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Propulsion Experimental Research on the Structure of Swordfish's Lunate Caudal Fin[1]

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Abstract: Swordfish is the fastest fish in the world, which can reach a high speed of 110km/h. Depending on the swing of the caudal fin, swordfish gets the power of swimming. The caudal fin of the swordfish shows crescent and wide broadening which exceed the highest part of the body. The unique caudal fin of the swordfish and the way of swing are the main reasons for swimming fast.

By testing and analyzing the structure of caudal fin of swordfish, it is built the parametric description of the geometric structure .R1 and R2 are radius of the two circles, and that R1＜R2, A is center distance of two circles. The two circles intersect to form the shape of crescent. This research choose the R1、R2 and A as parameters, then make a geometric shape description of crescent.

The research optimizes the structure parameter of swordfish's caudal fin by the method of experimental optimization. The experiment result shows that the smaller aspect ratio may have grater propulsion (R2 much bigger than R1, aspect ratio close to 2) when the swing frequency above the 2Hz and the increasing aspect ratio may enhance the propulsion when the swing frequency below the 2Hz.

Keywords: Propulsion; Lunate Caudal Fin; Optimization; Swordfish

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1. INTRODUCTION

The general methods fish swim are the following three categories (Breder, 1926): first, the anguiliform which is named after the swimming of the eel; second, the carangiform, where the front part of the body has little flexibility and the flexural movements are confined to the rear half or the rear one-third of the body length; third, the balistiform, where the propulsion is caused by the synchronized movements of dorsal and anal fins, while the body and the caudal fin are held rigid, by which the latter is of no direct use for the propulsion of the fish.

G.I. Taylor is one of the early investigators of the swimming of aquatic animals. He developed a so-called resistive theory. A bending wave travels with constant speed along the body of the animal (Taylor, 1952). This theory is suitable for the swimming of snakes, leeches and so on.

Lighthill M.J. (Lighthill, 1960) determined what transverse oscillatory movements a slender fish can make, which will give it a high propulsive efficiency. The procedure is for the fish to pass a wave down its body at a speed of around of the desired swimming speed, the amplitude increasing from zero over the front portion to a maximum at the tail, whose span should exceed a certain critical value, and the waveform including both a positive and a negative phase so that angular recoil is minimized.

Wu (WU, 1971) seeks to evaluate the swimming flow around a typical slender fish whose transverse cross-section to the rear of its maximum span section is of a lenticular shape with pointed edges, such as those of spiny fins, so that these side edges are sharp trailing edges, from which an oscillating vortex sheet is shed to trail the body in swimming.

A consistent slender-body approximation is developed by J. N. Newman & Wu (Newman &WU, 1973). The flow past a fish- like body with arbitrary combinations of body thickness and low-aspect-ratio fin appendages, but with the fins confined to the plane of symmetry of the body. Attention is focused on the interaction of the fin lifting surfaces with the body thickness, and especially on the dynamics of the vortex sheets shed from the fin trailing edges. This vorticity is convected by the (non-lifting) flow past the stretched-straight body, and departs significantly from the purely longitudinal orientation of conventional lifting-surface theory.

Cheng, Zhuang and Tong (CHENG et al., 1991) researched the swimming of a flexible rectangular plate of finite span numerically, hence it partly shows to which extent the analytical two-dimensional theory of Wu (Section 11) is valid for finite span. The considered plate has chord-length 1, the incoming velocity in the x-direction is given by U = 1. The prescribed motion of the plate has the form $h(x, t) = xm \cos(\omega t - kx)$, where $m = 0,1,2$ or 3, $\omega = 8$ and $-3 \leq k \leq 7$. One of the remarkable results is then that the efficiencies of these swimming plate motions are only very weakly dependent on the aspect ratio A which are considered for A = 0.5, A = 1 and A = 8.5. The dependency is increasing somewhat with m, where for m = 3, contrary to expectation, the efficiency is slightly decreasing with increasing values of A.

Almost all fish swim at a high speed swim at the second form. They have the similar lunate Caudal Fin, and Oscillating the caudal Fin and a tail peduncle to obtain propulsion. Some fish swim at second form are showed in figure 1. The top speed they can reach is showed in table 19.

Swordfish is the fastest fish in the world, with the highest speed of 110km/h. Depending on the swing of the caudal fin, swordfish gets the power of swimming. The caudal fin of the swordfish is in the form of crescent and the spreading exceeds the highest part of the body. The unique caudal fin of the swordfish and the way of swing are the main reasons for swimming fast.

The propulsion mode of caudal fin has such advantages as high efficiency, good applicability in water areas, little disturbance to the flow, low noise, etc. The mode is especially suitable for the propulsion of biomimetic robot fish, underwater robots, and so on.

[9] http://www.speedofanimals.com/animals/swordfish.

The present study aims to reveal preliminarily the highly efficient propulsion mechanism of the caudal fin of swordfish through studying and testing the relationship between structure parameter of swordfish's caudal fin as well as way of movement and propulsion speed.

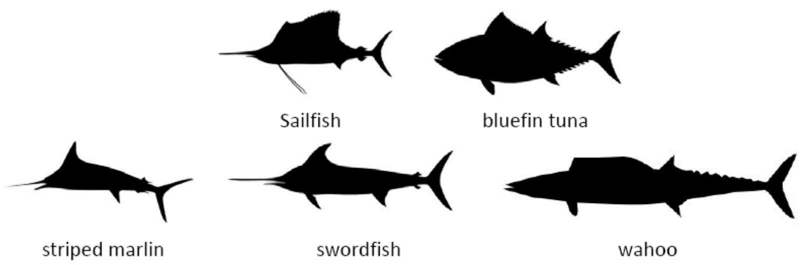

Fig. 1: Some high-speed fishes

Table 1: The top speed of some fish

Categories	Sailfish	Bluefin tuna	Striped marlin	swordfish	wahoo
Top speed (mph)	60.3	43.5	50.3	68.4	47.8

2. CONDITIONS FOR EXPERIMENT

2.1 Equipment for Experiment

The experiment of caudal fin propulsion optimization is carried out in the circular pool, with the diameter of 2m and the depth of 1.2m. A vertical axis is fixed in the center of the pool. The experiment boat is connected with the vertical axis through the rotary arm. Surrounding the vertical axis, the boat is made to navigate levelly by relying on the swinging of the caudal fin.

The knuckle mechanism is used to realize the swing of the caudal fin. The oscillation frequency is adjusted according to the rotational speed of the drive motor. Two kinds of oscillation frequencies, namely 1.5Hz and 3.5Hz, are used in the experiment. The length of the crank is adjusted in order to regulate the oscillation amplitude between 80mm and 120mm in the experiment. The rotation angular velocity of the rotary arm is measured by photoelectric sensor, and then the circumferential velocity of the experiment boat is obtained. Figure 2 is for the tank experiment device, and Figure 3 for the swing mechanism of the caudal fin.

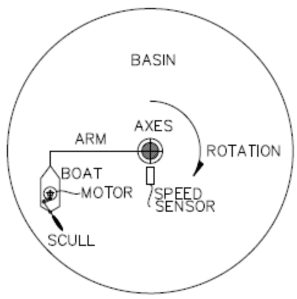

Fig. 2: Experimental Device for Caudal Fin Propulsion

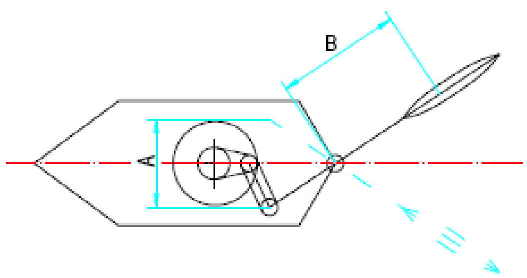

Fig. 3: Schematic Diagram of the Oscillating Structure of the Caudal Fin

2.2 The Design and Manufacture of the Experiment Sample of Imitating Swordfish Caudal Fin

The caudal fin of swordfish, whose length-to-width ratio is between 5 and 7, is in the form of the crescent. Two circles are intersected to form crescent-shaped structure. The diameters of the two circles are named as

R1 and R2 respectively, whose values are shown in Table 2 and structures in Figure 5 and Figure 6. The appropriate center distance is selected so that the crescent-shaped intersection area is 4000 mm2.The centers of the crescent-shaped interaction areas are different, so caudal petioles with different length are designed for every caudal fin sample according to the position of the centroid, with the purpose of ensuring the equivalence of every distance from the centroid to the swing pivot.

The three-dimensional model of the experimental sample is made according to the designed geometry parameters with the help of the three-dimensions rapidly forming system. The material of the experimental sample is the ABS engineering plastics.

Table 2: Parameters of the Caudal Fin Structure

number	01	02	03	04	05	06
R_1(mm)	100	90	80	70	60	50
R_2(mm)	100	150	200	250	300	350
R_2-R_1(mm)	0	60	120	180	240	300

Fig. 4: The Caudal Fin of Swordfish

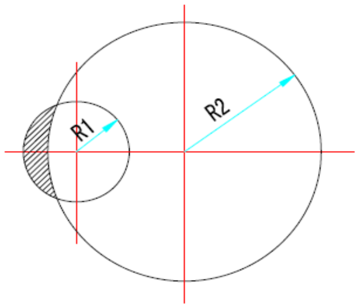

Fig. 5: Geometric Parameters of the Crescent-shaped Caudal Fin

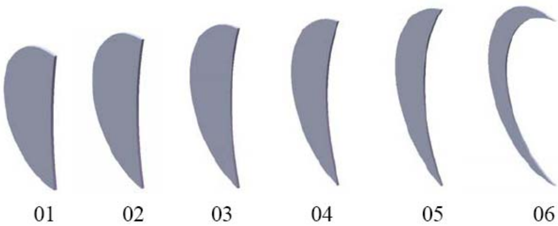

Fig. 6: Structures of the Crescent-shaped Caudal Fin with the same area but different Geometric Parameters

2.3 Parameters of the Experimental Environment

The temperature of the water in the experiment is 21.5 degree Centigrade. The indoor temperature is 25.5 degree Centigrade. The specific gravity of the water is 0.99g/mm3.

3. SCHEME AND RESULT ANALYSIS OF THE EXPERIMENT

3.1 Scheme of the Experiment

Through analyzing the factors which affect the propulsion performance of the swinging caudal fin, three factors are taken into consideration in the present experiment, including the shape parameter of the caudal fin (R2-R1), the swing frequency (F) and the swing amplitude (A). The interaction of the three factors is not considered. The L12(61×22)orthogonal experiment design is selected to arrange the experimental program. The navigation speed of the ship model is the index of the experiment. Levels of each factor in the experiment are shown in Table 3. Each test point is repeated for three times.

3.2 Scope of the Experimental Factors

With the size of the model boat and the volume of the sink taken into consideration, the parameters of caudal fin model are listed in Table 2, showing that the maximum ratio of the spreading is 8.3 and the minim ratio 1.9. Considering the oscillating frequency of the caudal fin when the fish is cruising and fast swimming respectively, as well as the characteristics of the sample's swing, we choose 1.5Hz and 3.5Hz for the swing frequency, and the scope from 60 to 90 degrees for the wing angle, or from 80mm to 120mm for the swing amplitude.

Table 3: Levels of Factors Selected for Orthogonal Experiment

Level	A Shape Parameter（R2-R1）	B Frequency(Hz)	C Amplitude(mm)
1	0	1.5	80
2	60	3.5	120
3	120		
4	180		
5	240		
6	300		

3.3 Experiment Results and the Range Analysis

The results are showed in figure 7-9, and the range analysis are showed in table 4.

Table 4: Experiment Scheme and the Range Analysis of Experimental Results

No.	A (R2-R1)	B Frequency (Hz)	C Amplitude (mm)	Index Speed (m/s)
1	60	1.5	80	0.398
2	240	1.5	120	0.443
3	240	3.5	80	0.475
4	60	3.5	120	0.726
5	180	1.5	80	0.413
6	0	1.5	120	0.538
7	0	3.5	80	0.608
8	180	3.5	120	0.697
9	120	1.5	80	0.552
10	300	1.5	120	0.426
11	300	3.5	80	0.456
12	120	3.5	120	0.762
y_{j1}	1.146	2.77	2.902	$\bar{y} = \frac{1}{12}\sum_{i=1}^{12} y_i = 0.541$ Primary and secondary factors : A, B ,C Excellent level : A_3, B_2,C_2 Optimal combination A_3 B_2C_2
y_{j2}	1.124	3.724	3.592	
y_{j3}	1.314			
y_{j4}	1.11			
y_{j5}	0.918			
y_{j6}	0.882			
Av.(y_{j1})	0.573	0.462	0.484	
Av.(y_{j2})	0.562	0.621	0.599	
Av.(y_{j3})	0.657			
Av.(y_{j4})	0.555			
Av.(y_{j5})	0.459			
Av.(y_{j6})	0.441			
R_j	0.216	0.159	0.115	

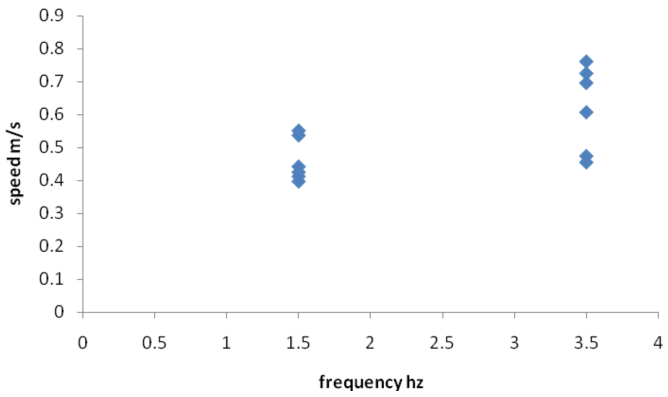

Fig. 7: Speed as a function of frequency

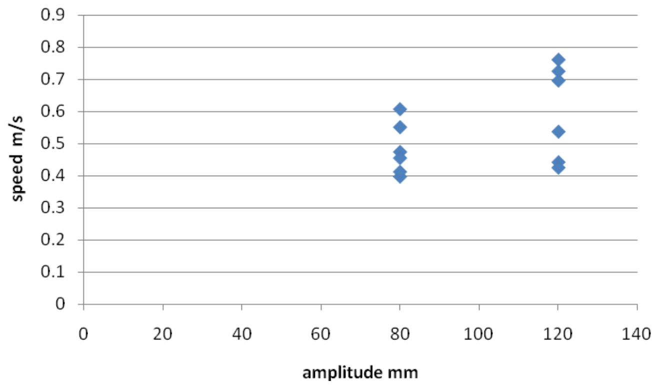

Fig. 8: Speed as a function of amplitude

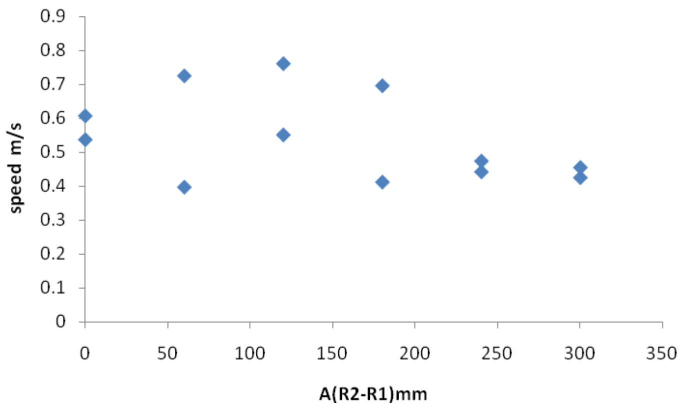

Fig. 9: Speed as a function of A=R2-R1

4. RESULT ANALYSIS

The results obtained by using the method of range analysis are listed in Table 4. As is shown in Table 4, the order of the primary and secondary factors is A, B, C and the excellent level is A3B2C2.The analysis of variance and the results are shown in Table 5.

The ratio F can be calculated according to the formula:

$$F_A = \frac{S_A / f_A}{S_e / f_e} = \frac{\hat{\sigma}_A^2}{\hat{\sigma}_e^2}, \text{ where } S_e = S - S_A - S_B - S_C .$$

From the table for the analysis of the variance, it can be seen that Factor A, B and C are all primary, and the results are more sensitive to B and C compared with A. According to the results of the comprehensive range analysis and the analysis of variance, the Primary and secondary order of impact factors is B, C and A from. The optimal combination is B2C2 A3.

Table 5: The Variance Analysis of the Experiment Results

Source of variance	Total Sum of Squares: S	Degree of Freedom	*Mean* Sum of *Square*	value of F	*Critical* Value	Level of Significance
A	0.063678	5	0.0127356	12.511	$F_{0.05}(5,4) = 6.26$	0.05
B	0.075839	1	0.075839	74.5	$F_{0.01}(1,4) = 21.2$	0,01
C	0.0396713	1	0.0396713	38.97	$F_{0.01}(1,4) = 21.2$	0,01
Deviation (e)	0.033504	4	0.008376			
Total Sum	0.2126923	11				

5. CONCLUSION AND PROSPECT

The impetus of the thing like swordfish's caudal fin is related to geometric parameters of the crescent caudal fin, whose swing frequency and amplitude have great impact on the propulsion. Under the experimental condition, if the oscillating frequency and amplitude are intensified, the impetus would increase significantly. The results show that if the frequency and amplitude are at the same level, the optimized structure of the caudal fin can improve the impetus.

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