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A method based on potential theory for calculating air cavity formation of an air cavity resistance reduction ship

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Abstract: This research is intended to provide academic reference and design guidance for further studies to determine the most effective means to reduce a ship's resistance through an air-cavity. On the basis of potential theory and on the assumption of an ideal and irrotational fluid, this paper drives a method for calculating air cavity formation using slender ship theory then points out the parameters directly related to the formation of air cavities and their interrelationships. Simulations showed that the formation of an air cavity is affected by cavitation number, velocity, groove geometry and groove size. When the ship's velocity and groove structure are given, the cavitation number must be within range to form a steady air cavity. The interface between air and water forms a wave shape and could be adjusted by an air injection system.

Keywords: air cavity resistance reduction; forming of air cavity; potential theory; cavitation number
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1 Introduction

The air cavity resistance reduction ship is to just create a certain groove in the bottom and supply excessive air to it, thus air cavity can be formed between hull bottom surface and water which works like air lubrication and reduces the ship resistance. The air cavity resistance reduction method has been researching since 18th century and is applied in mechanism, marine and shipbuilding domain etc. Considerable attention has been paid to its potential great value. Currently, the resistance reduction method could mainly be classified as: 1) air layer resistance reduction; 2) bubble curtain resistance reduction; 3) micro-bubbles resistance reduction; and 4) air cavity resistance reduction. Air layer resistance reduction, which relies on artificial thin air space in the hull-form bottom created by use of differentiations of viscosity and density between air and water, reduces viscosity resistance. Bubble curtain resistance reduction, based on differentiation of viscosity and density between air and water, which generates two-phase mixed flow on the bottom of the ship by supplying air to the bottom, reduces frictional resistance by varying the viscosity, density or flow mode of the two-phase mixed fluid. Micro-bubbles resistance reduction reduces hull-form resistance in uncertain mechanism by forming micro bubbles-water mixed layer on the bottom of the ship. Air cavity resistance reduction creates air cavity in the hull-form bottom, which is useful in the reduction of the effective wetted surface area and formation of air cushion wave, and hence reduces the viscosity resistance and wave-making resistance. The air cavity resistance reduction researched in this paper is widely applied today. In the recent researches of it, the theoretical researches are on the basis of layer theory[1] and two-phase flow theory[2-6] and discussion on how the air cavity works on the resistance reduction, while the experimental researches focus on how to form the air cavity, how to make the air attach to the surface of ship, how to confirm the movement of bubbles in the air layer, the distance between each bubble and the size of bubble and so on[7-10]. But as to application of the air cavity resistance reduction, it's more important to know the parameters directly related to the forming of air cavity, how these parameters work and how to form and control the steady air cavity. To solve these problems, it will be a great loss in money and effort if applying the tentative and repetitive experiment method, and till now, no related research result has been reported. According to the potential theory and

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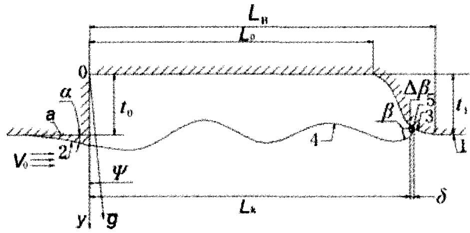
new slender ship theory in hydromechanics, this paper has made certain simplification for building up the theoretical calculation method to predict the formation of air cavity, which is useful for a series of theoretical and experimental researches on the forming and controlling of air cavity.

2 Theory model

Assume that the flow where the air cavity lays is ideal uncompressible and irrotational. As shown in Fig.1, the schematic drawing of air cavity, that the air cavity starts in the front step of the groove and ends in rear block. To make it easy when dealing with this problem, neglect the width effect on the flow field, therefore the model could be considered in a two-dimensional style. It is hypothesized that the model has no trim, coordinate axes x, y are in horizontal stern direction and vertical down direction respectively, and the origin stays in the junction of the step and the bottom of the groove. Because the air cavity is extremely thin comparing with the hull-form, assume that $V_x = \frac{\partial \varphi}{\partial x}, V_y = \frac{\partial \varphi}{\partial y}$ is in low value, and two and above order value could be neglected. The vessel velocity is V_0, and the pressure in the air cavity is P_0.



1. the horizontal hull bottom surface; 2. the curving border in the front of the step; 3. the rear block; 4. the interface of air and water; 5. the baffling board; *a*. the length of curving border; L_0. the length of groove; L_B. the length between the step and the ending point of the rear block; L_k. the length between the step and the forepart of the baffling board; δ. the length of baffling board; t_0. the height of step; t_1. the height of rear block; α. the angle of curving border; φ. the angle of trim; V_0. the velocity of flow

Fig.1 Schematic drawing of the air cavity

The physical quantities of the flow are made dimensionless with groove length L_0, and then the equation that satisfies the boundary condition and initial condition of velocity potential could be got as follows:

$$\nabla^2 \varphi = 0, \tag{1}$$

$$\begin{cases} \dfrac{\partial \varphi}{\partial y} = 0, & -\infty < x < -a \quad L_B < x < \infty; \\ \dfrac{\partial \varphi}{\partial y} = V_0 \alpha, & -a \le x \le 0; \\ \dfrac{\partial \varphi}{\partial y} = -V_0 \beta, & L_k \le x \le L_k + \delta. \end{cases} \tag{2}$$

As the air cavity is thin, the simulation of interface between the air and water could be made by distributing singularities along the bottom of the air cavity according to slender ship theory. The source strength is q, $q(x) = 2V_0 \frac{\mathrm{d}\eta}{\mathrm{d}x}$, and the velocity potential could be approximately described as

$$\varphi(x) = \frac{1}{2\pi} \int_{-a}^{L_B} q(\xi) \ln|x - \xi| \mathrm{d}\xi . \tag{3}$$

Then the height of the interface satisfies

$$\eta(x) = t_0 + \frac{1}{2V_0} \int_{-a}^{x} q(\xi) \mathrm{d}\xi . \tag{4}$$

Combining Bernoulli's equation with equations gained already, the relationship between the shape of interface, the pressure in the air cavity, the ship velocity and the geometric shape of groove could be evaluated as follows:

$$\frac{1}{\pi} \int_0^{L_k} \frac{\tilde{\eta}'(\xi)}{\xi - x} \mathrm{d}\xi + f_{L_0} \int_0^{x} \tilde{\eta}'(\xi) \mathrm{d}\xi - \frac{1}{\pi} \tilde{\beta} \ln\left|\frac{L_k + \delta - x}{L_k - x}\right| + \frac{1}{2}\tilde{\sigma} = -\frac{\tilde{\alpha}}{\pi} \ln\left|\frac{x + a}{x}\right| - \frac{1}{\pi} \int_{L_k+\delta}^{L_B} \frac{\tilde{G}'(\xi)}{\xi - x} \mathrm{d}\xi - f_{L_0}(\tilde{\alpha} a + \tilde{\psi} x), \tag{5}$$

$$\int_0^{L_k} \tilde{\eta}'(\xi) \mathrm{d}\xi = \tilde{G}(L_k + \delta) + \tilde{\beta}\delta - \tilde{\alpha} a - 1, \tag{6}$$

where, $\tilde{\alpha} = \frac{\alpha}{t_0}$, $\tilde{\beta} = \frac{\beta}{t_0}$, $\tilde{\psi} = \frac{\psi}{t_0}$, $\tilde{\eta} = \frac{\eta}{t_0}$, $\tilde{\sigma} = \frac{\sigma}{t_0}$,

$\sigma = \frac{p_0 - p_k}{\frac{1}{2}\rho V_0^2}$ is the cavitation number in the air cavity,

and $f_{L_0} = \frac{g L_0}{V_0^2}$ is the transformed Froude number.

3 Numerical dispersion and calculation result

Divide the length $[0, L_k]$ into n parts along the bottom of the groove, the abscissa of the node in each part being ξ and the abscissa of singularity being x, and

$$\xi_{i-1} \le x \le \xi_i \qquad (i=1,2,\cdots,n\ ;\ \xi_0 = 0\ ;\ \xi_n = L_k)$$

$$x_j = 0.5(\xi_{i-1} + \xi_i) \qquad (j=1,2,\cdots,n).$$

According to a series of dispersion in Eq.(6), the equation referred to the geometric size, height of the interface, and angle of the baffling board and cavitation number could be got.

The effect of dimensionless number f_{L_0} on the shape of air cavity and cavitation number σ could be illustrated by calculating, when the geometric shape and size of the groove is given. The selected physical parameters are shown in Table 1.

Table 1 Physical parameters of the model

n	L_B/m	L_k/m	L_0/m	t_1/m	t_0/m	a/m	δ/m
150	1.116	1.1	0.85	0.20	0.20	0	0.002

1) The effect of dimensionless number f_{L_0} on the forming of air cavity.

While f_{L_0} is selected to be 8.25, 12, 17, 24, different shapes of the interface could be got respectively, which are shown in Fig.2, where abscissa represents source point and y-axis represents wave height, with the unit m.

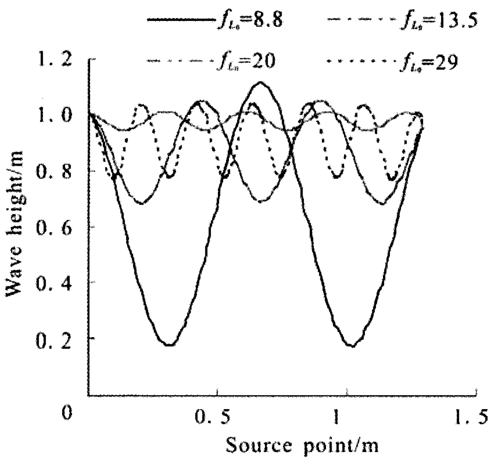


Fig.2 Effect of f_{L_0} on the interface shape

As no experiment data is supplied for comparison, whether the figure can describe the shape of the interface exactly couldn't be confirmed, but a reasonable conclusion can be drawn that the interface is in wave shape though it varies from one pattern to another as the vessel velocity is changed, and in the mean while, the air cavity could be in steady style when the interface is in wave shape.

2) The relationship between f_{L_0} and cavitation number σ

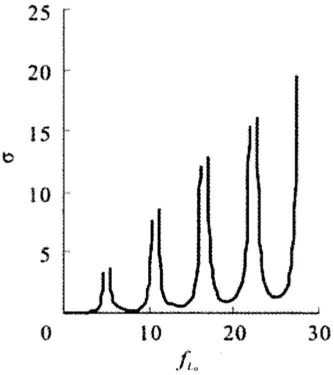


Fig.3 Effect of f_{L_0} on σ

As shown in Fig.3 that f_{L_0} varies discontinuously with the cavitation number σ and the proper cavitation number to form steady air cavity is infinite when $5.15 + 2k\pi < f_{L_0} < 6.0 + 2k\pi$, thus no steady air cavity could be formed under this condition.

4 Conclusions

This paper indicates that the forming of air cavity is related to the ship velocity, pressure in the air cavity and geometric size and shape of the groove. It can be concluded from the calculation that, to form steady air cavity, it is critical to control the shape of the interface which varies with the vessel velocity as the shape and principle dimension of the groove are confirmed; when the velocity is certain also, the state of air cavity relies on the cavitaton number varying discontinuously and periodically with f_{L_0}; and the air cavity can't be in steady state in some cavitation numbers.

The geometric shape of groove and the angle of rear block $\Delta\beta$ could largely affect the forming of air cavity, and further study should be conducted on the basis of experimental data when the parameters are correctly selected. The numerical result in Fig.3 agrees with the statement in related documents, which proves the correctness of the calculation method offered in this paper.

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