MODIFICATION OF HULL DESIGN INSPIRED BY SAILFISH

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SYNOPSIS

Modification of hull design for improving performance and resistance in a ship has been of interest to ship building industries for decades. In the present study hydrodynamic analysis of morphological adaptations in sailfish having v-shaped protrusions on its skin has been done. The paper shall discuss a hull design integrated with v-shaped protrusions, inspired from sailfish. A quantitative analysis will be discussed with simulation proofs worked on Computational Fluid Dynamics (CFD) software. CFD results for total hydrodynamic resistance with detailed pressure distribution, velocity distribution, boundary layer separation are presented. The final result is an optimized hull form which shows interesting characteristics, as its overall resistance has decreased in respect to a conventional hull.

*Keywords**:** ship hull modification, sailfish, CFD, biomimicking, drag reduction, anti-fouling.*

1. INTRODUCTION

1.1. MOTIVATION

In an engineering structure there is a close relationship between its shape and its performance. Hydrodynamic performance specifications such as resistance and propulsion are determined by the hull form, in case of ship. It's very important to choose a hull form with righteous performance in the initial phase of design. Many researchers and designers have tried to optimize hull forms for example: - reverse bows, ram form titan class seismic vessels and batik icebreaker, to suit their requirements.

Since decades humans have tried to mimic characteristics of living organisms to enhance the performance of manmade systems and enhance the quality of their life, as Bar-Cohen said "through evolution, nature has experimented with various solutions to challenges and has improved upon successful solutions" (Bar-cohen, 2005). Biomimiking is what it is termed as, meaning imitating and learning from nature's methods, designs and process to enhance the performance of engineering systems. Based on this premise, a ship hull can be designed

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inspired from nature to tackle today's maritime problems.

Another serious problem the marine facing today is biological fouling commonly referred to as **biofouling**. More than 4000 kinds of marine biofouling species have reported globally (Cao, 2008)which adheres, grows and reproduces on the ship's hull causing adverse effects such as higher fuel consumption, rough hull surface, increase in weight and susceptible to corrosion. at nature for antifouling lessons reveals that, in the marine environment plants, corals and fish employ several physical and chemical controls which include low adhesion, low drag, microtexture, sloughing and grooming and various secretion.

Being the largest predators in the ocean, Sailfish (*istiophoridae*) have been known as the fastest fishes among sea animals with a maximum speed of 110 km/hr. From postulations it has been believed that the drag reducing adaptations have evolved in these fishes to reach such speeds and reduce energy requirement for locomotion. Hydrodynamic characteristics of a fish such as drag friction and flow separation are governed by the boundary layer flow above its surface. It has been conjectured that boundary layer flow over sailfish are turbulent at their maximum speeds, and turbulent boundary layer exist even at low speeds (Woong Sagong, 2013). Therefore in order to understand their hydrodynamic characteristics, body surfaces have to be analyzed through simulations. Amusingly, when observed it was found that the adult sailfish has numerous **v-shaped protrusions (VSP)** on its skin.

Therefore in our study we investigate the role of these VSP in increasing hydrodynamic characteristics in these fishes and simulate a hull design encouraged from sailfish.

1.2. SCOPE OF WORK

The objective of this research is to attain hydrodynamic characteristics of a modified hull design integrated with VSP.

This research would comprise of:-

1. Detailed study of role of VSP on sailfish.

2. Designing hull model in SOLIDWORKS.

3. Performing CFD analysis in ANSYS FLUENT for hydrodynamic resistance and wave pattern, pressure distribution, drag and velocity distribution.

4. Discussion and analyzation of achieved results.

5. Study on antifouling surface integrated with VSP's.

2. HYDRODYNAMIC CHARACTERISTICS OF SAILFISH

On May 14 2013 Woong Sagong, Woo-Pyung Jeon and Haecheon Choi conducted experiments on euthanized sailfish specimens and investigated the hydrodynamic characteristics of the sailfish at their cruise speeds by placing taxidermy specimens in a wind tunnel, probing the boundary layer velocities above the body surfaces and directly measuring the drags on the bodies. The drag coefficients of the sailfish at the cruise conditions were about 0.0075 based on the free-stream velocity and wetted area respectively, which is significantly smaller than those of swordfish , dogfish, small size trout, tuna and pike. They also found that turbulent boundary layer flows exist over most of the body surfaces even at their cruise conditions and flow separation doesn't occur on the whole body surfaces. In addition, their drag reduces remarkably when all of the fins are depressed or attached to the body whenever it moves fast to catch a prey. The drag increases by about 25% and wetted area increases by 6% in the presence of fins, since the fins generate the form drag and interference drag between the body and fins as well as the friction drag. They also mentioned that the angle of attack of the pectoral fins is set to be nearly zero, so in swimming the drag should be even larger because the attack angles are non-zero for lift generation.

The sailfish have noticeable morphological features from those of other fast moving fishes, as shown in Figure 1. Many v-shaped protrusions were found on the body skin. In their research study they have examined the role of these protrusions in delaying flow separation by performing tuft visualization at cruising speeds but didn't notice any considerable change in the drag forces on the body with and without the protrusions.

In their research paper they have also stated that, "the results discussed were obtained at the conditions of cruise speeds in gliding postures. The hydrodynamic characteristics of the sailfish at the maximum speed are important subjects to pursue in the near future."

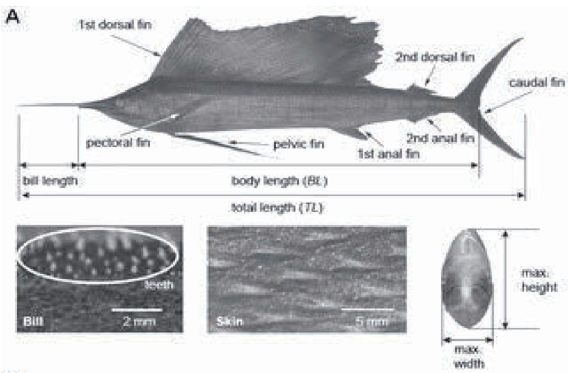

Figure 1: Sailfish body visualization observed by Woong Sagong, Woo-Pyung Jeon, Haecheon Choi(2013).

3. ANALAYSIS OF V SHAPED PROTRUSIONS USING NUMERICAL SIMULATIONS

In order to understand physics of these protrusions and how they aid in boundary layer flow separation we designed various models of v shaped protrusions with varying dimensions and the most appropriate model was adopted as depicted in Figure 2. Numerical simulations have been made on curve plate integrated with the VSP and the results are compared with curve plate without protrusion. The boundary layer thickness was also used in determining the dimensions of VSP. The VSP is placed on the curve plate as shown in Figure 3. The 3D model was developed in SOLIDWORKS designing package. The computational flow analysis was done using ANSYS FLUENT software package. With water as flowing fluid at incompressible speed of 30.5 m/s, the VSP was analyzed using large eddy simulation method with WALE sub-grid scale model and no sub-grid scale turbulent viscosity, by solving the unfiltered form of the Navier–Stokes equations with the 5th order Bandwidth-optimized WENO scheme, which is generally referred to the so-called implicitly implemented LES. The adiabatic, zero-gradient of pressure and non-slipping conditions is adopted at the wall. Taking chord of the curve plate as characteristic length, the Reynolds number was found to be 193,326 for free stream velocity of 30.5 m/s. The inlet turbulence intensity was set to be 5%.

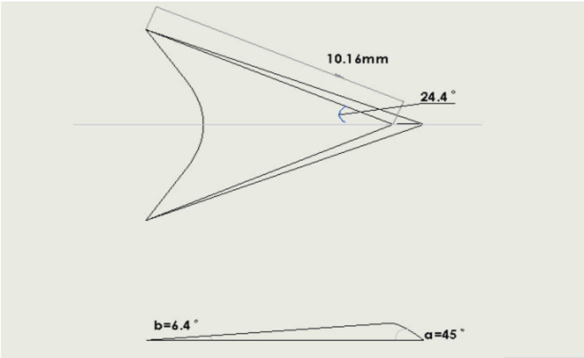

Figure 2: 2-D schematic diagram of v shaped Protrusion

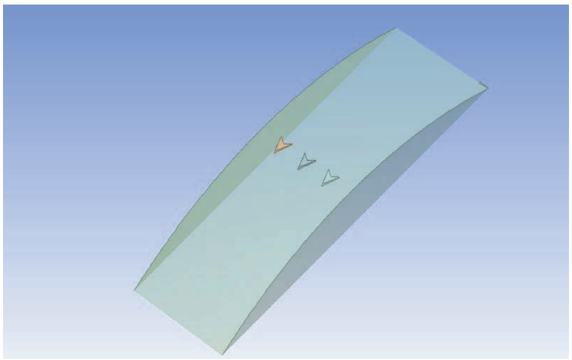

Figure 3: Curve plate with VSP

3.1. FLOW FIELD VISUALIZAITON

In investigating the effectiveness of VSP on curve plate, the flow field was visualized along the spanwise direction for both curve plates with and without VSP as shown in Figure 4.(a),(b). The velocity contour, velocity streamline , velocity vector and velocity isosurface has been compared for both the versions as shown in Figure 5.(a),(b) , Figure 6.(a),(b) , Figure 7.(a),(b) , Figure 8.(a),(b).

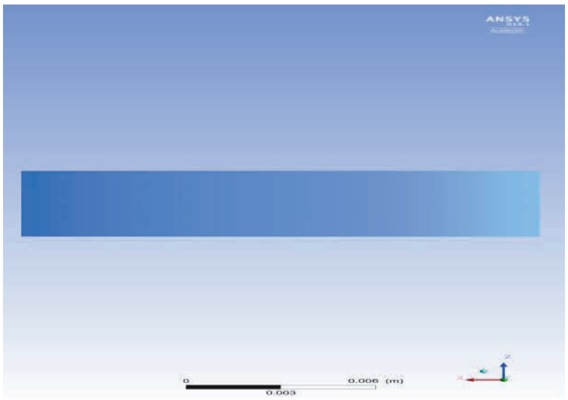

Figure 4.a: Curve plate without VSP

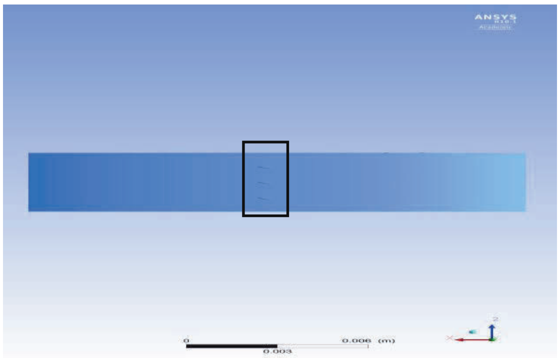

Figure 4.b: Curve plate with VSP

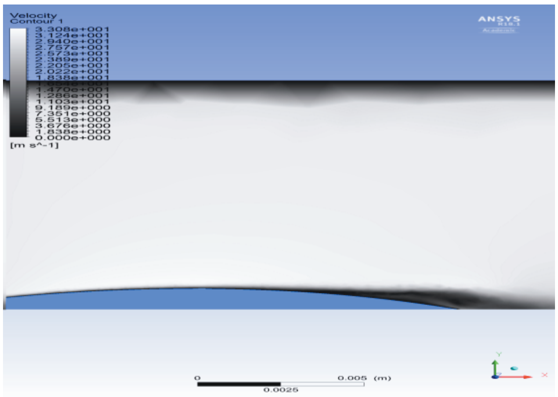

Figure 5.a: Represents the velocity contour on curve plate without VSP

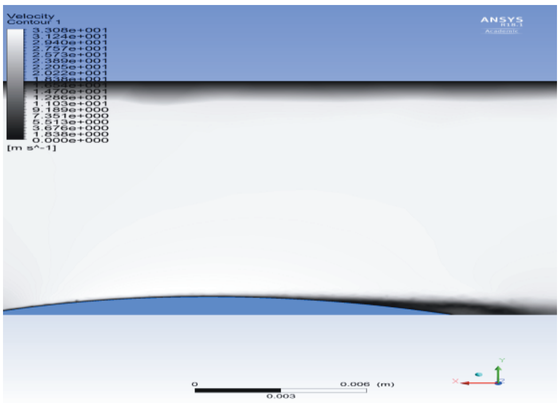

Figure 5.b: Represents the velocity contour on curve plate with VSP.

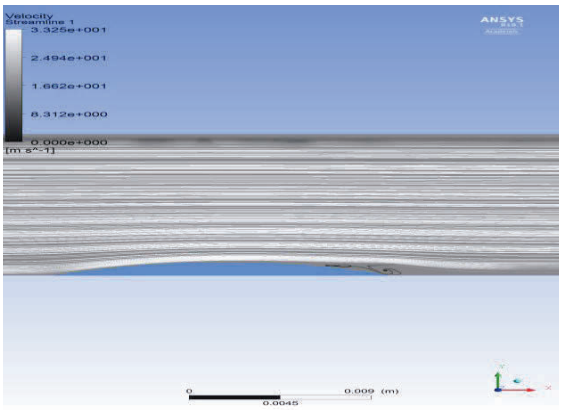

Figure 6.a: Represents the velocity stream-line on curve plate without VSP.

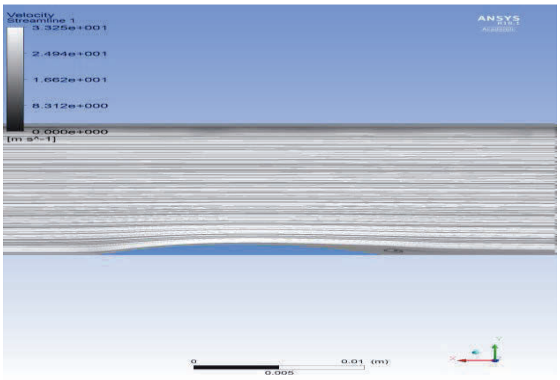

Figure 6.b: Represents the velocity streamline on curve plate with VSP.

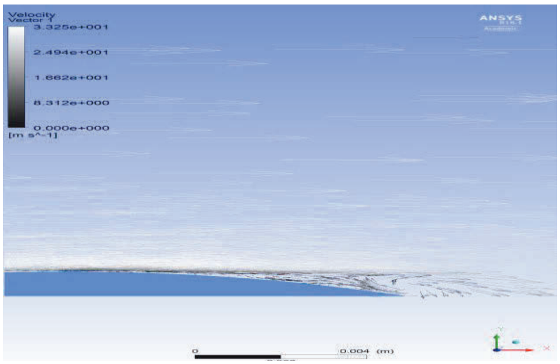

Figure 7.a: Represents the velocity vector on curve plate with without VSP.

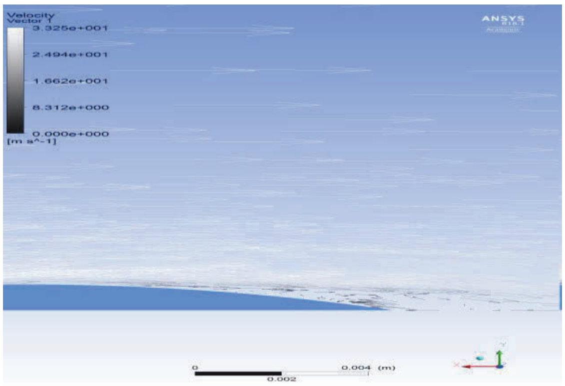

Figure7.b: Represents the velocity vector on curve plate with VSP.

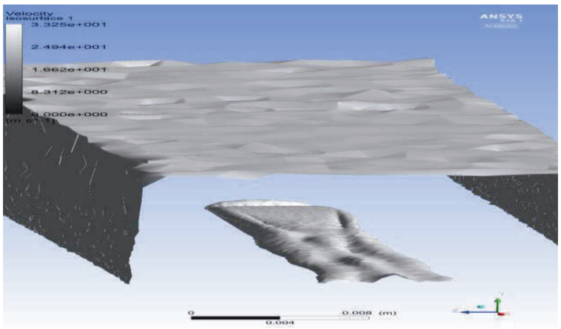

Figure 8.a: Represents the velocity isosurface on curve plate without VSP

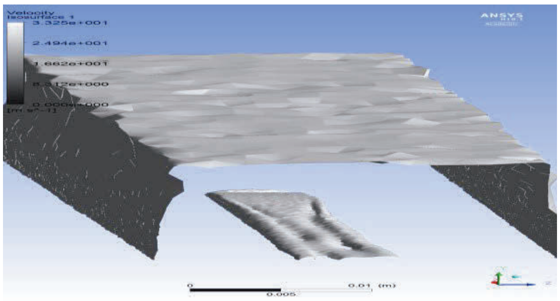

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Figure 8.b: Represents the velocity isosur-face on curve plate with VSP.

From the above flow physics analysis it can be seen that a large recirculation zone exist over curve plate without VSP near trailing edge due to boundary layer separation caus-ing due to vortices created. However, once the VSP's were employed on the surface the flow field on the surface of curve plate changed. The VSP seemed to delay the boundary layer separation, reduced the boundary layer thickness in the flow past them and hence suppressing the recirculation zone. For fixed Re the value of Cd was observed to be less in curve plate with VSP indicating the reduction of drag force.

4. CFD Analysis of Resistance characteristics of optimized hull form integrated with VSP

The hull form used for analysis is created in SOLIDWORKS software where the bow design is inspired from sailfish bill as shown in Figure 9 and Figure 10.Two types of hull models will be compared computationally i.e. conventional hull form and modified hull form. The hull models are scaled by a factor 1:30 according to Froude scaling laws to reduce computational effort. The main dimensions of the parent hull form are tabulated in the Table 1.

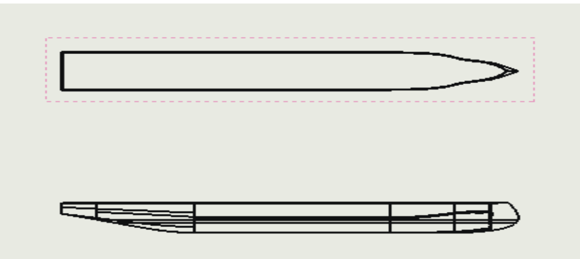

Figure 9: 2D Schematic diagram of hull form

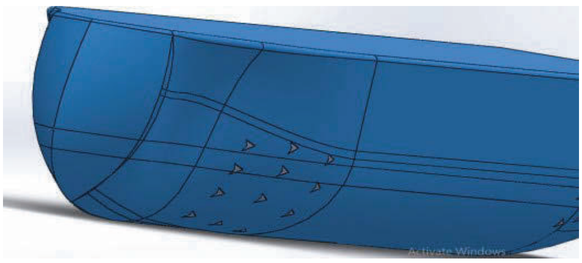

Figure 10: 3D view of hull form with VSP

Table 1. Parameter of the model used for analysis

Parameters	***Full Scale***	***Model Scale***
Overall length	175 m	5.833 m
Waterline length	165 m	5.499 m
Draught	6.3 m	.2099 m
Wetted surface	4125 m^2	4.582 m^2
Beam	25 m	.8325 m
Beam waterline	23 m	.7695 m
Length beam ratio	7 m	.233 m
Speed	10.2889 m/s	1.8775 m/s
Midship coefficient	.725	.725
Block coefficient	.512	.521

4.1. COMPUTATIONAL DOMAIN

The solid body was imported to ANSYS design modeler IGES format as geometry and the domain is created where the fluid medium will flow. The origin is located on a fixed point close to the stern of the hull, on the waterline directly above the hull center of displacement. The x-axis is along the incoming flow direction. CFD software's takes long duration to complete a simulation. Since the model is symmetric, they could be modeled as a half domain along the central longitudinal axis to reduce the computational time. The domain was divided into different regions which were named as inlet, outlet, symmetry and hull so that each region can be studied properly. The inlet was specified at the front of the domain at 1.5 times the model scale and the outlet was named at the rear of the domain at 1.5 times the model scale.

4.2. MESH GENERATION

In order to analyze the flow numerically, discretization of the domain was done using unstructured grid with 4957321 elements and skewness 0.7999. The mesh was slightly inflated near the hull in both controlled and uncontrolled configuration, to obtain a fine quality mesh as depicted in Figure 11.(a),(b). Sufficiently large number of elements was issued at the sharp edges and low curvature points. The hull faces were further refined using face sizing to achieve proximate flow characteristics around hull as shown in Figure 11.c.

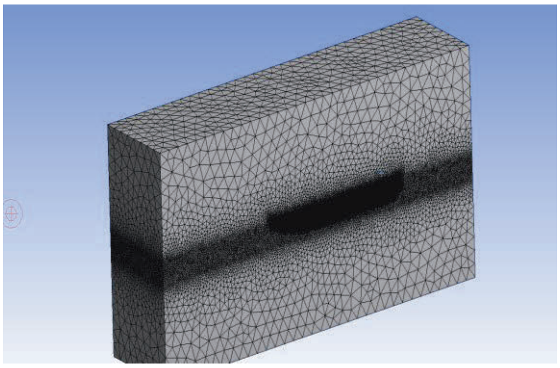

Figure 11.a: Mesh of model

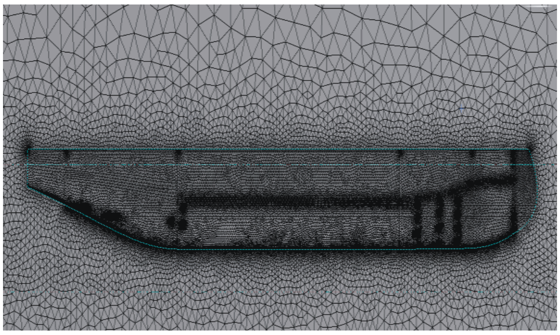

Figure 11.b: Grid around hull

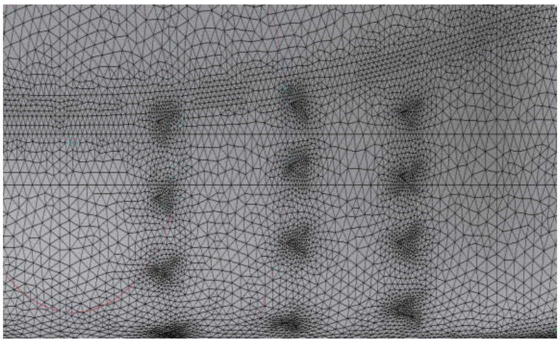

Fig.11.c. Refined mesh around VSP

4.3. SOLUTION SETUP AND BOUNDARY CONDITION

In the following research the computational flow analysis was done using the ANSYS FLUENT software package. The system was considered as a three dimensional implicit unsteady, incompressible, multi-phase, viscous and turbulent flow. The gravitational acceleration is taken in the y direction since the motion of the free surface is governed by gravitational force. Volume of fluid (VOF) formulation is applied in CFD to solve multiphase free surface flows. Multi-phases are chosen for the fluid condition, which is defined as air and water for more practical scenario. The primary phase is set to water, while the secondary phase is the air having lower density. The fluid properties of water are given in Table 2.

Table 2 Fluid Properties of Water

Density, ρ	**998.46 kg/m³**
Kinetic viscosity, □	**1.004x 10^-6m2/s**
Dynamic viscosity, □	**0.001 Pa-s**

The 3D model was analyzed using RANS equations, with a Re=1896580 and 5% turbulence intensity. k-□Model was employed to understand the mechanism which is affecting the turbulent kinetic energy. The model consists of two transport equations, one for the turbulent kinetic energy k and one for the turbulent dissipation rate□. The boundary condition and solution method used in this study are given in Table 3.

Table 3 Boundary condition and solution method

Inlet/Outlet	Pressure inlet/ pressure outlet
Volume fraction	Compressive
Pressure	PRESTO!
Velocity	Field Function
Turbulent kinetic energy	First order upwind
Turbulent Dissipation rate	First order upwind
Transient formulation	First order implicit

5. RESULTS and DISCUSSION

5.1 REDUCTION IN DRAG FORCES

The meshed geometry is analyzed in ANSYS FLUENT by applying the specified boundary conditions and the variation of the flow parameters are plotted and studied.

Flow field near the flow separation point for hull model in the form of velocity vectors is shown in Figure 12, similarly wave distribution and velocity distribution is shown in Figure 13 and Figure 14 respectively, which are presented at a height of .209m(model scale) from the base line.

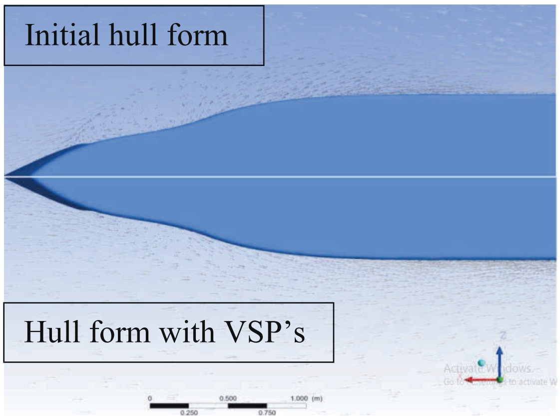

Figure 12: Velocity vector around hull

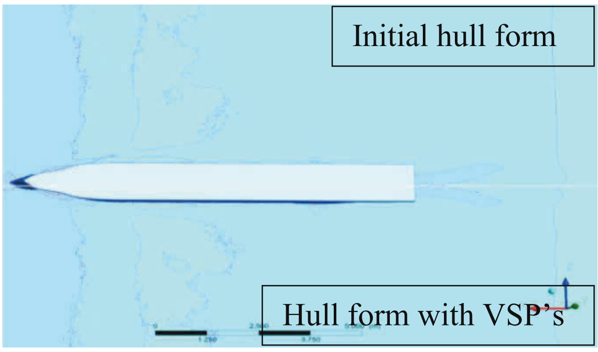

Figure 13: Wave distribution around hull

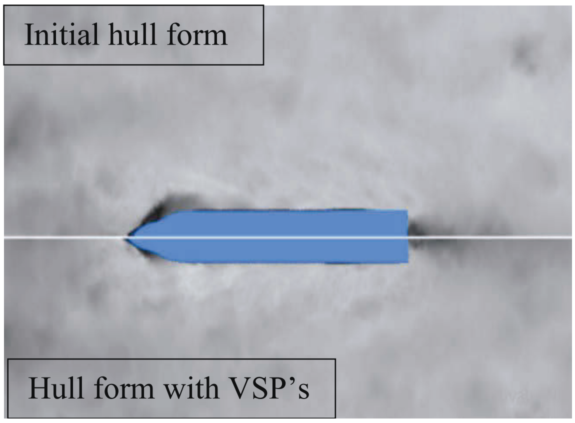

Figure 14: Velocity distribution around

From the above flow physics visualization, it is observed that near the stern of the modified hull (with VSP's) low velocity region is narrowed, boundary layer thickness is reduced, thus formation of eddies or vortices are reduced this inturn decreased the drag force on the hull depicted by Figure 15.

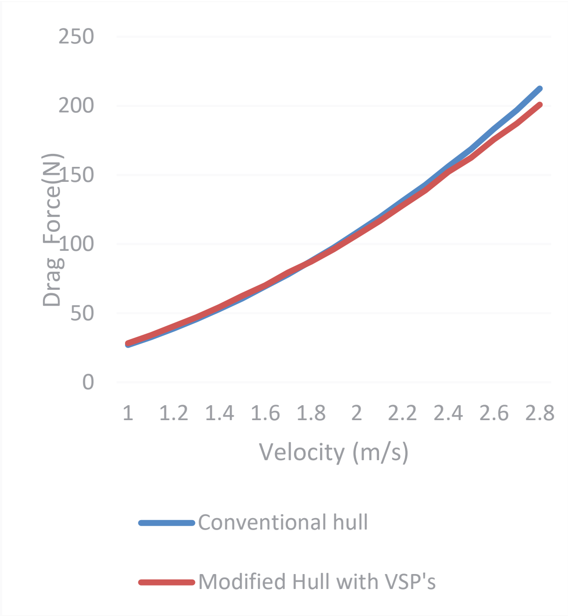

Figure 15: Comparison of total force acting on hull designs with respect to velocity.

From the above result it can be seen that with increase in inlet velocity the reduction of drag force increases on the modified hull. But at initial velocities i.e., lower than 1.69 m/s the drag force on the modified hull was observed to be slightly more than the initial hull design which suggests that the VSP's does not significantly affect the boundary layer thickness and hence the recirculation zone remains the same. Percentage difference in resistance of model varied from -4.43% to 5.8%.

It's notable that the above analysis was done on a particular hull design. Variations in the percentage drag reduction value are expected but the overall reduction in the resistance characteristics will remain same for different styles of hull form.

5.1.1 Explanation

When a ship moves through calm water, a total hull resistance acts on the hull which is comprised of viscous resistance, wave making resistance and air resistance (D.Sen, 2008), which can be written as:

$$\boldsymbol{R}_T = \boldsymbol{R}_W + \boldsymbol{R}_V + \boldsymbol{R}_{AA}$$

$\boldsymbol{R}_T$ = total hull resistance

$\boldsymbol{R}_W$ = wave making resistance

$\boldsymbol{R}_V$ = viscous resistance

$\boldsymbol{R}_{AA}$= air resistance caused by ship moving through calm air.

In our current study we have analyzed the viscous resistance acting on the ship's hull. As a result of viscosity there are two types of resistances that occurs i.e. Viscous Pressure Resistance and Friction Resistance. Viscous pressure resistance acts normal to the body and Friction resistance acts tangential to the body.

The friction resistance is a function of the hull's surface roughness, wetted surface area and water viscosity. The modified hull form (with VSP's) has a greater surface roughness and wetted surface area than the initial hull form. The friction resistance of VSP integrated hull form will be more than the initial hull form, resulting in an increase in overall viscous resistance in case of modified hull(with VSP's) therefore the drag force on the modified hull was observed to be slightly more than the conventional hull design during initial speeds. Experimental data have shown that friction resistance can account for up to 85% of a hull's total resistance at low speed (Ridley, 2014).

At greater speeds the viscous pressure resistance of the modified hull was observed to have decreased significantly due to the integration of VSP's on the hull, than the initial hull form resulting in an over-all decrease in the viscous resistance.

5.2 VSP'S AS AN ANTIFOULING SURFACE

For thousands of years marine vessels have been plagued with issues of bio-fouling, which lead to the invention of different forms of biocides for resisting biofouling organisms (Lee, 2014). Although these biocides are effective, but they can cause extreme hazard to the marine environment. According to International Maritime Organization (IMO), biofouling organisms such as algae, barnacles, and slime that are attracted to submerged surfaces of ship's hull increases drag resistance and decrease speed, resulting 40% increase in fuel costs. (Abbott, 2000)

When observed, these VSP's on the sailfish skin behaves as an antifouling surface to protect itself from bio-fouling. These microtopography on the surface can repel significant amount of algae that comes in contact with the scales. When analyzed, these topography generates mechanical stress on colonizing bacteria known as **Mechanotransduction**. The surface dissimilarity causes Nanoforce gradients creates stress gradients within the lateral plan of the surface membrane of the colonizing microorganism. This stress gradient hampers normal cell functions, forcing the microbes to adjust its contact area on each topographic feature to equalize the stresses. This inturn increases the energy required to adhere and stay under such stress, forcing the microorganisms to seek another place to grow or die. The modified hull structure integrated with VSP's will be extremely efficient against algae, preventing algae and barnacles from attaching to ships. Effectiveness of these nano-scale textures will be observed only when the ship is sailing. But, since the wetted surface area and surface roughness has increased due to the VSP's on the hull therefore biofouling would likely to occur when the vessel is at static condition for a considerable period of time.

Reduction in the quantity of microorganisms adhered to the hull has many advantages aside from being cleaner. It does not require environmentally toxic chemical for cleaning biofilm on ships hull, lowers the amount of invasive species transported from one location to another and will also add in the overall percentage reduction of drag forces hence eliminating the unnecessary costs incurred due to fuel loss.

6. CONCLUSIONS

The future of my work is twofold. We expect that a notable increase in drag reduction will be seen using biometric application of hydrophobic surfaces across the entire surface. Additionally, atomic force microscope studies of the nanoscale surface characteristics on sailfish skin should be done to investigate the possibility of nano roughness improving the overall hydrophobicity of the hull surface and analysis on their swimming kinematics is needed. Flow visualization at the microscopic scale is needed to increase the understanding of protrusions and their effect of reducing drag.

Following conclusions have been drawn-

1. It is found that the stream wise vortices are formed because of VSP thus shifting the flow separation point down the stream and also narrowing flow separation region.
2. Hydrodynamic friction reduced by maximum of 5.8%.
3. At speeds lower than 1.69 m/s, increase in hydrodynamic friction was observed.

4. The nano- scale texture of modified hull design provided resistance to bacterial attachment.

Based on the results it is determined that the reduction of ship resistance through induced turbulent boundary layers was a success for this hull form, however hypothesis needs motivation for further investigation and a more systematic approach can be taken. I believe that collaboration and exchange of information between biologist and technology will provide great opportunities in the field of biomimetic flow control to find nature-inspired simple and efficient solutions.

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