fins.

In figures 2 and 3, 28 species of fish have been considered. While the database is limited and some caution needs to be exercised, the trends are surprisingly clear. The slenderness ratio $T/L$ represents the importance of side area ($TL$): a large side area will produce a large side thrust, but may be undesirable for fast cruise swimming. The dorsal fin adds to the side area and, therefore, improves maneuverability. The same is true for the caudal fin: a large side area helps maneuverability, while a small area allows high-speed cruising.

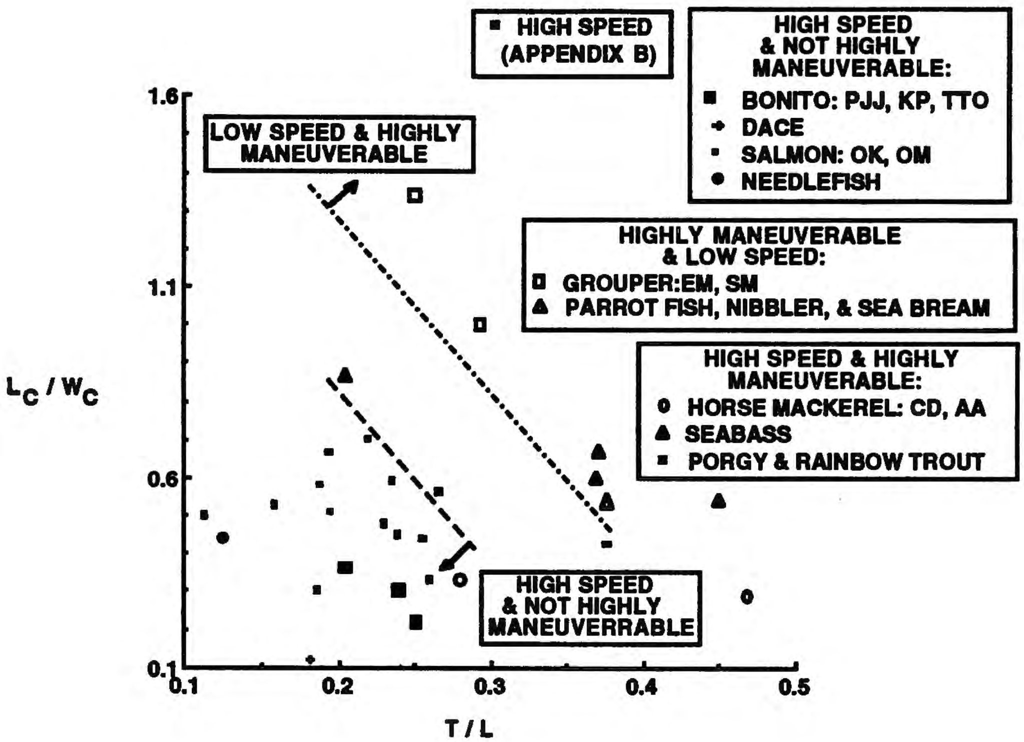


Figure 2. Overall morphology and caudal fins of fish families.

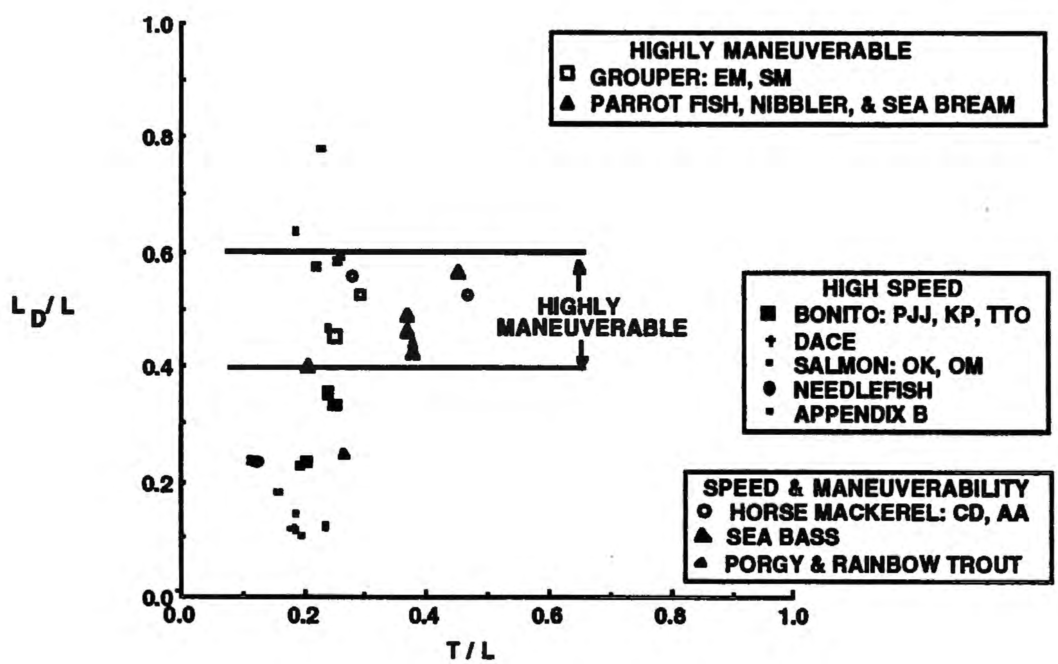


Figure 3. Morphology of dorsal fins of fish families.

The aspect ratio of the dorsal fin is defined as $S_D/L_D$. The reciprocal of the aspect ratio of the dorsal fins is shown in figure 4. While all of the data generally fall between two radial lines (not shown) through the origin, the data for maneuverable fishes are also bounded between two radial lines originating at $T/L = 0.2$ and $L_D/S_D = 3$. This "telescoping" of the data set of maneuverable fish families suggests an underlying closer scaling of their dorsal fins with their overall fish morphology. The families having a low-aspect-ratio dorsal fin (higher values of $L_D/S_D$) and a low-aspect-ratio main body (large values of T/L) are highly maneuverable. Note that the horse mackerel is both highly maneuverable and can cruise at high speed.

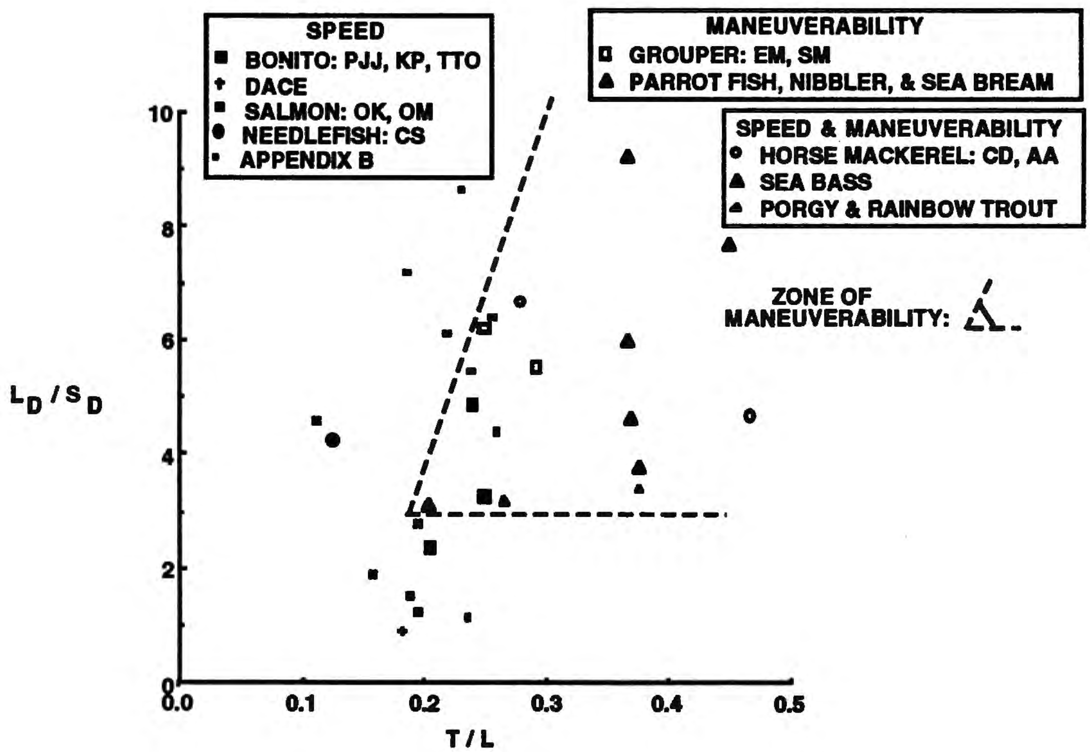


Figure 4. Reciprocal of aspect ratio of dorsal fin.

## 2.4 Second Dorsal and Anal Fins

The dorsal fin is frequently composed of two fins: the first (or spinous) fin and second (or soft) fin. In the bonito, horse mackerel, and sea bass, the junction between the first and second dorsal fin is as shown in figure 1. However, in the maneuverable families like the grouper, parrot fish, nibbler and sea bream, the junction is a line and not a point, and the second dorsal fin has a finer texture, the leading edge being characterized by a clear increase in span.

Figure 5 compares the second dorsal fin with the anal fin. It shows a universal trend, viz., that the second dorsal fin is roughly as long as the anal fin and is located roughly at the same axial location. In other words, these two fins are roughly the mirror image of each other.

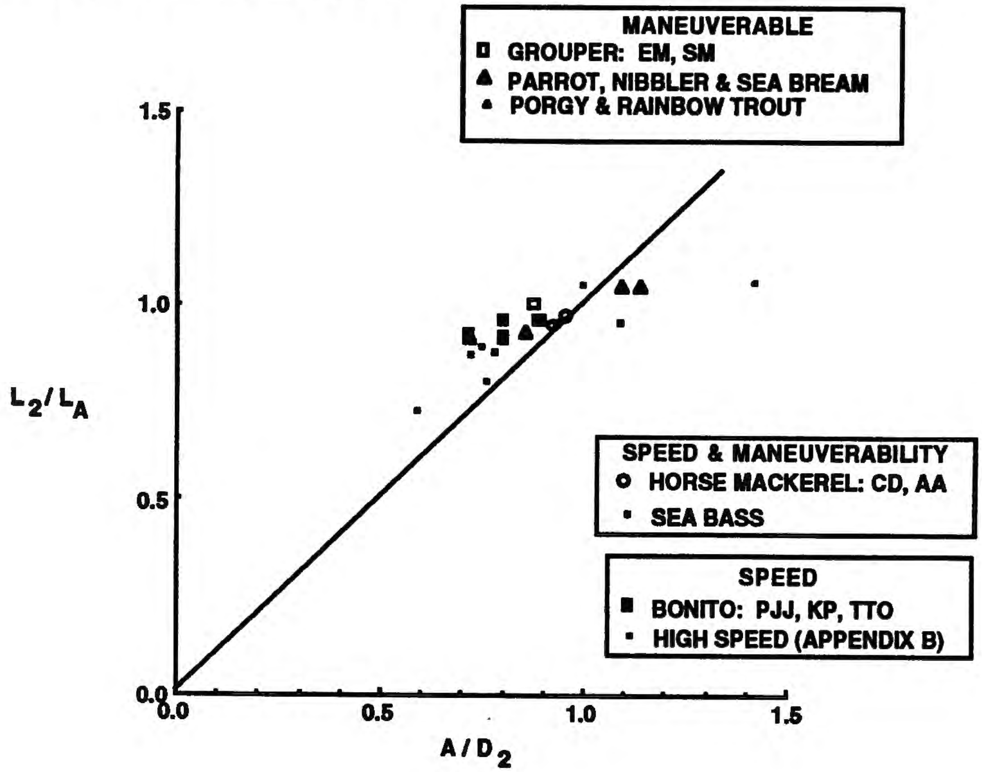


Figure 5. Relative length and axial position of leading edges of second dorsal and anal fins. The solid line indicates equal proportionality.

## 3. CONCLUSIONS

A preliminary study of the morphology of fish families has been carried out. Twenty eight species of fish have been considered. A well defined hydrodynamic inquiry has been made, viz., what hydrodynamic appendage makes a fish highly maneuverable?

The fish families examined belong to three categories: those that are highly maneuverable, those capable of high speed, and those having both of these characteristics. Because these examples are from nature, the differences in the characteristics of their locomotion are not entirely sharp. Yet, interestingly, several trends in the aspect ratios of the main body and dorsal fins have been identified.

The following conclusions of engineering interest can be drawn:

1. The dorsal fin versus overall aspect ratio plot indicates that maneuverable fishes have low aspect ratio main body and dorsal fins, that is, low values of $L/T$ and $S_D/L_D$, respectively.

2. The morphology of a highly maneuverable fish is characterized by long dorsal fins ($L_D/L$) whose span ($S_D/L_D$) is small, compared to those families that can cruise at high speed but are not highly maneuverable.

3. In highly maneuverable fishes, the mean axial length of the dorsal fin is $0.5L \pm 0.1L$.

4. The second dorsal fin and the anal fin are roughly the mirror image of each other in axial length and the location of their leading edge.

5. Fish morphology indicates an unconventional design strategy for making underwater cylindrical bodies highly maneuverable. It is advantageous to start with cylinders that have a low aspect ratio (low values of $L/T$). Furthermore, a dorsal fin that is axially long but narrow along the span, viz., $L_D > 0.4\ L$, but $S_D < L_D/4$, mounted closely (and deployed abruptly) on such a flow aligned cylinder and given an appropriate camber, could enhance the cylinder's maneuverability. This design strategy will be the subject of a future study.

## 4. FUTURE WORK

In the present work, a quantitative basis for classifying the mobility of fish families is lacking. Although bio-hydrodynamicists generally agree with the classification adhered to here, a quantitative classification is essential for a rigorous scientific study. Such a classification can be based on the number of maneuvers per unit time, or on the comparative proportions of red and white muscles relative to the total body weight (McLaughlin and Kramer, 1991). The quantification of the mobility patterns will be carried out in the future, but it appears to be an involved issue.

In closing, it is noted that, because of the physical properties of water vis-a-vis air, and because of the generally lower energetic costs of locomotion in water, the diversity of feasible propulsion mechanisms is greater in water than in air (Daniel and Webb, 1987). Engineering disciplines have been slow to investigate the richness of aquatic locomotion and find appropriate use for the knowledge gained. However, in the future, we might see a greater interest from engineers on this subject.

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## APPENDIX A

### GENUS AND SPECIES OF FISH FAMILIES STUDIED*

1. Families that are highly maneuverable (including burst of speed):

| ***Family*** | ***Abbreviations: Genus & Species*** |
|---|---|
| Grouper: | EM: Epinephelus moara<br>SM: Sebasticus marmoratus |
| Parrot Fish: | OF: Oplegnathus fasciatus |
| Nibbler: | GP: Girella punctata |
| Sea Bream: | MM: Mylio macrocephalus<br>CM: Chrysophrys major |

2. Families that have high speed:

| ***Family*** | ***Abbreviations: Genus & Species*** |
|---|---|
| Bonito: | PJJ: Pneumatophorus japonicus japonicus<br>KP: Katsuwonus pelamis<br>TTO: Thunnus thynnus orientalis |
| Dace: | THH: Tribolodon hakonensis hakonensis |
| Salmon: | OK: Oncorhynchus keta<br>OM: Oncorhynchus masou |
| Needlefish: | CS: Cololabis saira |

3. Families that have both speed and maneuverability:

| ***Family*** | ***Abbreviations: Genus & Species*** |
|---|---|
| Horse Mackerel: | CD: Caranx delicatissimus<br>AA: Atropus atropus |
| Pisces: | Sea Bass |



* From Azuma (1992).

# APPENDIX B*

## GENUS AND SPECIES OF HIGH-SPEED FISH FAMILIES

| *Family* | *Genus & Species* |
|---|---|
| Dolphin | Coryphaena hippurus |
| Yellowtail | Seriola quanqueradiata |
| Atka Mackerel | Pleurogrammaus monopterygius |
| Gray Mullet | Mugil cephalus |
| Barracuda | Sphyraena pinguis |
| Sockeye Salmon | Oncorhynchus nerka |
| Bluefin Tuna | Thunnus thynnus |
| Skipjack | Katsuwonus pelamis |
| Spanish Mackerel | Scomberomorus niphonius |
| Pacific Slury | Cololabis saira |



* From Wu (1994).

# APPENDIX C*

## GENUS AND SPECIES OF HIGH-SPEED, HIGHLY-MANEUVERABLE FISH FAMILIES

| ***Family*** | ***Genus & Species*** |
|---|---|
| Porgy | Pagrus pagrus |
| Rainbow Trout | Salmo gairdnerii |



* From Wu (1994).

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