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A FURTHER STUDY ON RELATION BETWEEN WAVE-MAKING RESISTANCE AND HULL FORM IN FROUDE NUMBER RANGE LESS THAN 0.26

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Abstract. *In our previous study published in 2018, we conducted a theoretical analysis aiming to clarify the cause of the large difference in residual resistance between two model ships with the same form of aft body. The result showed that the large difference is not due to the difference of overall fore body form, but due to only the difference in bow (fore-end) form. We are applying this result to the development of new technologies. In this paper, we discuss two studies we have conducted preparing for the developments. First, we have confirmed the reliability of our previous study result by additional theoretical analysis and by a discussion with related other model test results. Second, we have studied how to manufacture a model for a CWC (Circulating Water Channel): we are developing a new model test method for a CWC using our previous study result. For development, a model is necessary and important. So, we have started the development with the study of model manufacture.*

Keywords: *hull form, wave-making resistance, energy-saving, model test, model manufacture, Froude number*

1. INTRODUCTION

In our previous study (Fabrício Filho et al, 2018), we analyzed the resistance test results of two model ships, M.No.1 and M.No.5, of a 354,000 ft³ refrigerated cargo ship, that were conducted in 1968 at NSMB (MARIN at present). The test results show that M.No.5 has a considerably lower residual resistance than that of M.No.1 at Froude number below 0.26. Froude number is a parameter which controls ship wave and is given by Eq. (1):

$$F_n = V_s \big/ \sqrt{g L_{wl}} \quad (1)$$

Where: V_s = ship speed, g = gravitational acceleration, L_{wl} = load waterline length of a ship. Lower residual resistance means lower fuel consumption of the main engine of a ship. Because of such lower residual resistance, the hull form and model test results of M.No.5 have been often used either for hull form design or for ship speed-power curve estimation for other ships with design Froude number from 0.22 to 0.26, such as container ships or pure car carriers. By our analysis with the linear wave-making resistance theory, we could clarify that the cause of the large difference in residual resistance between both model ships is not the difference in overall forebody (fore half of a ship body) form but that in only bow (fore-end of a ship) form.

In this paper, first, we confirm the reliability of our previous study (Fabrício Filho et al, 2018) result by additional theoretical analysis and by a discussion with related other model test results. Next, we study and develop a manufacturing process of a model for a test in a CWC. Figure 1 shows the CWC purchased by our university. We are developing a new model test method for a CWC using the above our previous study result. For development, a model is necessary and important. However, in our university, there was no experience of manufacture of the model and, further, we found some difficulties in asking the manufacture to some makers around us, though they might have technologies such as auto shaping or 3-D printing. So, as the first step of the development, we manufacture a model for a test in a CWC by ourselves to find the issues we would meet in the manufacture and to study the ways how to solve them.

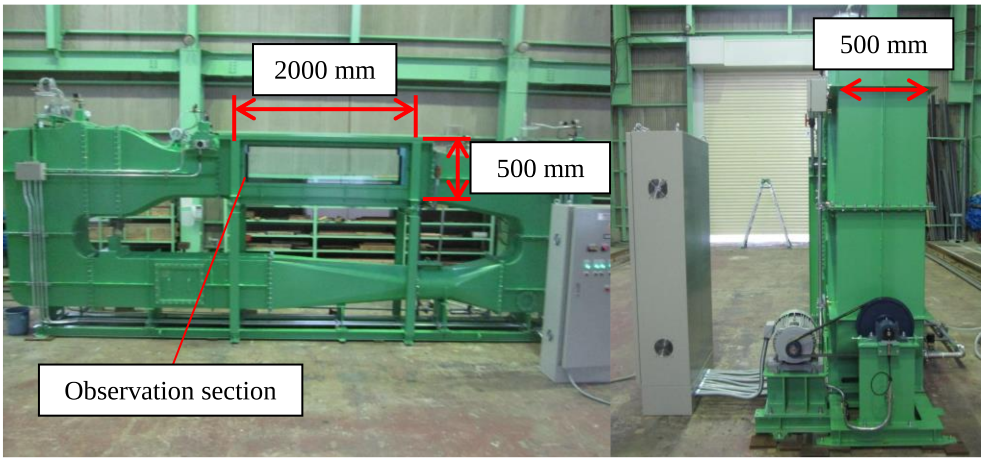


Figure 1. CWC (Circulating Water Channel) of UFPE, with an observation section of length = 2000 mm × breadth = 500 mm × height = 500 mm, and with a maximum flow speed of 1.5 m/s.

2. OBJECTIVES

The objectives of this paper are:

1) to confirm the reliability of our previous study (Fabrício Filho et al, 2018) result that has pointed out the outstanding importance of bow form of a ship in wave-making resistance at Froude number below 0.26

2) to clarify the issues and the ways how to solve the issues regarding the manufacture of a model for validating in a CWC, as the first step of the development of a new model test method for a CWC based on our previous study (Fabrício Filho et al, 2018) result.

3. METHODOLOGY

3.1 Confirmation of the reliability of our previous study result

By additional theoretical analysis: The linear wave-making resistance theory (Havelock, 1924; 1932) is used for the analysis. Using the linear theory, we can understand how each part of the forebody affects the wave-making resistance. In our previous study (Fabrício Filho et al, 2018), calculations are made for the overall forebody. In our present study, calculations are made only for the bow. Both results are compared and discussed.

By discussion with related other model test results: We have searched for other model test results which we can use to confirm our previous study result and found the paper written by Yamano et al., 1995. It has two model test results which are useful for us to discuss our previous study result.

3.2 Study of manufacture of a model for a test in a CWC

By the manufacture of a model by ourselves: As described in 1, in our university, there was no experience of manufacture of a model for a test in a CWC. Further, we found some difficulties in asking the manufacture to some makers around us. In such a condition, the best way we should take to achieve our objective is to manufacture the model by ourselves first. The reason is that through our manufacturing the model, we can find the issues in the manufacture and they can be studied the ways how to solve them. So, we design and manufacture a partial model for a test in a CWC.

4. CONFIRMATION OF RELIABILITY OF OUR PREVIOUS STUDY RESULT

4.1 Additional theoretical analysis

(1) *Fundamentals of theoretical analysis:* The principle of linear wave-making resistance theory is the superposition of elementary waves. Elementary wave is a two-dimensional wave in a direction θ. The wave generated by a ship is considered to consist of innumerable elementary waves with direction θ from -π/2 to π/2. Used coordinate system xyz is

shown in Fig. 2: origin is at the fullest section, hull centerline plane and load waterline plane of a ship with length 2ℓ and draft d;. the x-axis is in the load waterline plane and hull centerline plane, and points to the aft of ship; y-axis is in the load waterline plane and fullest section plane, and points to the starboard direction; z-axis is in the fullest section plane and hull centerline plane, and points to the upward direction). V is the speed of a uniform flow towards the positive direction of the x-axis.

The flow is disturbed by the ship and waves are generated. The θ is the direction of an elementary wave as shown in Fig. 2 (b). The θ ranges from –π/2 to π/2. S(θ) and C(θ) are called amplitude function of a sine elementary wave and a cosine elementary, respectively. The wave-making resistance R_w can be calculated by integrating these amplitude functions squared over θ from -π/2 to π/2 with Eq (2).

$$R_w = \pi\rho V^2 \int_0^{\pi/2} \left[S^2(\theta) + C^2(\theta)\right] cos^3 \theta d\theta \tag{2}$$

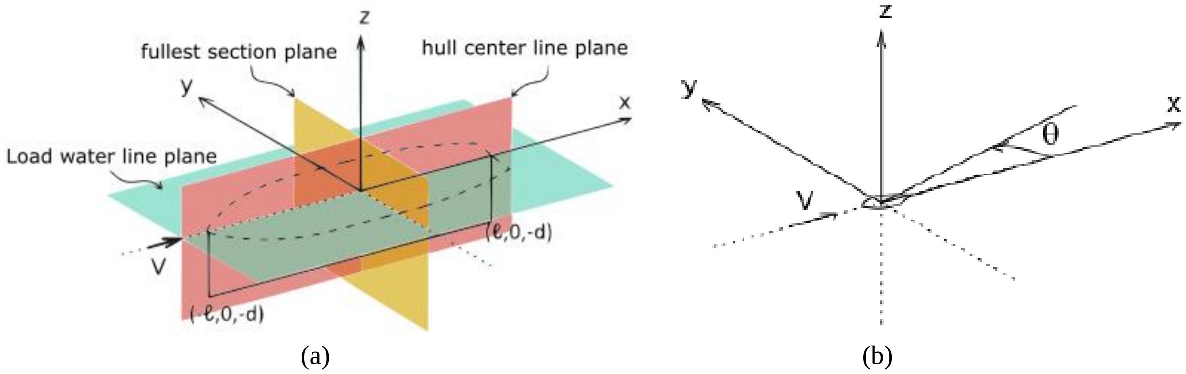


Figure 2. (a) Coordinate system definition. (b) The direction θ.

In our calculation, we use the following non-dimensional coordinates ξ, η and ζ: $\xi = x/\ell$; $\eta = y/b$; $\zeta = z/\ell$, where ℓ is the entrance length (the length from FP to the fullest section), b is the half breadth of the ship. To input the forebody hull form into the theoretical calculation, we simplify the hull form and represent it with just three important parameters: sectional area curve, load water line, and fore-end breadth. We apply polynomial approximations for the sectional curve $\eta_1(\xi)$, and the load waterline $\eta_0(\xi)$. The polynomial has the form of Eq. (3). The simplification of a transverse section form of the forebody is illustrated in Fig. 3. The expression of simplified hull surface η (ξ, ζ) with sectional area curve $\eta_1(\xi)$ and load water line $\eta_0(\xi)$ is shown in Fig. 4.

$$\eta_1(\xi) = 1 - \sum_{n=1}^{5} a_{2n}\xi^{2n}, for -1 \le \xi \le 0 \tag{3}$$

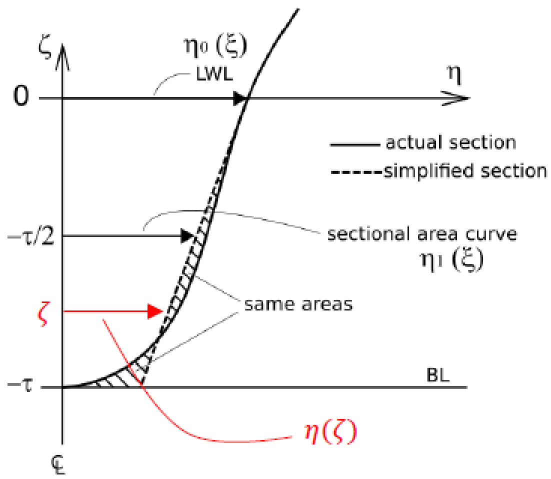


Figure 3. Simplification of a transverse section form.

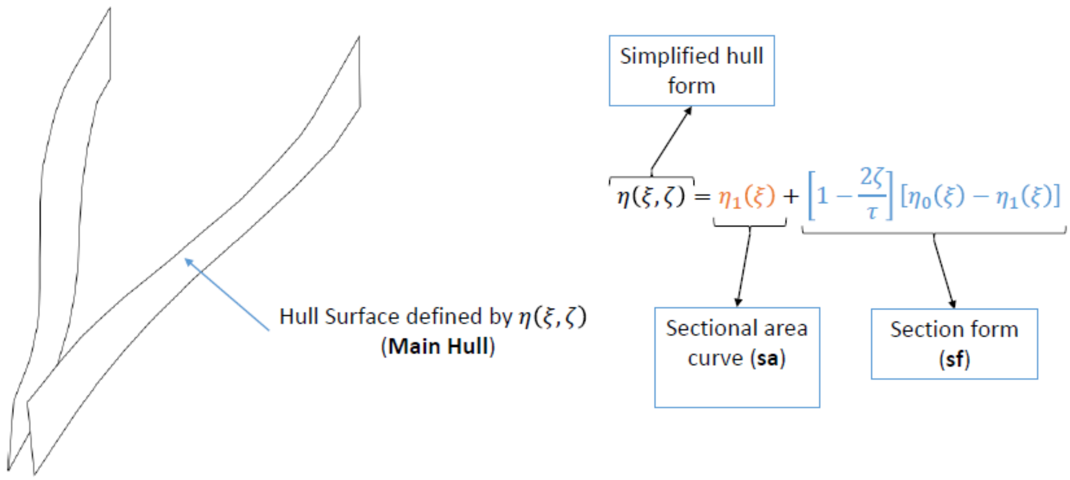


Figure 4. Simplified hull surface η (ξ, ζ) (main hull) expressed with sectional area curve η_1 (ξ) and LWL curve η_0 (ξ).

To calculate S(θ) and C(θ), we represent the hull form with singularities (sources, sinks, and doublets) distributed over the hull center line plane. In our case, we represent the forebody main hull with a source distribution over the hull centerline plane (-1 ≤ ξ ≤ 0, -τ ≤ ζ ≤ 0) and the fore-end part with a line source located a little aft FP (ξ = $-1+\varepsilon_{ls}$, -τ ≤ ζ ≤ 0). Figure 5 shows the relation between source density σ (ξ, ζ) and hull form η (ξ, ζ). Figure 6 shows the equations to calculate S(θ) and C(θ) for each of the three hull form parameters (sectional area curve, section form, and fore-end form). The integration of these S(θ) and C(θ) squared over θ from -π/2 to π/2 with Eq. (2) gives the wave-making resistance due to each of these parameters separately or also due to all of them.

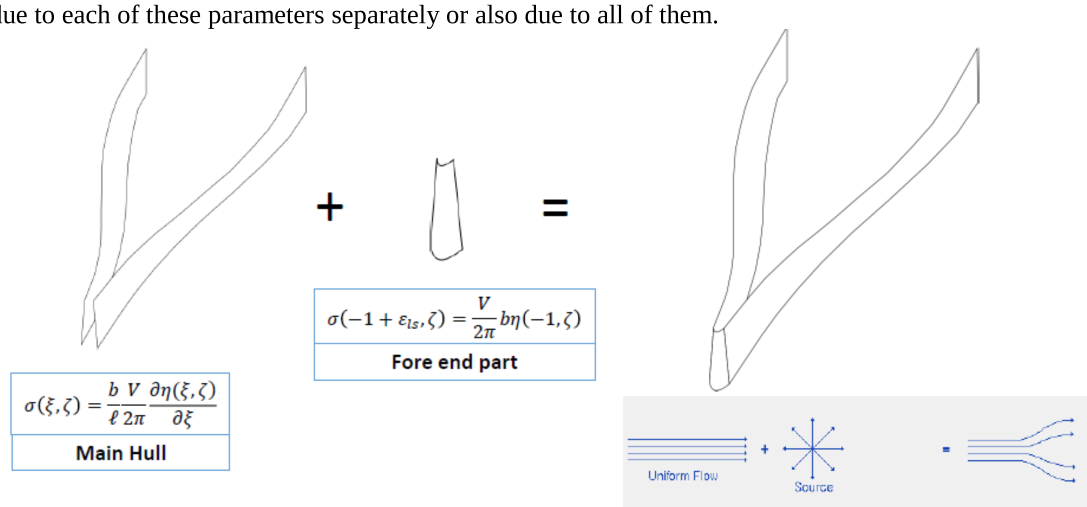


Figure 5. The relation between source density σ (ξ, ζ) and hull form η (ξ, ζ).

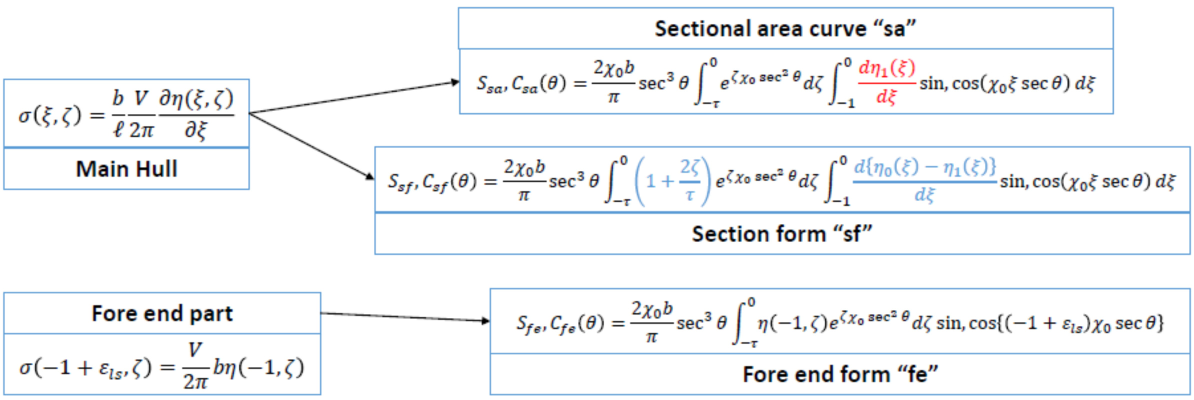


Figure 6. Equations to calculate S(θ) and C(θ) of forebody hull.

(2) *Calculation procedure:* In our previous study, we calculated the wave-making resistance due to each of the three parameters (sectional area curve, section form, and fore-end form) and due to all of them, using the equations shown in Fig. 6 above, integrating in ξ from FP (ξ = -1) to the Fullest Section (ξ = 0). In our present study, we calculate the wave-making resistance for the same parameters as before, but the integration range in ξ: from FP (ξ = -1) to Square Station No. 9 ½ (ξ = -0.90654).

(3) *Calculation Results:* Figures 7, 8 and 9 show the calculated results in terms of wave-making resistance coefficient, r_w, which given by Eq. (4):

$$r_w = \frac{R_w}{\rho \nabla^{2/3} V^2} \tag{3}$$

where ρ = water density, ∇ = displacement volume and V = ship speed).

Figures 7 and 8 compare the results from our previous study with those of our present study for the sectional area curve and section form. From these results, we can see that the wave-making resistance due to the sectional area curve and section form is small compared with that due to the fore-end. Therefore, the difference in wave-making resistance between due to the integration range in ξ from FP to SS No. 9 ½ and due to the integration range from FP to the fullest section is also small.

The wave-making resistance due to the fore-end form, represented by a line source a little aft FP is the same for the above both cases. The wave-making resistance coefficient due to the fore-end form is shown in Fig. 9.

From the above analysis, we have confirmed that our previous study result, that has pointed out the outstanding importance of bow form of a ship in wave-making resistance at Froude number below 0.26, is reliable.

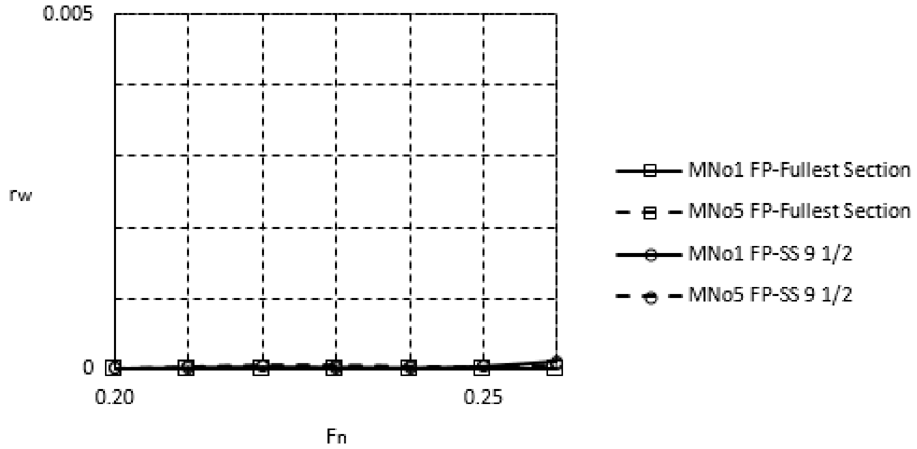


Figure 7. Comparison of the calculated wave-making resistance coefficient due to the sectional area curve.

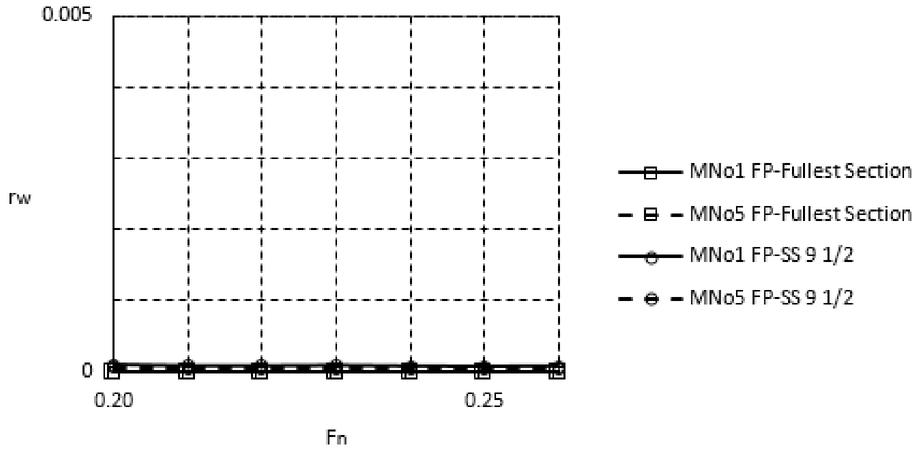


Figure 8. Comparison of the calculated wave-making resistance coefficient due to the section frame.

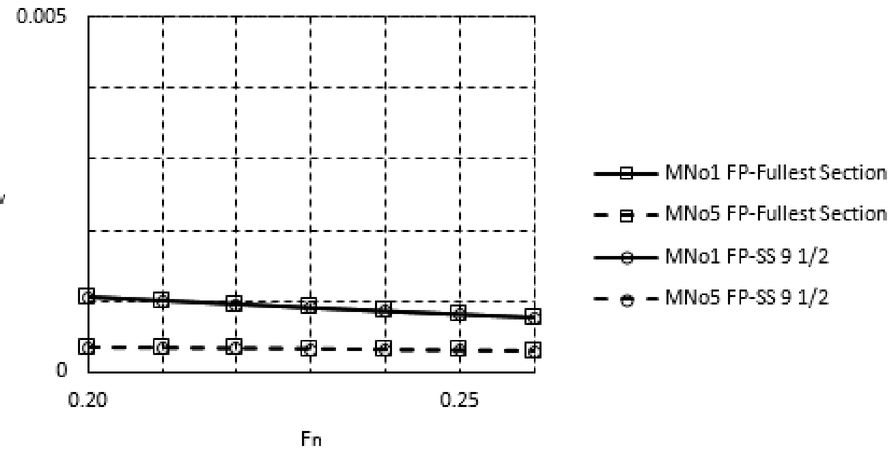
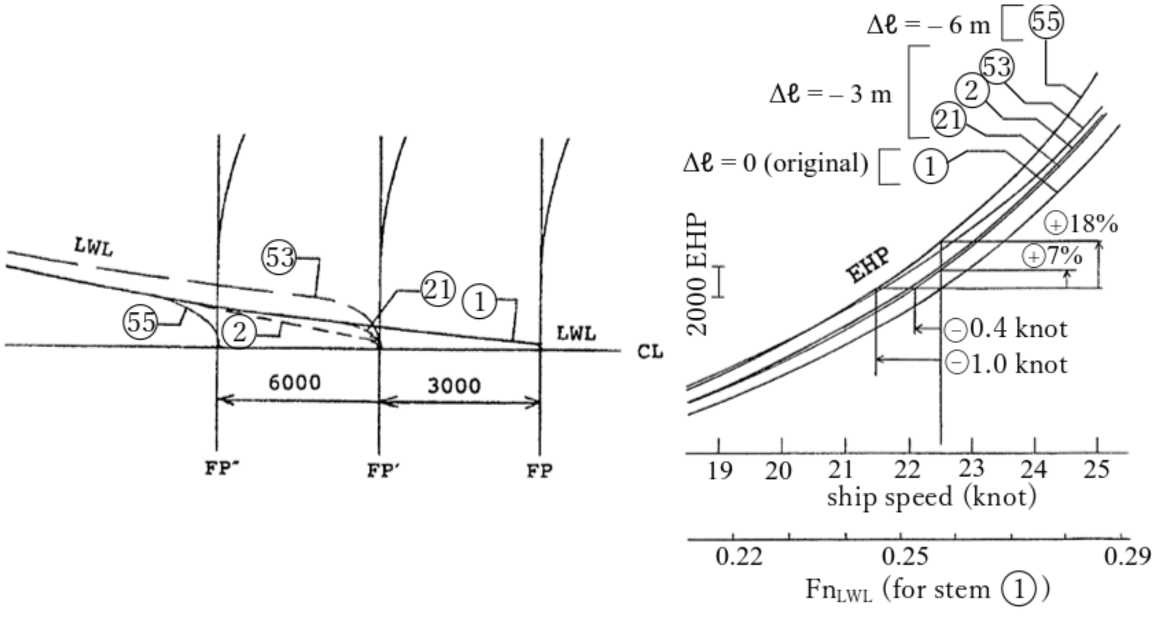


Figure 9. Comparison of the calculated wave-making resistance coefficient due to the fore-end form.

4.2 Discussion with related other model test results

The following two resistance test results are much related to our previous study (Fabrício Filho et al, 2018) result. So, we discuss our previous study result with the two resistance test results.

(1) *Effect of bow form on wave-making resistance of a container ship with L_{pp}= 206.0 m* (Yamano, 1995, 1997): They investigated five stem forms shown in Fig. 10 (a) by resistance tests. Form ① is the base form. The part from fore end up to 6 m (2.9%Lpp) aft of FP was mainly modified. The results show that the stem form difference makes a very large difference in EHP, as can be seen in Fig. 10 (b): at 22.5 knots (41.7 km/h), there is an EHP increase ratio of up to 18% from form ① and a ship speed drop up to knot from form ①. This data clearly shows that the form of bow part with a length of only 2.9% L_{pp} largely controls hull resistance.



(a) (b)

Figure 10. (a) Investigated bow forms: LWL fore-end forms. (b) Comparison of EHP curves among the investigated bow forms – resistance results. Source: Yamano et al., 1995.

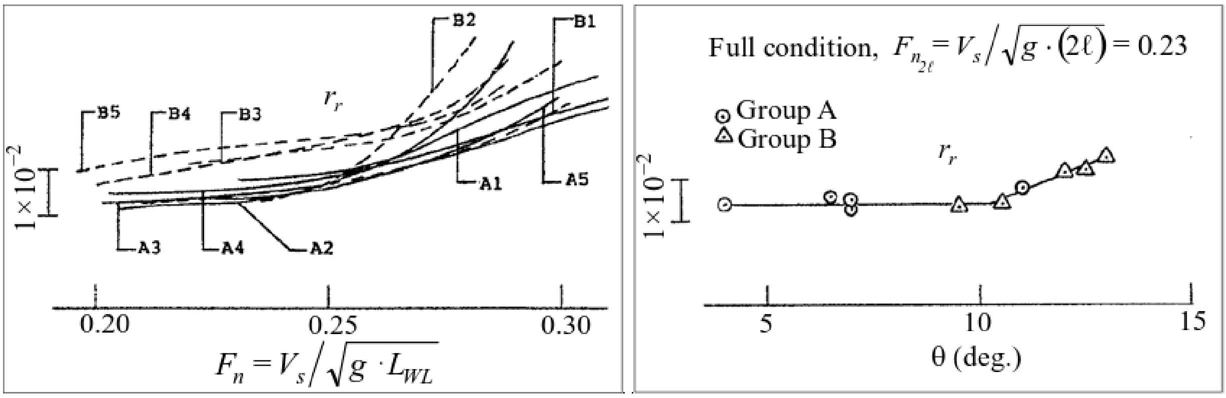
(2) *Effect of LWL entrance angle on wave-making resistance of ten fine ships* (Yamano, 1995, 1997): The residual resistance coefficients of ten ships are compared in Fig. 11 (a). The principal particulars of the ships are shown in Tab. 1. The five ships of Group A are designed by the shipbuilder A completely independently from those of group B designed by the shipbuilder B.

In Fig. 11 (a), we can see that the three ships of Group B have a higher r_r (residual resistance coefficient) at Froude number lower than 0.26 compared with the other seven ships. The difference corresponds to about 8 % of EHP. The authors of the paper have made all the efforts to find the cause of the large r_r difference. At the last, they found that the large r_r difference can be explained by only the difference of the LWL entrance angle as shown in Fig. 11 (b). The ships of group A were designed independently from those of Group B as explained above. It means that many other hull form factors besides the LWL entrance angle are different from each other between the two groups of ships. Nevertheless, the large r_r difference can be explained by only the LWL entrance angle difference. It shows how large the influence of the LWL entrance angle to wave-making resistance is.

From the above discussion, we know that the above two resistance test results strongly support our previous study result that has pointed out the outstanding importance of bow form of a ship in wave-making resistance at Froude number below 0.26.

Table 1. Hull particulars of the ten fine ships. Source: Yamano et al., 1995.

Group:	A					B				
Ship No.:	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5
L/B	6.67	6.90	7.14	7.00	6.72	6.72	6.65	6.60	6.60	6.90
B/d	2.76	2.35	3.08	3.13	3.13	2.58	2.42	2.65	2.53	2.76
Cp	0.57 ~ 0.61									
ℓ (m)	72.1	79.6	70.0	89.3	87.4	79.6	76.9	82.4	81.6	104.0
L_{WL} (m)	143.7	160.6	136.1	180.2	174.5	166.0	155.8	161.5	164.4	213.0
θ (deg.)	11	7	7	6.5	4	10.5	9.5	12.5	12	13
b/2 (m)	0.15	0.10	0.12	0.25	0.45	0.05	0.05	0.18	0.08	0.05



(a) (b)

Figure 11. (a) Comparison of r_r of ten fine ships. (b) Correlation between LWL entrance half-angle θ and measured r_r. Source: Yamano et al., 1995.

5. STUDY OF MANUFACTURE OF A MODEL FOR A TEST IN A CWC

We are developing a new model test method for a CWC as an application of our previous study (Fabrício Filho et al, 2018) result. For the development, we need a model for a test in a CWC. However, we have no experience of manufacture of the model by ourselves and, further, there are no makers around us who have such an experience. Therefore, we have to study the way how to prepare such a model by ourselves, as the first step of the development.

5.1 Conditions necessary for models and model manufacture

The model to be used for the development should satisfy the following conditions: for a model, 1) Accuracy, 2) Strength and 3) Water-resistance; for model manufacture, 4) Accuracy control and 5) Time-schedule control should be possible.

5.2 Model manufacture through out-sourcing or by ourselves

Since there are no makers around us who have the experience of manufacture of such a model, we cannot expect the makers to do the conditions 4) and 5) described in 5.1 at an acceptable level. We also have no such experience. Therefore, the best way we should take would be for us to manufacture the model by ourselves, at least first, and to find the issues that we might meet and to study the ways how to solve the issues by ourselves.

5.3 Manufacture of a partial model for a test in a CWC

To clarify the probable issues we will meet in the manufacture of a model and to study the ways how to solve them, we have designed and manufactured a partial model for a test in a CWC by ourselves. The issues we have found in the process, the ways how to solve the issues and our prospect of manufacture of a model for a test in a CWC are discussed in the following:

(1) *Structure and manufacture process*

The structure of the model consists of the following parts:

1) Center plane
2) Transverse frames with accurate section forms shown in Fig. 12 (a), (b) and (c)
3) Horizontal members with accurate waterline forms shown in Fig. 12 (a), (b)
4) Plastic to be inserted into the rectangular space surrounded with two transverse frames and two longitudinal members shown in Fig. 12 (c).

Regarding the manufacturing process:

- The inserted plastic is shaped using the forms of surrounding frames and longitudinal members as shown in Fig. 12 (c).

(a) (b) (c)

Figure 12. (a) Transverse frames and longitudinal members before the cut, drawn in A4 papers. (b) Assembled frames and longitudinal members on a center plane. (c) Frames, longitudinal members and inserted “Plastic 1”.

(2) *Materials*

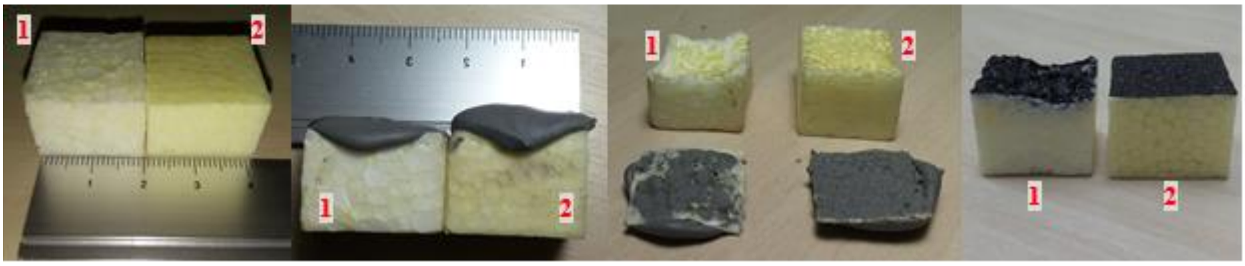
1) Paper with size A4 (210 mm × 297 mm) and with a density of 180 g/m² was used for the center plane, transverse frames, and longitudinal members.

2) “Plastic 1”, the material (styrofoam) used for a float in a swimming pool found in a super-market is used as the plastic to be inserted between the frames and longitudinal members. We tried to apply polyester resin and oil paint over the “Plastic 1” for water-resistance, but it could not bear neither the resin nor the paint as shown in Fig. 13. As a result, we could not use the polyester resin and oil paint for the partial model.

3) Glue gel was used for joining the paper members and joining “Plastic 1” to paper members.

4) Filler made of white glue and wood powder is used to fill gaps in the partial model.

5) Water-paint usually used for cloth painting was used for painting the completed partial model, which has been confirmed not to damage “Plastic 1”.



(a) (b-1) (b-2) (c)

Figure 13. Tests of two plastics against polyester resin and oil paint. “1” refers to “Plastic 1” and ”2” to “Plastic 2”. (a) Samples with size: 20 mm × 20 mm × 15 mm before tests. (b-1), (b-2) Samples after polyester resin application. (c) Samples after oil paint application.

(3) *Test of partial model*

The completed partial model is shown in Fig. 14 (a).

1) Accuracy: We have confirmed that we can keep the accuracy of form by the way where we use transverse sections and horizontal sections even with papers. By increasing the number of sections and by using wood for transverse and horizontal sections, we can increase the form accuracy.

2) Strength: Material for the center plane, transverse frames, and horizontal members is paper. However, the completed partial model was rigid enough and seemed able to be used for the test in a CWC.

3) Water-resistance: We have soaked the completed partial model in water for a day, to check its water-resistance. As a result, it showed that the water had penetrated the model as shown in Fig. 14 (b). It showed that the water-paint used did not realize its water-resistance.

(a) (b)

Figure 14. (a) Completed partial model before the water-resistance test. (b) Partial model after the water-resistance test.

(4) *Discussion of the result*

1) Accuracy: We have confirmed that we can keep enough accuracy of the model by manufacturing the model by the method above described. If we need more accuracy, we can get it by increasing the number of transverse frames and horizontal members and by using wood instead of paper.

2) Strength: Even with structure members made of papers as described above, the completed partial model was rigid and seemed to have enough strength for the model test in a CWC. Therefore, if we use water-resistant wood for the center plane, transverse frames, and horizontal members, we can surely get a model with enough strength for the model test in a CWC. The wood will improve the accuracy of the model also compared with the paper.

3) Water-resistance: To get water-resistance, we need such material that can bear polyester resin and oil paint. We have searched for such material and found it. It is “Plastic 2”. It is the material used for a styrofoam block. We have tested whether “Plastic 2” can bear polyester resin and oil paint. The result is shown in Fig. 13. The result shows that “Plastic 2” can bear them.

4) Our prospect of the model for a CWC: Through the above study, we have found that we can manufacture such a model that has enough accuracy, strength, and water-resistance and so we can use for the model test in a CWC. It has strength members made with water-resistant wood, “Plastic 2” as material to be inserted among strength members, polyester resin and oil paint to be laid over the model.

6. CONCLUSIONS

The conclusions of our present study are as follows:

(1) We have confirmed, by our additional theoretical analysis and further discussion with related other model test results, that our previous study result (Fabrício Filho et al., 2018), which has pointed out the outstanding importance of bow form of a ship in wave-making resistance at Froude number below 0.26, is quite reliable.

(2) We have designed and manufactured a partial model for a test in a CWC, by ourselves. Through these studies, we have clarified the issues we meet in the model manufacture. Then, we have studied the ways how to solve the issues. As a result, we are now ready for the manufacture of a model for the test in a CWC.

7. ACKNOWLEDGMENTS

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