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Research on the influence factors of ship resistance and navigation drag reduction

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Abstract. With economic growth, ship transportation plays a major role in global logistics. The optimization of the ship form based on minimum resistance has been the research focus of ship builders for hundreds of years, but the actual process is quite complex, which also brings huge benefits. Ship drag reduction is not only conducive to industrial economic growth, but also helpful to improve the global energy consumption and environmental problems. In this paper, the Reynolds number and the Froude number are obtained by a dimensional analysis, and then the data are obtained from the model ship experiment with the same Froude number by the law of similarity. The total resistance is subdivided into four kinds with different causes, namely the friction resistance, wave-making resistance, form resistance, and additional resistance. In this way, the ship resistance can be reduced more scientifically and efficiently.

Keywords: drag reduction, dimensional analysis, Froude number, Reynold number, air curtain.

1. Introduction

Shipping is the most important way of logistics. With the rapid development of the world economy shipping industry undertakes 90% of the world's trade, and at the same time, consumes a large amount of energy (mainly coal) [1]. The International Maritime Organization has launched several initiatives for reducing emissions from ships. One of these is the known as Ship Energy Efficiency Management Plan (SEEMP) [2]. Therefore, all countries have raised awareness of saving non-renewable energy. For ship, drag reduction is the major approach, so how to use energy-saving technology is the biggest problem for the ship designers. From the dimensional analysis and data of the model ship in the test pool, the shape of a ship can be improved based on the factors affecting the ship resistance. This way is widely used all over the world.

This paper divides the total resistance into four types according to their different causes, and various drag reduction measures can be obtained. Combined with new technologies, such as air curtain, the ship resistance can be effectively reduced.

2. Resistance calculation of ships

2.1. Dimensional analysis of factors affecting ship resistance

As a mathematical analysis method, dimensional analysis can not only accurately express the relationship between variables, but also facilitate experimental design and data collation [3]. It is a common method to bring numerical values into theory by reducing the size of model experiments. In the analysis of the resistance of ship navigation, the MLT (mass, length, time) dimension system is used, and the independent dimensional variables are F, v, ρ, μ, l, and g. F is the resistance of the ship during navigation, v is the ship velocity, ρ is the density of the liquid (usually in water), μ is the viscosity of the water, l is the length of the ship, and g is the gravitational acceleration.

[F]=MLT-2, [v]=LT-1, [ρ]=ML-3, [μ]=ML-1T-1, [l]=L, [g]=LT-2

$$F = f(v, \rho, \mu, L, g) \tag{1}$$

Table 1. Different variables in MLT dimension system.

	M<kg>	L<m>	T<s>
F	1	1	-2
v		1	-1
ρ	1	-3	
μ	1	-1	-1
l		1	
g		1	-2

Through the number of variables(n) and the number of the dimensions(j), the Buckingham π theorem can be used to find the number of the π-groups(k).

$$k = n - j \tag{2}$$

There are six variables and three dimensions, so there are three π groups for this problem.

$$\begin{cases} \pi = F v^{\alpha_1} \mu^{\beta_1} l^{\gamma_1} \\ \pi' = \rho v^{\alpha_2} \mu^{\beta_2} l^{\gamma_2} \\ \pi'' = g v^{\alpha_3} \mu^{\beta_3} l^{\gamma_3} \end{cases} \tag{3}$$

In accordance to the MLT analysis, these three dimensions (mass, length, time) are calculated separately, making these π groups dimensionless.

The following equations are given from the first π.

$$\begin{cases} 1 + \beta_1 = 0 \\ 1 + \alpha_1 - \beta_1 + \gamma_1 = 0 \\ -2 - \alpha_1 - \beta_1 = 0 \end{cases} \tag{4}$$

The calculation is easy, and given below.

$$\begin{cases} \alpha_1 = -1 \\ \beta_1 = -1 \\ \gamma_1 = -1 \end{cases} \tag{5}$$

$$\pi = F v^{-1} \mu^{-1} l^{-1} = \frac{F}{v\mu l} \tag{6}$$

The way of calculating the rest two groups is the same, so

$$\begin{cases} \pi = \frac{F}{v\mu l} \\ \pi' = \frac{\rho v l}{\mu} \text{(Reynold number, Re)} \\ \pi'' = \frac{gl}{v^2} \end{cases} \tag{7}$$

$$\pi = f(\pi', \pi'') \tag{8}$$

π'and π" are transformed as follows.

$$\begin{cases} \pi = \frac{F}{\rho l^2 v^2} Re \\ \sqrt[2]{\frac{1}{\pi''}} = \frac{v}{\sqrt{gl}} \text{(Froude number, Fr)} \end{cases} \tag{9}$$

After transforming, the consequence shows that

$$\frac{F}{\rho l^2 v^2} = f(Re, Fr) \tag{10}$$

The author assumes that CD is the resistance coefficient

$$C_D = f(Re, Fr) \tag{11}$$

It is the final equation which expresses the resistance of the ship and the relationship of various factors.

$$F = C_D \rho l^2 v^2 \tag{12}$$

From this formula, it can be seen that the ship resistance is not only proportional to the square of length and the square of ship velocity, but also a function of Reynolds number and Froude number. When the ship model is geometrically similar to the actual ship, the Reynolds similarity and Froude similarity give the following equations.

$$\begin{cases} \frac{v_m l_m}{\mu_m} = \frac{v_a l_a}{\mu_a} = Re \\ \frac{v_m}{\sqrt{g_m l_m}} = \frac{v_a}{\sqrt{g_a l_a}} = Fr \end{cases} \tag{13}$$

However, in order to meet the Reynolds equation, when lm is reduced to more than dozens of times the original actual length, vm must also be increased several times. In that case, the Froude equation will be inequality.

It is impossible to meet the same Reynolds number and Froude number at the same time. The resistance of the model CD cannot be directly converted into the resistance of the actual ship by using the resistance coefficient obtained from the ship model data.

2.2. Froude postulate

In the mid-19th century, in order to solve the problem of resistance conversion between the model ship and the real ship, William Froude made the following assumptions.

$$R_0 = R_f + R_r \tag{14}$$

$$R_r = R_w + R_e \tag{15}$$

Resistance of the ship R0 consists of two parts, frictional resistance Rf and residual resistance Rr. In the case of geometric similarity, the friction resistance can be approximately calculated by using the plate friction resistance with the same length, velocity, and wet surface area as the hull, suitable for both model ship and real ship.

As for the rest resistance, Froude postulate believes that eddy resistance Re and wave-making resistance Rw are combined into the residual resistance. It is only influenced by the Froude number, which means it can be calculated as long as the Froude number of model ship and real ship is the same.

The Froude postulate is widely adopted and used in test pools all over the world. The reason is that the results obtained by calculating according to this assumption are generally quite close to the reality, and there are many difficulties in establishing a more perfect and reasonable assumption. Strictly speaking, the Froude's assumption is neither perfect nor reasonable [4].

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3. Various resistance and drag reduction measures

When a ship is sailing, it is influenced by various resistances, which are mainly related to the ship size, speed, sailing environment, and other factors. This also leads to a cumbersome calculation of ship resistance. This paper divides the total resistance into friction resistance, form resistance, wave-making resistance and additional resistance. Their causes and reduction measures will be mainly introduced in the following sections.

3.1. Friction resistance

As one of the most common forms of energy loss in nature, the force that hinders the movement will be generated when the mutually squeezed objects have relative motion or have a trend of relative motion. This happens in ship navigation and is the friction shear stress between a layer of water around the ship and the wet surface of the bottom of the ship.

When the ship's speed is low, the magnitude of friction is directly proportional to the quadratic of the ship's speed.

In addition, it is also related to the wet area of the ship. The larger the volume immersed in the water, the greater the resistance. The volume immersed in the water is related to whether the ship loads goods or not and the draft of the ship.

In fact, the faster the speed, the smaller the wet area and the smaller the friction resistance. The speedboat is a good example. When the speedboat moves at high speed, the hull of the bow will rise above the air, and the contact area with the water will become smaller, so the friction will be smaller. However, hull lifting is difficult to occur on large ships with heavy load.

A technology uses the similar principle by using the contact with air to reduce friction, and it is called the Air Curtain. The air or waste gas produced by the ship can be injected into the outer wall through the ship pipeline system to form an air curtain that formed with dense continuous small bubbles between the bottom of the ship and the water to reduce friction. The results of the model test and ship test show that the air curtain formed at the bottom of the ship can reduce the ship's drag by 15% to 30% [5].

In the past decade, this technology has developed well and adopted by many countries, but there are still some problems that are needed to be solved.

Obviously, if the air curtain is intended to be formed, the ship needs to consume an extra energy, in order to transport gas. If the extra energy consumption is too large, especially in some trade ships, such as the container ship or VLCC (Very Large Crude oil Carrier), the larger the volume of the ship, the larger the area of the air curtain will be formed, and the greater the extra energy consumption. This will lead to an uneconomical and impractical situation. Therefore, now this technology is mainly used in special ships, such as submarines.

3.2. Wave-making resistance

The ship will stir up waves during the navigation, and the wave energy is part of the energy lost by the ship movement. This part of the resistance is called wave-making resistance, and it is measured by the wave amplitude. As the ship moves, waves continue to form. After the impact with the bow, the water gets rising energy and it is a kind of incompressible and viscous liquid, it continues to rise before the final fall which is affected by gravity, and constant waves are the results of repeated processes.

In the long-term experience summary, people have invented and designed several measures that can be applied to ordinary ships to reduce the wave-making resistance, among which the most common one is to install the bulbous bow.

The wave generated by the bulbous bow and the wave generated by the main hull form a favorable interference, which reduces the combined wave amplitude, thus greatly reducing the wave-making resistance.

For bulbous bow, the volume and shape can be redesigned to change the wet area or the position can be slightly adjusted, the wave-making resistance can be reduced by about 10％ after optimization, taking the KVLCC ship as an example [6].

3.3. Form resistance

Different cargo demand and navigation environment have created a variety of ships to meet different work needs.

The types of various ships are also different, which will bring great differences in ship stability, rapidity, unsinkability and so on, for example, passenger ships, from the beginning of design, are fully considered for ship safety, so they will ensure unsinkability and maneuverability to be the priority.

These shape differences are expressed by the coefficient of form, including the waterplane coefficient, the block coefficient, the prismatic coefficient, and the midship section coefficient.

The block coefficient and prismatic coefficient influence resistance factor is relatively small, except for military ships requiring higher speeds. However, the requirement of waterplane coefficient for ship length and width is an important influencing factor of ship resistance [7]. The longer the ship is, the narrower the ship width is, the smaller the number is. However, to ensure the basic unsinkability, it is necessary to maintain the prismatic shape, which is why ships today are prismatic ships.

The shape of the ship should be constantly optimized through computer simulated experimental data, so that not only a good performance of the ship can be ensured, but also the resistance of it during navigation and the energy consumption can be continuously reduced.

3.4. Additional resistance

Air resistance and fouling resistance both belong to additional resistance, and rough sea resistance depends on sea state completely.

Compared with other modes of transportation, the air resistance in water only takes a small part of the total resistance (about 2% to 4% of total resistance), which is not the main direction of ship drag reduction [8]. However, it is worth noting that it is necessary to avoid excessive and unreasonable accumulation of goods on the deck, which can not only avoid unnecessary cargo damage, but also reduce air resistance.

Fouling resistance is caused by the unclean underwater surface of the hull, which may be attached by ocean animals and plants, thus essentially increasing the friction resistance of the ship [9].

4. Conclusion

Through the dimension analysis method applied in this paper, it is obtained that the resistance of the ship during navigation is related to Reynolds number and Froude number. In actual calculation, the resistance of the ship can be calculated by measuring the value of the model according to Froude's postulate.

The resistance is divided into four kinds, namely the friction resistance, wave-making resistance, form resistance, and additional resistance, according to the different ways of generation and the corresponding drag reduction methods. In the future, the direction of ship drag reduction is to optimize the air supply mode of ship blower, so as to optimize the air curtain technology [10].

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