Research on the Shape Optimization of Three-Dimensional Bow

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Abstract. Boat is mainly composed of hull, ship frame, deck, cabin and ship deck building. When people are designing the boat, one key consideration is the shape of the bow in order to decrease the resistance and fuel-consumption. In this paper, theoretical analysis of resistance to bow and the optimization aimed for lower resistance were produced by using COMSOL Multiphysics 6.0. Firstly, a simple and ordinary model of bow is presented. Then, the mathematical and physical model are established by COMSOL. Afterwards, after I exam whether the computational model is effective enough for the further optimization, the calculating results are worked out and I compare them with the common bow's experimental data, with the purpose of the optimization, the lower resistance, in different conditions such as different ship speed and draft. The polynomial expression of several important section is used to construct the basic outline of the three-dimensional bow with different width, bow length, angle of bow top and the possible maximum and its position. Then, I choose the bow length, angle of bow top and the possible maximum and its position as the optimization parameter. Finally, I reach the conclusion of a better-performing bow design for newer high-speed boat requirements and future studies are discussed.

Keywords: Boat, the shape of the bow, optimization, COMSOL, computational model.

1. Introduction

High speed passenger ships were first short distance passenger ships with high speed in the 1960s. The original passenger ship speed was below 20 knots, which could not meet the passenger transport needs. Since the birth of some high-performance ships, such as hydrofoil ships and hovercraft, they have a high speed. With them for passenger transport, high-speed passenger ships have emerged. For example, in reference [1], yachts and recreational boats have been popular in the United States with a 2% annual growth rate and a relational pleasure boat database BOATDSS-Boat Decision Support System is put into practice [2].

High speed passenger ships often sail between straits and islands, and can also sail in rivers and lakes. High speed passenger ships adopt new ship types [3]. The main engines are small and light, but the power is large, so they can sail at high speed. At present, the maximum speed of high-speed ships can reach 60 nautical miles per hour, compared with 18 nautical miles per hour in the early days [4].

There are many types of high-speed passenger ships, including monohull, catamaran, hydrofoil, hovercraft, small water plane catamaran, wave piercing catamaran and their composite ship types [5].

Hydrofoil ship uses underwater wings to lift the ship out of the water, greatly reducing the ship's power to achieve high-speed navigation. Hydrofoil passenger ships used to operate in the Yangtze River and Pearl River waters, but they basically disappeared under the impact of expressway [6].

Air cushion passenger ship is a kind of ship that uses air to lift the hull, reduce resistance and improve speed [7]. There are still hovercraft in operation along the coast of Guangdong.

The small water plane area catamaran is used to support the cabin deck on two floating bodies submerged in the water with small section struts, so that the hull is higher than the sea surface, reducing the disturbance of waves to the hull, improving the seaworthiness and increasing the speed [8]. In 1980, Japan made a small waterplane plane catamaran. The Haiyang Lala of Huada Marine in Taiwan is also a small water plane catamaran passenger ship. It is the first high-speed ship in Taiwan, with a sailing speed of 35 knots and a draft of 2 meters. It can withstand the sea waves of Class 9 [9].

The high speed passenger ships can sail on the sea, rivers and lakes. At present, domestic high-speed passenger ships are mainly located in the Pearl River Estuary, the Yangtze River Estuary, the Taiwan Strait and the North Sea, mainly aluminum alloy high-speed catamarans. The largest high-speed passenger ship is the wave piercing aluminum alloy catamaran Ro Ship "Strait", which is sailing with the three links of the Taiwan Strait. Its length is nearly 90 meters, and its maximum speed is nearly 40 knots (74 kilometers per hour) [10].

Like [3], the observation and optimization focus on the analysis of resistance which were produced by the boat while cruising that can enhance the performance and also help the boat to reach its highest speed. The structural design of high-speed ships usually follows the following principles, checking the overall longitudinal strength and stability of components, checking the overall vibration and local vibration structure. The design method can be divided into normative design method and computational design regulation. Norm design method refers to the determination of structural dimensions by relying on the official specifications. Because the specifications are based on experience, they are conservative. Because the evolution of conventional ship forms and shipbuilding materials is very slow, high-speed ships are developing rapidly and ship types are diverse. Ship societies of various countries are actively formulating and modifying the construction of high-speed ships to adapt to their large-scale and diversified development.

2. Basic setting of the model

2.1. Governing equations

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \tag{1}$$

Navier-Stokes equation:

$$\rho \frac{D\vec{u}}{Dt} = \rho f - \nabla p + \mu^2 \nabla^2 \vec{u} \tag{2}$$

Specific equation of k-ε:

$$\rho(\vec{u} \cdot \nabla)k = \nabla \cdot [\left(\mu + \frac{\mu_T}{\sigma_k}\right) \nabla k] + P_k - \rho\varepsilon \tag{3}$$

$$\rho(\vec{u} \cdot \nabla)\varepsilon = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right) \nabla \varepsilon\right] + C_{\varepsilon_1} \frac{\varepsilon}{k} P_k - C_{\varepsilon_2} \rho \frac{\varepsilon^2}{k} \tag{4}$$

Where, $\varepsilon = ek$.

2.2. Boundary conditions

In this study, for the water flow, there are no flow through and no slip boundary at the wall of the bow. At the entrance of the model, I define the velocity by Reynolds number and I define a constant pressure at the export of the model. No flow through (v_norm = 0), no slip (v_tan = 0), inlet, outlet.

2.3. Dimension and key performance parameters

In the consideration of designing high speed boats, the resistance from water is mainly composed of the resistance from the bow, so the resistance caused by the front is my optimization goal. Also, for the high speed boat, turning its direction is seldom. Or it needs a large space to do so, which means that its resistance is about the symmetry of the central axis of the boat. So the drag force can be expressed as "-spf.T_stressx" in COMSOL because the drag in the y direction is almost 0.

In Reynolds number, $\mathrm{Re} = \frac{\rho v d}{\mu}$, d represents the width of the bow and μ represents the water viscosity coefficient. Re is about 1000.

2.4. Dimension and key performance parameters

First, use the data from the design drawing of the boat, I can figure out its simple outline because it is mainly composed of straight lines. Then I build a structure under the water surface like bulbous bow but it is more sharp. Take width, bow length, angle of bow top and the possible maximum and its position into consideration, the section of its bottom and its top is composed of the quadratic function with monotonic decreasing in the first quadrant symmetric to the x axis because there are 5 determining coefficient. Finally, the structure between the 2 section is made by lofting.

2.5. Mesh

The finite element model obtained after grid generation is shown in Figure 1 and Figure 2 below:

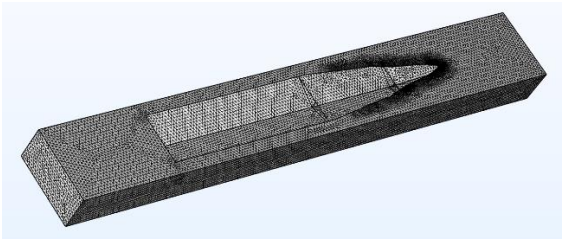


Figure 1. Mesh of the overall stator

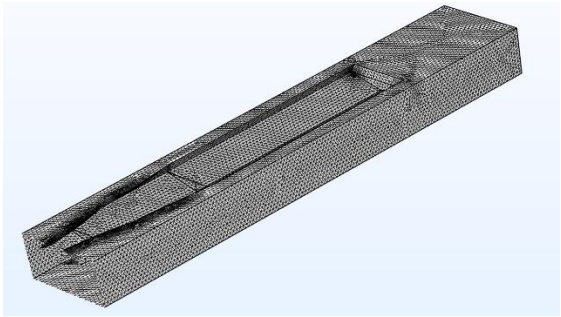


Figure 2. Mesh of the stator from a section

3. Examination of model

3.1. Computational configurations

The CFD separate solver goes to convergence within 60 steps' calculation. The velocity monitor, pressure monitor and turbulence monitor are all go to convergence despite they sometimes have a tendency to divergent so the result is reasonable enough for effective optimization. In the optimization, I choose Nelder-Mead method.

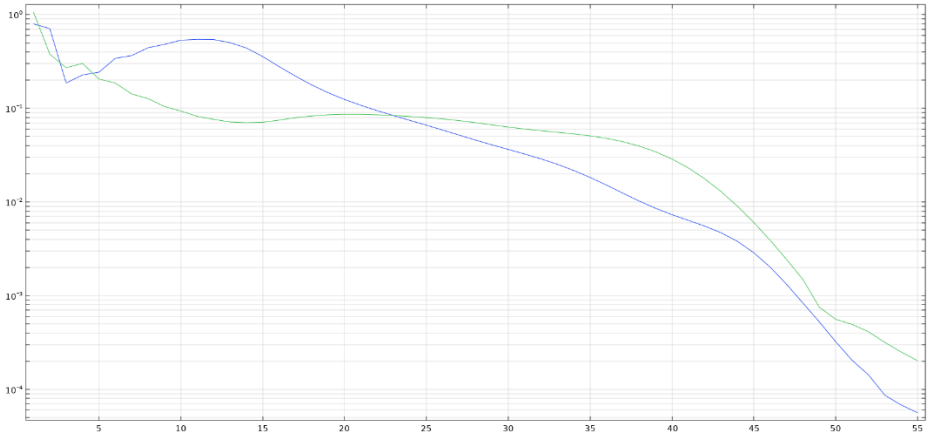


Figure 3. Velocity, pressure and turbulence monitor (X axis is the speed, m/s; Y axis is the pressure, pa.)

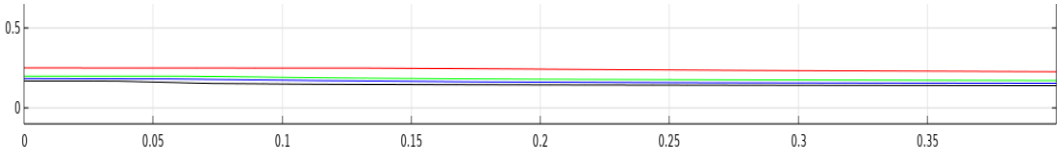


Figure 4. The pressure along the edge of the boat

3.2. Mesh sensitivity confirmation

For the purpose to confirm the effectiveness of the optimization and other results, a mesh sensitivity confirmation is represented by selecting the pressure along the bottom edge of the boat and its result is shown in Figure 4. Table 1 shows the drag of four cases. The differences between case1,2 and 4 are too big but case 3 has relative low difference with case 4. As a result, the mesh density and its generation method in case 3 are both reasonable enough for an effective outcome.

Table 1. Different cases of the model

case number	number of mesh elements	characteristic parameter value	relative difference	Line color
1	98593	0.0089731	68.5976%	red
2	336920	0.0063032	18.4322%	green
3	694791	0.0056264	5.7157%	blue
4	2075033	0.0053222	0	black

Therefore, we can come to the conclusion that 694791 nodes in case 3 have sufficient effectiveness for the simulation of the boat. The optimized boat will use the same meshing and calculation way to maintain the effectiveness.

4. Result & discussion

Figure 5 and 6 show the optimization result and its rural pattern and for the purpose to clear the comparison, the hull behind the bow is hidden. The main difference is the forward part of the bow which moves downward, from deck position to below waterline and extends greatly.

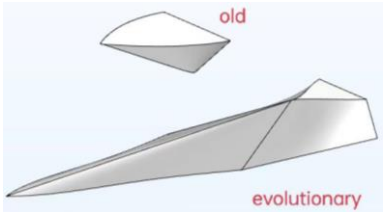


Figure 5. The evolution one and the original one from the top

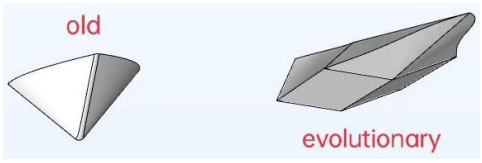


Figure 6. The evolution one and the original one from the bottom

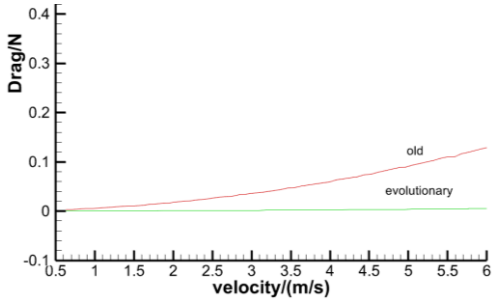


Figure 7. The comparison of drag

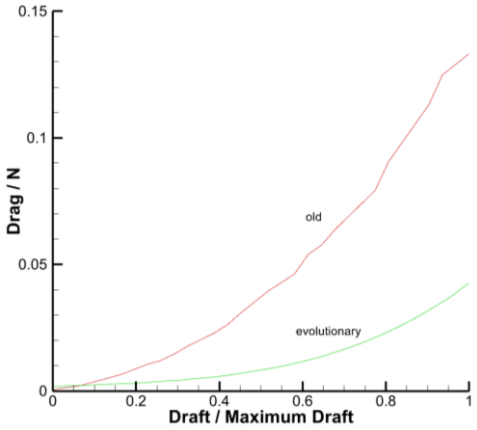


Figure 8. The comparison of drag in different drafts at 6.3198m/s

Figure 7 illustrates the drag related to the boat's velocity for the old one and the optimized one. As it is shown in the figure, the drag is lower when the velocity is above 0.5 meter per second. Also, the new boat's drag remains almost the same when the old one's drag increases faster and faster with the increasing speed of the boat. That means the evolutionary boat has much lower resistance when it is running compared with the old one and the difference will increase if the boat accelerates.

Figure 8 illustrates the drag of the boat in different draft with a flow of 6.3198 meters per second for the old one and the optimized one. From the figure, at the relative draft (draft divided by maximum draft) over 0.15, the old one's resistance is higher than the evolutionary one and the difference is increasing with the increase of relative draft. That represents the evolutionary boat has less drag in most cases because the effective draft of the boat cannot be too low, or the boat cannot hold too much weight.

5. Conclusion

In a nutshell, an optimization method for high speed ship bow has been shown. This method combines an optimization with a geometry definition consisting of a few variables and was applied on two different determining section of the bow. Through the optimization, the resistance reduces more and more as the speed increases.

A high-speed ship must meet a very important requirement: minimum hull resistance, so that engine power will not spend too much energy to overcome resistance. Future research should pay attention to the optimization weighting factors in terms of the design method. What's more, in the on-going research project, the application to high speed boat should be pursued to a favorable effect, considering the actual working condition of the boat, especially the propeller behind the ship.

References

[1] Vasconcellos J. M., Latorre R. Development of BOATDSS high speed boat design database. Ocean Engineering, 1999, 26: 891-904.

[2] Caramatescu A., Mocanu C., Modiga A. Advanced high-turning A New Concept of Composite Material for High Speed Boats. Materiale Plastice, 2019, 56: 11-17.

[3] Bagiyo S., Akbar H. M. A., Sahir A., Munazid A. Outrigger RC Boat Model Hull Development as A High Speed Craft Based on Resistance and Lift Force. Procedia Engineering, 2017, 194: 197-202.

[4] Hasegawa Y., Shikazono N. Model-Based Shape Optimization of Three-Dimensional Complex Structure for Heat Transfer Enhancement in Single-Phase Flows. Begel House Inc, 2014, 34: 201-203.

[5] Dong-Mei H. E., Zhang Y., Zhang Z. K. Design and application of the three-dimensional face bow in the zygomatic fractures. China Journal of Oral and Maxillofacial Surgery, 2004, 25: 598-605.

[6] Mitamura B., Yoshinori T. Three-dimensional shape optimization of a cemented hip stem and experimental validations. Journal of artificial organs: The official journal of the Japanese Society for Artificial Organs, 2015, 7: 313-336.

[7] Hagiwara T., Minakuchi Y., Banno S. Biomechanical Adaptation Shape Analysis of Three-Dimensional Ankle Joints Using Growth-Strain Method. BME, 2012, 50: 283-288.

[8] Zhang, B. Shape Optimization of Bow Bulbs with Minimum Wave-Making Resistance Based on Rankine Source Method. Journal of Shanghai Jiaotong University, 2012.

[9] Masters A., Achilleos N., Dougherty M. K. An empirical model of Saturn's bow shock: Cassini observations of shock location and shape. Journal of Geophysical Research: Space Physics, 2008, 92: 102788.

[10] Raju M., Sivabalan P., Thamby T. Effect of Bulbous Bow on Resistance of a Tuna Longliner. Social Science Electronic Publishing, 2020, 57: 440-455.