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Performance Analysis on Biomimetic Fin with Cupping Base and Cupping Ratio Variation

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***Abstract*—**Research on fish locomotion has been widely conducted since the last two decades, but the effect of fish tail cupping shape when swimming is rarely discussed in detail [2][3][4]. In this paper, a model is proposed for a rounded shape caudal fin with a rear profile made to simulate a cupping phenomenon shape. The models are made to simulate cupping phenomenon in various cupping parameter setting. The model is then used to run a CFD simulation to find their respective cruising speed, where drag equals thrust produced. Performance parameter that will be observed in this paper is thrust generated, based on the cruising speed and efficiency. From the data obtained we can figure out the relation between performance and cupping parameters. The result is expected to help future research or optimization of existing fin designs. Other performance category such as efficiency and noise generation is not included in this paper.

***Keywords*—**Fin, cupping, efficiency, thrust, cruising speed.

I. INTRODUCTION

MANY scientists have begun the studies in regard of alternative underwater propulsion. These studies are started due to the growing concern of the human generated underwater noise harmful effects on marine wildlife, which ship propellers contributed quite a large part to it [1]. Other than noise generation, thrust capability and efficiency are also major research point that is actively pursued. Fin is the more common alternatives that are widely studied today. The idea is to mimic the way fish travels underwater using its fins. Fin propulsion is said to have efficiency more than 80% [4]. Some fish have extraordinary maneuverability, some other excel in long distance cruising or high speed cruising [2]. These traits depend on each of their unique fin shape and motion types. During motion, the rear end of the fish fin bends to form the “C” shape (**Figure 1**), this phenomenon which is known as cupping. The variations in cupping is identified by the cupping ratio or c/L (**Figure 1**), where c is the deflection on the midpoint of the fin’s span and L is the distance between the two tip of the fin after contraction. Cupping shape fin produces higher velocity vortices, and a smaller, but higher velocity jet as the fin swept through the water. This result in the higher thrust produced by the cupping fin compared to the flat fin [5]. In this paper we will discuss the effect of various cupping configuration to the amount of thrust generated and efficiency of the said fin using ANSYS® CFX Simulation. A fish body model (**Figure 2**) will be used to imitate a natural swimming condition of the fluid flow around the fish body and fin in the simulation. The fish body model that we make doesn’t have pectoral fins, dorsal fin and anal fin like real life fish for simplification reason. The dimension of the fish body is 0.32m×0.54m×0.46m (length × max high × max width). In the simulation the fin’s movement will be independent from the body to simplify the simulation.

II. FIN MODEL DESIGN

A. Rounded Shape Fin

The effect of cupping phenomenon is more apparent on fish with rounded fin. Thrust generated by rounded fin is greater than other shapes, coupled with thrust increasing characteristic of cupping phenomenon will make changes on thrust caused by the stiffness and cupping ratio variation more apparent [3]. Rounded shape fin also simplify the design and making of the 3D model with the stiffness variations.

B. Fin dimensions

For the simulation to be valid we will make models that represent identical fins with different rear end profile during the swimming motion. The fin model is generated using SolidWorks® 2014. As shown in the drawing (**Figure 3**), the length is 180mm measured on the fins axis. The span is 150 mm on idle state and contracted during cupped state. The front interface of the fin is an ellipse with 25 mm major axis and 22 mm minor axis. The rear end face of the fin has 3mm thickness. This base model with no span contraction will be used as comparison where the fin is completely stiff.

C. Cupping Base Axial Position

Cupping Base or C_b is the section where the cupped shape starts to form on the fin. The axial position is measured from the stem of the fin. The number 0 will show that the cupped shape formed right from the stem, 0.2 means that the cupped shape starts at 0.2 fin length position and so on. We will use four variations on the model (**Figure 4**) which is 0.0, 0.2, 0.4, and 0.6.

D. Cupping Ratio Variation

The cupping ratio or CR (c/L), where c is the furthest point from the straight line between the tips of the fin in the cupping shape and L is the length between the tips of the fin will be used

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as the fin variation. The cupping ratios used are 0.1, 0.15, 0.2. Each variation has different c and L to accommodate the span constraint of 150 mm during idle position.

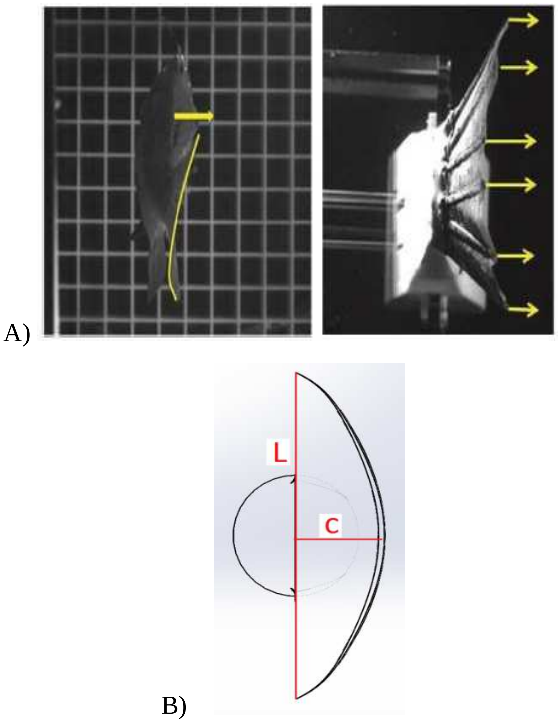

Figure 1 A) Cupping motion on fish caudal fin. Pictures are taken from [3], B) cupping fin shape

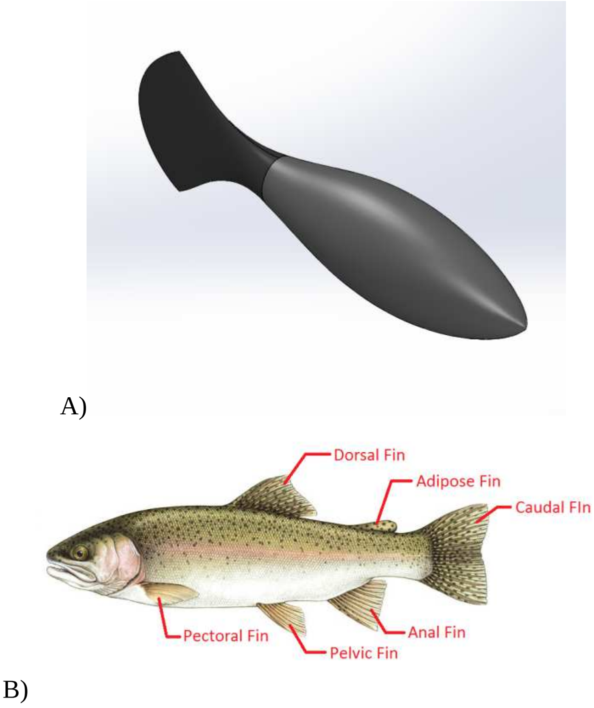

Figure 2 A) Fish body model, B) image of trout, taken from http://blogs.courierpostonline.com/fishhead/2008/10/15/20000-trout-set-free/

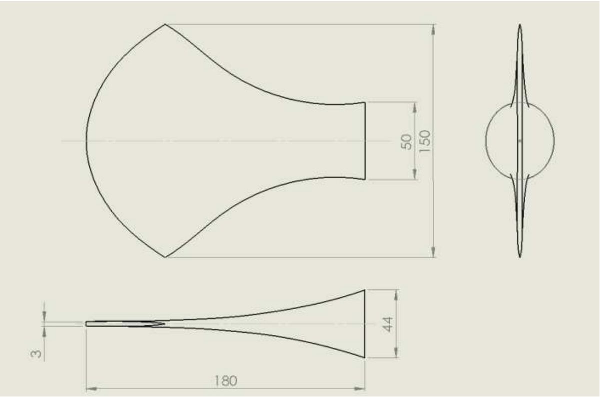

Figure 3 Base fin model dimensions

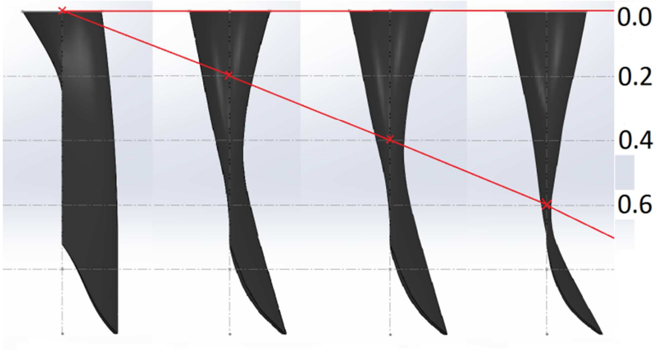

Figure 4 Cupping base position along symmetry axis

III. SIMULATION PARAMETERS

E. Simulation Environment

The fin is the simulation is conducted using the Ansys® 15 Software. There are 13 3D models in total, which include the base model and 12 combinations of cupping base position and cupping ratio. All of the models are subjected to the simulation using some predetermined parameters. Enclosure is generated around the fish model using ANSYS® 15 software to serve as the water tunnel for the simulation environment. The dimension of the enclosure made is 2 m × 0.75 m × 0.75 m. The Axis of the fish body is located at the center of the cross section and the distance between the fish head and the inlet is 0.5 m. The simulation is conducted on three different water velocity i.e. 0.5 m/s, 0.6 m/s and 0.7 m/s in the X positive direction, against the fish head direction.

F. Defining of the Motion of the Fin

Fish body and tail model are imported to ANSYS® 15 FEA Solver. The fin is rotated with amplitude of 20^{o} and going through half wave cycle from midpoint to extreme lateral position and back. The time period of the full wave cycle is 3 s. The movement type of the fin will be based on *Subcarangiform* swimming where one third of the fish moves to create thrust.

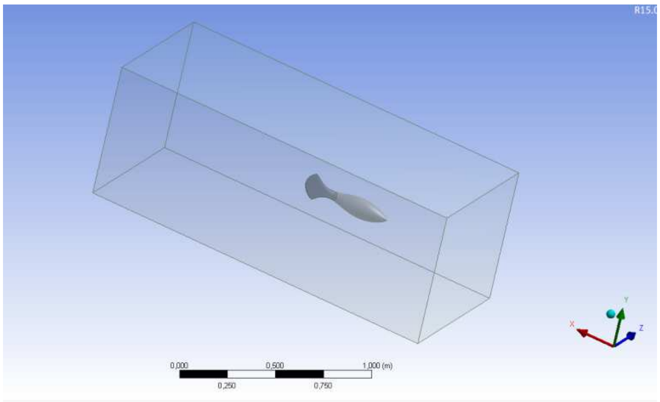

Figure 5 Fish inside the enclosure

G. *Observed Parameters*

The movement simulated on ANSYS® 15 FEA Solver is then imported to the CFX Solver to be analyzed. We monitored 3 parameters in the simulation, total force working on the body part along x axis, total force working on the fin part along x axis and total y axis moment working on the fin part.

To evaluate the thrust produced we use cruising speed as the representation. At cruising speed the fish model didn't accelerate or decelerate which means the net force sums up to zero (thrust produced is same as drag experienced). Drag increases as speed increases. This means that higher thrust is produced if the fish model is cruising at higher speed. After running the simulation at three different speeds mention in the previous section the net force data is then interpolated using second order polynomial function to obtain the speed at zero net force or cruising speed. The simulation for that particular model is then conducted again using the cruising speed obtained from the interpolation. This step is done to the other models to obtain their respective cruising speeds and parameters on said cruising speed.

Efficiency is the ratio of useful power (thrust times forward velocity) divided by the power expended by the fish the fin [4]. The forward velocity used varies for each model of the fin according to their parameters. The power expended is the result of total moment working on the fin times the angular velocity of the fin (calculated from the tail beat amplitude and frequency). The data is then collected and plotted into a graph with Microsoft® Excel program.

The data presented in the graph uses a dimensionless ratio of a particular model's cruising speed compared to the cruising speed of the base model. The efficiency is also presented this way to emphasize more on the effects of cupping configuration than the exact number alone.

IV. SIMULATION RESULTS

The graph (**Figure 6**) shows cruising speed ratio (cruising speed divided by cruising speed of the base model) represented by the red bars, efficiency ratio (efficiency devided by efficiency of the base model) using the green bars and thrust ratio (thrust devided by thrust of the base model) as the blue bars.

A. *Efficiency*

Data showed on the graph didn't show any significant change, but overall efficiency increases as C_b increases and decreases as CR increases. The efficiency ratio on all cupping configuration is lower than 1 which means that efficiency is higher on base model. On 0.15 and 0.2 CR efficiency at C_b = 0.4 dropped compared to the efficiency at $C_b = 0.2$ opposed to the overall increasing trend. The highest efficiency achieved at this simulastion is 90.2% using the base model, with the difference of 20,5% in efficiency compared to the lowest efficiency model with 0.20 CR, 0 C_b which has 69,7% efficiency. Increase in efficiency caused by the cupping base configuration is not too significant, ranging from 5%-8% difference between fin with $C_b = 0$ and $C_b = 0.6$.

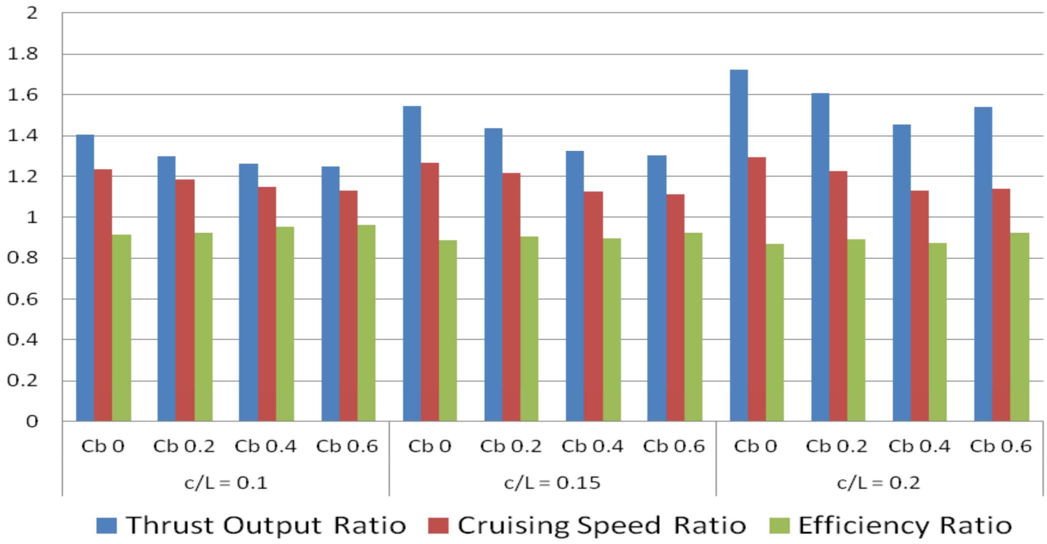

Figure 6 Simulation result graph

B. *Thrust and Cruising Speed*

The trend that occurred on the graph suggests that maximum thrust generated decreases as C_b increases and increases as CR increases. Maximum thrust is highest at 0.2 CR with $C_b = 0$. Thrust increases from $C_b = 0.4$ to $C_b = 0.6$ at 0.2 CR by 10,5% unlike the other data which show consistent decrease. Cruising speed also decreases as C_b increases similar to thrust. The highest thrust output is generated from c/L = 0.2 and $C_b = 0$. The highest thrust generated is 2.37 N, 72.5% higher than the thrust of the base model. Compared to the change in efficiency, change in thrust is much more apparent. Change in thrust goes up to 18% from one C_b configuration to another excluding the base model.

C. *Analysis*

Increase in thrust is caused by the higher velocity vortices, and a smaller, but higher velocity jet produced by the cupping shape of the fin [5]. Efficiency increase when C_b increase is caused by the decrease in required power move the fin. The decrease on cruising speed also decreases the drag as it also directly proportional to the cruising speed, same as thrust. With this decrease in drag the moment working on the fin also decreased which also reduce the required power. Efficiency obtained from this simulation is similar with result in [4].

V. CONCLUSION

In this paper, a computational fluid dynamic model was built for a biomimetic rounded shaped fish fin. Model of the fish body is simplified by removing the other fins on the main body. Performance parameter data of the fin that is observed in this paper such as maximum thrust and efficiency have been obtained and relations between these performance parameters and cupping configuration have been concluded.

To maximize thrust use fin with smaller C_b and higher CR. To maximize efficiency use fin with higher C_b and smaller CR. Maximum efficiency is obtained using the base model at the cost of thrust produced. Change in efficiency caused by the C_b and CR is not too significant. Thrust is highly affected by the change in cupping configuration, this means C_b and CR need to be considered carefully during the design process to optimize the thrust produced.

In future research more accurate model can be used in the simulation to produce more reliable result. Experiment using fin made using current configuration (dimension and cupping configuration) will be done to verify the data obtained in this simulation. The fin that will be made expected to have the same form as the model from this simulation when it is flapped in the water tunnel. Four different fin types (round, truncate, forked and semi lunar) are going to be made for future experiment. Carbon fiber reinforcements will be embedded in the fin made from silicon rubber (**Figure 7**).

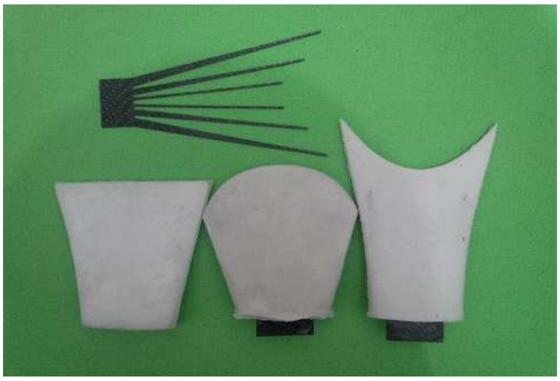

Figure 7 Fin made of silicon rubber and carbon fiber reinforcement

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