PREDICTION METHODS OF ROLL DAMPING OF SHIPS AND THEIR APPLICATION TO DETERMINE OPTIMUM STABILIZATION DEVICES

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SUMMARY

About 25 years ago, the author developed a prediction method of roll damping of a ship, and the method is widely used even now. The method is a component-based one, and each component is predicted by theoretical ways if possible, otherwise by empirical ways. For these 25 years, the methods have been modified to improve the accuracy and to extend their applicability to other kinds of ships. In this paper the author reviews these continuous works on the roll damping prediction of ships, and introduces the application to determine optimum size and location of bilge keels.

1. IKEDA'S ORIGINAL METHOD FOR CONVENTIONAL SHIPS

The original method for predicting the roll damping of ships was developed for conventional hull shapes of cargo ships, whose block coefficient, Cb, is around 0.56-0.85, and Froude number is up to 0.25. The method was composed by five components, friction, wave, eddy, lift and bilge keel components, on the basis of physical origins. The prediction methods for these components were published in four papers by Ikeda et al. (1976, 1977a, 1977b, 1978a), and English translated versions of these papers are available as Reports of Department of Naval Architecture, University of Osaka Prefecture, No. 401-404. The total feature of the method was summarized by Ikeda et al. (1978b) with the computer code, and Himeno (1981) made a comprehensive review on the roll damping prediction including the method.

2. MODIFICATION OF METHODS

2.1 HULL SHAPE EFFECT ON BILGE KEEL COMPONENT

In the original method, for simplification, a simple cross section (horizontal bottom, vertical side and quadrant-bilge) and the location of bilge keels (center of the quadrant-bilge) were assumed, and the pressure on hull surface was integrated over the simply assumed hull shape. For a slender ship with bilge keels, however, the assumptions were found to cause large error because the cross section and the location of bilge keels sometimes significantly differ from the simple assumption. Therefore the prediction was improved to be able to take into account the exact cross section and exact location of bilge keels (Ikeda et al. (1994)). Since the pressure distribution on and around a bilge keels are given in the original method, the pressure distribution are integrated over bilge-keels and hull surface to get the roll damping generated by bilge keels. To use the modified prediction method, detailed offset data of each hull section and the location of bilge keel must be input although only breadth-draft ratio and cross area coefficient of each section are needed for the original method. Fig. 1 shows the difference of the predicted result between by original and modified methods for a frigate hull with very slender hull shape.

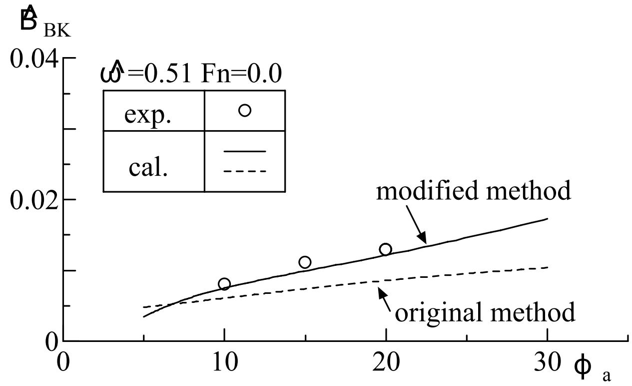

Fig.1 Improvement of accuracy of prediction by considering exact hull shape and exact location of bilge keels.

2.2 FORWARD SPEED EFFECT ON BILGE KEEL COMPONENT

In the original method, the forward speed effect on the bilge keel components was neglected. For wide bilge keels with relatively large aspect ratio, however, the lift force acting on bilge keels increases the roll damping at high speed. Using Jones theory for small aspect ratio wing, the roll damping generated by the lift force acting on bilge keels can be predicted as follows,

$$\hat{B}_{BKL} = \frac{\pi r^2 b_{BK}{}^2 U}{B^2 \nabla} \sqrt{\frac{B}{2g}} \qquad (1)$$

where r denotes distance between roll axis and centre of a bilge keel, ∇ , U and B are displaced volume, forward speed and breadth, respectively.

In Fig. 2, measured bilge keel component of the roll damping for a frigate are compared with the predicted results by the original method and the modified method using Jones theory. We can see that the predicted result is slightly improved by the modification. In very fast speed, however, some discrepancy from experimental result can be seen. More detailed studies on forward speed effects on bilge keel effects should be done.

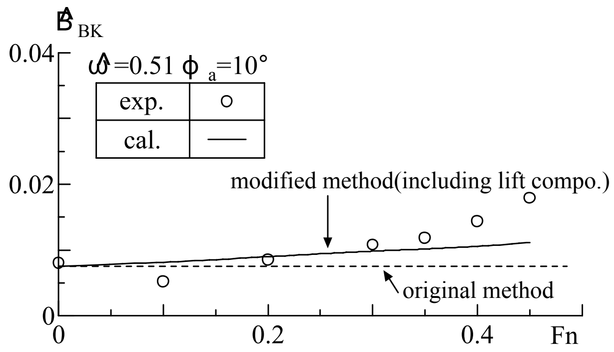

Fig.2 Forward speed effect on bilge keel component

2.3 NON-LINEAR EFFECT ON HULL LIFT COMPONENT

The lift component for a hull in the original prediction method of the roll damping was predicted using the Inoue's prediction formula for lift coefficients of obliquely-towed hulls. If the Inoue's formula overestimates or underestimates the lift, a more accurate lift coefficient, like measured one, is recommended to replace the value of lift coefficient by Inoue's formula used in the original method. Fig. 3 is an example of the lift coefficient for a slender frigate hull with big bulbous bow. The coefficient shows significant non-linearity, and Inoue's formula cannot predict it accurately.

For a fast ship with significant running trim like semi-planing and planing hulls, increase of running trim induces the large lift component of the roll damping, too. Fig. 4 shows an example of measured roll damping for a fast fishing boat. We can see rapid increase of the roll damping due to increase of running trim at high speed (Fn > 0.4).

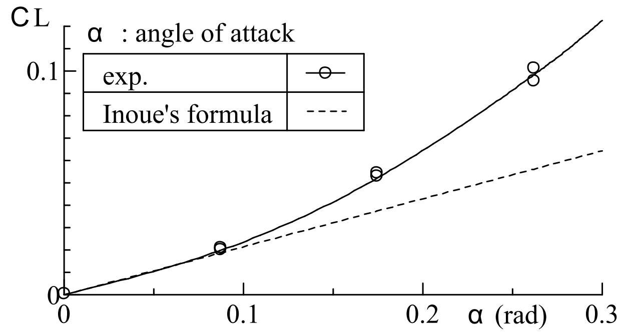

Fig. 3 Nonlineality of lift coefficient for frigate hull.

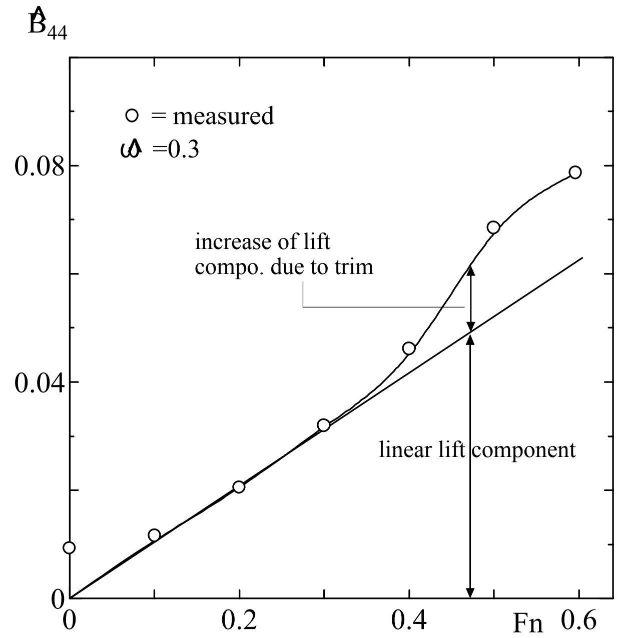

Fig. 4 Increase of roll damping due to increase of running trim of a fast fishing boat with skeg.

2.4 BARGE WITH SHARP CORNER

The original prediction method covered a sharp-cornered box hull with normal breadth-beam ratio, but not a very flat hull. Yamashita confirmed that the method gives good result for a very flat ship when the roll axis is located in water surface level (Yamashita S and Katagiri T, 1980). Standing (1991), however, pointed out that the original Ikeda's method underestimates the roll damping of a barge model. To confirm the contradictions, Ikeda et al. (1993) carried out experimental study on the roll damping of a very flat barge model. In the paper, they proposed a simplified formula for predicting the eddy component of the roll damping of a flat barge as follows,

$$B_e = \frac{2}{\pi}\rho L d^4 \left(H_0 + 1 - \frac{OG}{d} \right) \left(H_0^2 + \left(1 - \frac{OG}{d} \right)^2 \right) \phi_a \omega \quad (2)$$

As shown in Figs. 5 through 7, the experiments revealed that the simple formula expressed by Eq.(2) gives much better results than the original method when the center of gravity is located above water surface. It should be also noted that it was also confirmed that the formula is valid only when roll amplitude is smaller than about five degrees. Above five degrees of roll amplitude, the simple formula underestimates the roll damping of a barge as shown in these figures. This may be because interaction between water surface and shedding vortices from the edge cannot be neglected at larger roll angle.

In order to confirm the reliability of experimental results, the roll damping is measured by three different test methods, free decay test, forced roll test, and ship motion and wave excitation. In Fig.7, experimental results obtained by the three methods are shown. We can see that the three methods give almost same results and the predicted roll damping of a flat barge significantly overestimate in larger roll angle although the predicted one is in fairly good agreement with the measured ones below 5 degree.

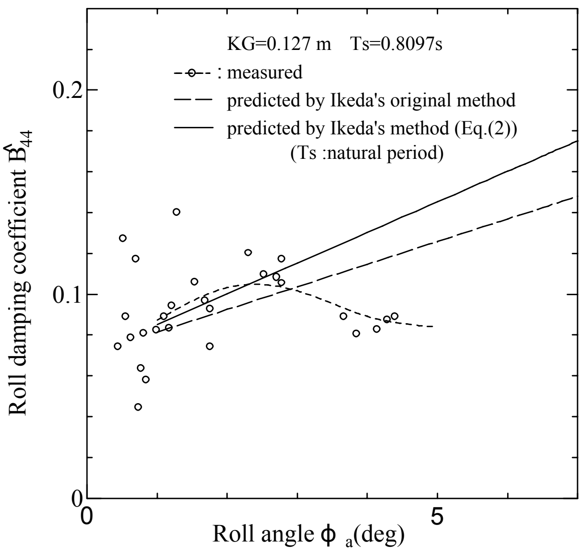

Fig. 5 Comparison between measured and predicted roll damping of flat barge model (1.662m long and 0.549m wide).

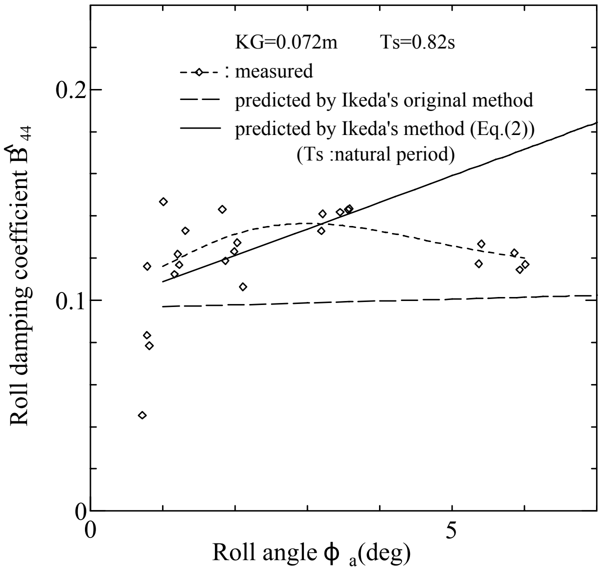

Fig. 6 Comparison between measured and predicted roll damping of flat barge model.

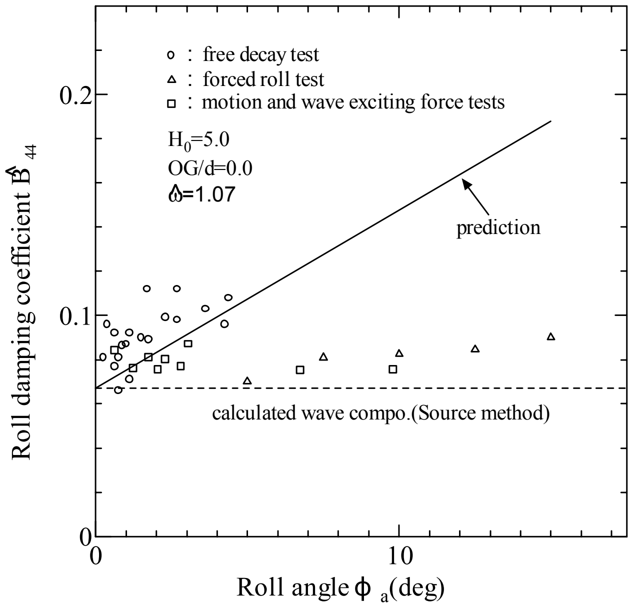

Fig.7 Comparison between experimental results by three ways and predicted results by Ikeda's original methods and modified one for flat barge model.

2.5 SMALL CRAFT WITH HARD-CHINE HULL AND SKEG

A hard-chine hull of a small craft increases the roll damping by strong vortices generating at the hard-chine. A skeg also increases the roll damping like bilge keels, but its efficiency for the roll damping significantly depends on rise of floor. When a ship has a flat bottom, the pressure component, which is created by vortices shed from the edge of a skeg on bottom surface of the hull, becomes to be negative.

A Prediction method for the roll damping of such a hard-chine hull with a skeg was proposed by Tanaka and Ikeda (1985), and was improved by Ikeda and Umeda (1990a). Forward speed effect on the roll damping was investigated by Ikeda et al. (1988) and Umeda et. al. (1988).

2.6 FLAT PLANING CRAFT

A planning craft has generally a flat hull. For such flat hulls, the asymmetrical vertical lift force acting the hull bottom in each side creates much larger roll damping than horizontal lift force acting on side of the hull, and the lift component due to vertical lift force is dominant in the roll damping at very fast speed. A prediction method of the roll damping component due to vertical lift was proposed by Ikeda et al. (2000). Fig.8 shows the comparison between measured and predicted roll damping at very high speed. In the method, the measured steady lift coefficient for vertical lift force is used. It was also confirmed that good prediction results can be obtained by using Savisky's formula for prediction of the vertical lift coefficient.

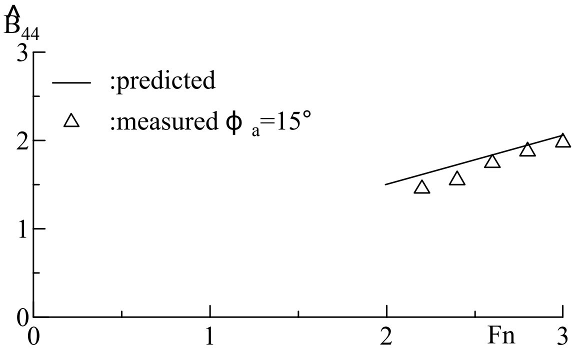

Fig.8 Comparison between predicted and measured roll damping of a hard-chine planning craft with very flat cross sections at very high speed.

2.7 OTHER PROBLEMS

Other problems concerning to the roll damping were investigated in the laboratory of the author as follows; reduction of the bilge keel effect of a shallow draft ships (Tanaka, 1981), increase of the roll damping by a large sonar dome(1994), interaction effects between fin stabilizers and bilge keels(1994), roll damping of bilge keel with fixed fins(1990b), vertical oscillating anti-rolling plates(1993), the roll damping for a twin-skeg ferry(1990b), effect of a flume-type anti-rolling tank(1991).

3. METHOD TO DETERMINE OPTIMUM BILGE KEEL

Fig. 9 shows the predicted results of the bilge keel component of the bilge keel for a full ship with C_B=0.8 and a slender container ship. Each line in the figure shows the predicted roll damping for a constant area of bilge keels, and the aspect ratio, b_{BK}/L, in the horizontal axis is systematically changed. The results demonstrate that for a slender ship bilge keels with large aspect ratio is better, and that for a full ship those with small aspect ratio is better. Although bilge keels of Series 60 with very large aspect ratio show good performance in the figure, such a wide bilge keel may be unrealistic in practice.

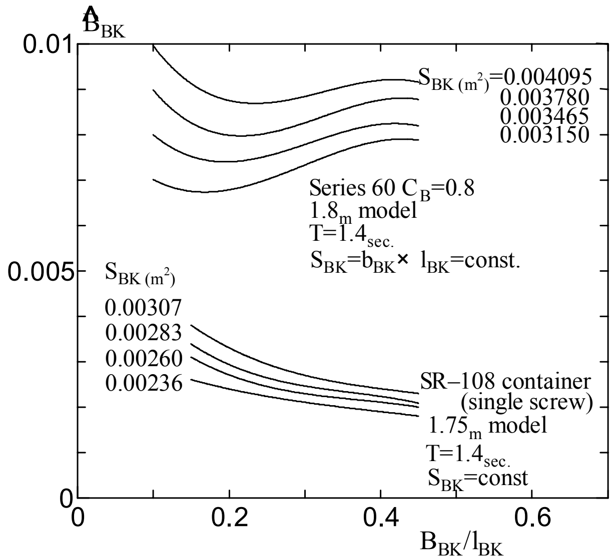

Fig. 9 Predicted bilge keel components by Ikeda's original method with various shapes of bilge keels for full and slender ships

Using the modified prediction method for bilge keels, in which exact shape of cross section and exact locations of bilge keels in it can be taken into account, the optimum location of bilge keels can be easily determined for a special shape of cross section. Fig. 10 shows the bilge keel component of the roll damping for the cross section shown in the same figure for various location of a bilge keel. The result suggests that the locations of No.5 and No.9 give the largest roll damping for a bilge keel and these points are optimum locations for bilge keels.

For three-dimensional hull shapes, the optimum location can be determined in the same manner. A small car-ferry (44m length) is selected as a sample ship, and the bilge keel components for various location of bilge keels at each cross section are predicted as shown in Figs. 11 and 12. We can find optimum location of the bilge keel in each cross section by taking the maximum point of the predicted results. The optimum points for each section can be seen in the body plan of the ferry as shown in Fig. 13.

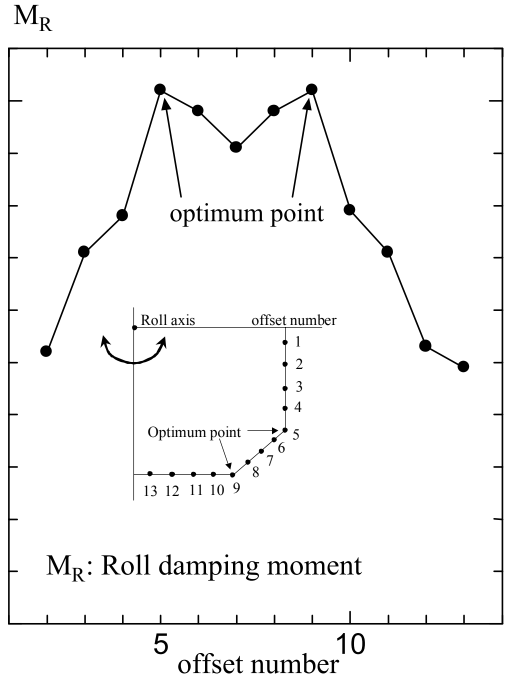

Fig. 10 Variation of roll damping of bilge keels with various locations in cross section having special shape.

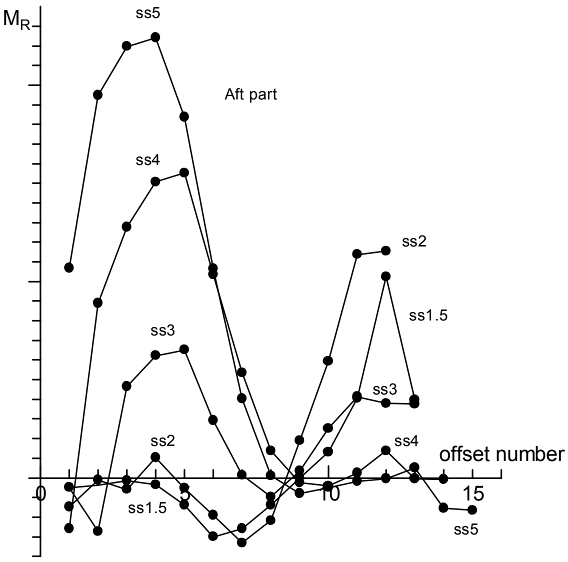

Fig. 11 Variation of roll damping moment created by bilge keels at each section of small car ferry. Locations of bilge keels are changed systematically in cross section.

Table 1 Location and length of bilge keels for optimisation shown in Fig. 14.

Case	Location	L_{BK}/L_{pp}
1	SS 2-8	0.6
2	SS 2-7	0.5
3	SS 3-8	0.5
4	SS 3-7	0.4
5	SS 3-6	0.3
6	SS 4-7	0.3
7	SS 4-6	0.2
8	SS 4-5	0.1
9	SS 5-6	0.1

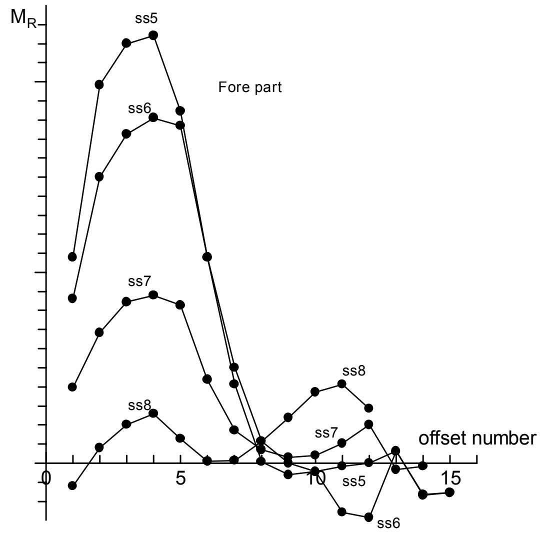

Fig.12 Variation of roll damping moment created by bilge keels at each section of small car-ferry. Locations of bilge keels are changed systematically in cross section.

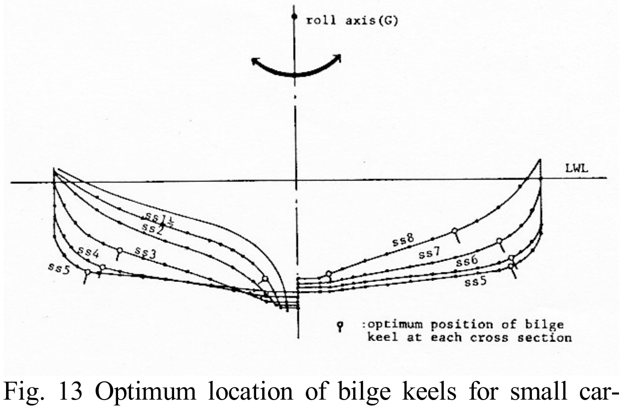

Fig. 13 Optimum location of bilge keels for small car-ferry obtained from Figs. 11 and 12.

In reality, it is impossible to fit the bilge keels on the optimum location shown in Fig.13 because the line connecting the locations of bilge keels in each cross section does not always coincide with longitudinal streamline. If not, the bilge keel must increase the resistance of the ship. Therefore the location of bilge keels should be determined along a streamline to reduce resistance of the ship. More sophisticated methods to determine the optimum bilge keels are needed.

A method developed by Ikeda predicts streamlines on the hull by a slender body theory at first, and then, for each streamline the roll damping is predicted for various aspect ratio of bilge keels. In this method, the bilge keels with smallest area are looked for under the constraint of a given roll damping value. Design valuables in this problem are aspect ratio and location of the bilge keels. Using the method, the optimum bilge keel is obtained for the same car-ferry as shown in Fig.13. The results are shown in Fig. 14. Each line shows the result for a certain required roll damping value. The horizontal axis, case, denotes the location of a bilge keel as shown in Table.1. From the figure, the optimum bilge keel with the smallest area can be determined as shown by black circles. The location of bilge keels for required non-dimensional roll damping coefficient $\hat{B}_{44}$ = 0.02 is shown in Fig. 15.

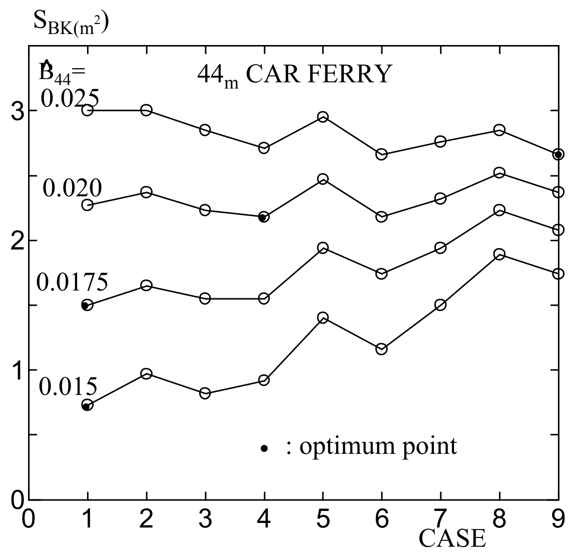

Fig. 14 Variation of area of bilge keel for certain required roll damping. Longitudinal location and aspect ratio of bilge keels at each case are shown in Table 1.

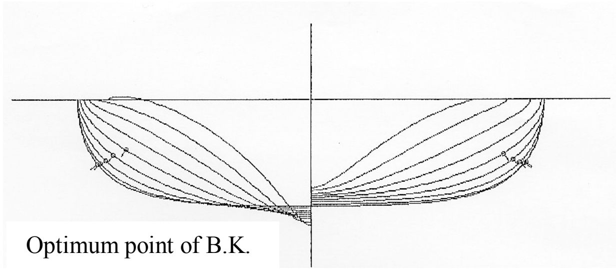

Fig. 15 Optimum location of bilge keels obtained from results shown in Fig. 13.

The required roll damping is determined from various viewpoints. The simplest one is a criterion of roll amplitude in waves. For examples, expected maximum roll amplitude should be lower than 30 degrees in 3m waves. Using a standard prediction method of ship motions, like a strip method, the corresponding required roll damping can be obtained for the criteria.

More sophisticated ways to determine the required roll damping on the basis of capsizing probability were proposed by Fujiwara et al. (1994).

4. CONCLUSIONS

Research activities on the roll damping prediction in Ikeda's laboratory of Osaka Prefecture University are reviewed. The original prediction method for conventional cargo ships proposed 25 years ago have been improved, and many prediction methods for other types of ship have been developed. An optimisation method for bilge keels using these methods is introduced.

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