# Experimental and Theoretical Study on Critical Condition of Bow-Diving

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**ABSTRACT**

Recent model experiments by the authors indicated that bow-diving is one of the crucial capsizing modes for a high-speed vessels travelling in following and quartering seas. Bow-diving is a phenomenon that the bow plows into the water, and initiated from the situation of surf-riding without broaching-to and finally she could capsize with large negative pitch angle. In our previous paper, we discussed the relationship between occurrence of bow-diving and water level at bow under the assumption that heave and pitch motions can be approximated by tracing their static equilibrium, and compared the numerical results with free running capsizing model experiments for several fishing vessels. In this research, model experiments with various ship speeds were conducted to examine the speed-dependence of bow-diving, and show that the model could suffer broaching-to when she is running at relatively lower speed, she could capsize due to bow-diving at intermediate speed and she could be stably surf-riding at higher speed. Moreover we attempted to improve theoretical prediction method by taking nonlinear Froude-Krylov calculation and speed-dependent ship running attitude into account.

**Keywords:** *bow-diving, capsizing, surf-riding, free running model experiment*

## 1. INTRODUCTION

Even now small ships, such as fishing vessels, occasionally capsize when they run in heavy following and quartering seas with high speed. To prevent capsizing phenomena, we conducted free running capsizing model experiments in following and quartering seas for different types of 11 models in the Marine Dynamics Basin at National Research Institute of fisheries Engineering (NRIFE). These experiments showed that the main causes of capsizing in following and quartering seas are pure-loss of stability, broaching-to, parametric resonance and bow-diving. Nowadays pure loss of stability, broaching-to and parametric resonance could be theoretically well explained (e.g. Umeda et al., 2000, Hashimoto et al., 2004, Bulian et al., 2003), however few attempts have been done on bow-diving (e.g. Jullumstroee, 1990, Renilson et al., 2000, Taguchi et al., 2000) because it is newly recognized phenomenon from experimental research.

In the previous work (Matsuda et al., 2004), the authors conducted free running model experiments for 3 types of fishing vessels to understand mechanism of bow-diving, and discussed the possibility of theoretical prediction of bow-diving occurrence by calculating relative water height to the bulwark top at bow under the assumption that heave and pitch motions could be calculated by Froude-Krylov assumption with the running attitude for the certain ship forward velocity corresponding to the wave celerity. As a result, the simple calculation of relative height between wave surface and height of bulwark top at bow could roughly estimate occurrence of bow-diving.

In this work, we have conducted free running model experiments for a latest 135 gross tonnage Japanese purse seiner with several Froude numbers. The model capsized due to bow-diving in severe following waves with intermediate propelling power, but experienced stable surf-riding with higher propelling power and did broaching with lower power. This means that a threshold exists for avoiding bow-diving even in surf-riding condition but the previous calculation method cannot predict it. We firstly show the results of free running model experiments of the purse seiner running in following seas. Secondly, we discuss the threshold of bow-diving and theoretical calculation with experimentally obtained ship running attitude as a function of Froude number in calm water and displacement of heave and pitch in waves with the nonlinear Froude-Krylov calculation. Moreover we apply this new calculation method to existing free running model experiments conducted with three fishing vessels.

## 2. EXPERIMENTAL OBSERVATION

Free running model experiments of the latest 135 gross tonnage Japanese purse seiner were carried out in the Marine Dynamics Basin of NRIFE (Fig.1). The body plan of this ship is shown in Fig.2 and its principal particulars are also done in Table 1. The ship model was propelled with an electromotor, whose power was supplied by onboard batteries. The propeller revolution number was controlled by a feed back control. They were steered by an autopilot system whose rudder gain is 1.0. The maximum rudder angle was 35 degrees. Roll, pitch and yaw angle was measured by an optical gyroscope. These measured signals were restored in the onboard computer in a digital form, and the measured yaw angle was used for the auto pilot control.

Wave parameters used in the model test were wave length to ship length ratio, $\lambda/L$, of 1.392 and wave height to wave length, $H/\lambda$, of 0.107.

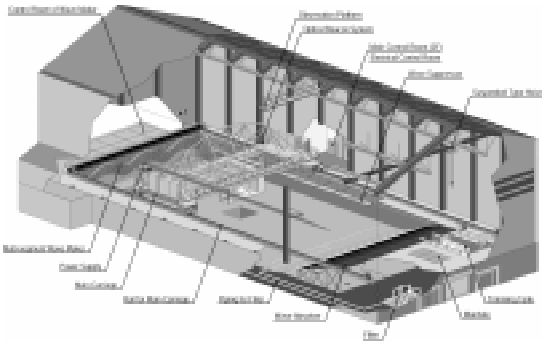

Figure 1  Marine dynamics basin of NRIFE

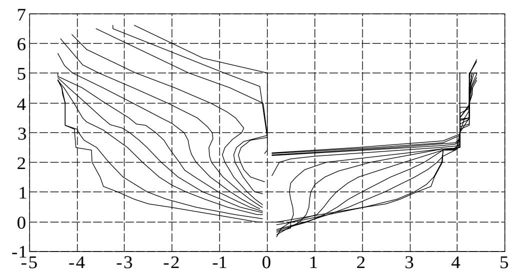

Figure 2  Body plan of the subject ship

Table 1  Principal particulars of the ship

| | ship | model |
|---|---|---|
| Length between perpendiculars: $L_{pp}$ | 38.5m | 2.14m |
| Bredth: $B$ | 8.10m | 0.45m |
| Depth: $D$ | 3.30m | 0.18m |
| Mean draught: $d_m$ | 2.85m | 0.16m |
| Block coefficient: $C_b$ | 0.511 | 0.511 |
| GM | 1.79m | 0.10m |
| Model scale | | 1/18 |

## 3. EXPERIMENTAL RESULTS

Experimental results are shown in Table.2. Bow-diving was observed when model speed is between Fn=0.445 to 0.454, while stable surf-riding appeared over Fn=0.464.

The relationship between Fn and trim angle obtained from the resistance test with free heave and pitch is shown in Fig.3. The trim angle is dramatically increasing where Fn is over than 0.37. Ship-generated waves due to high forward speed induce significant trim by stern and then the bow top is difficult to plow into water. Therefore the model experienced stable surf-riding instead of bow-diving.

Table 2 Experimental results

| Propeller revolution(rps) | Fn | Results |
|---|---|---|
| 40.00 | 0.492 | Stable surf-riding |
| 38.75 | 0.482 | Stable surf-riding |
| 37.50 | 0.471 | Stable surf-riding |
| 36.25 | 0.464 | Stable surf-riding |
| 35.00 | 0.454 | Bow-diving |
| 33.75 | 0.445 | Bow-diving |
| 32.50 | 0.435 | Stable surf-riding |
| 31.25 | 0.425 | Broaching-to |
| 30.00 | 0.415 | Broaching-to |
| 28.75 | 0.405 | Periodic |

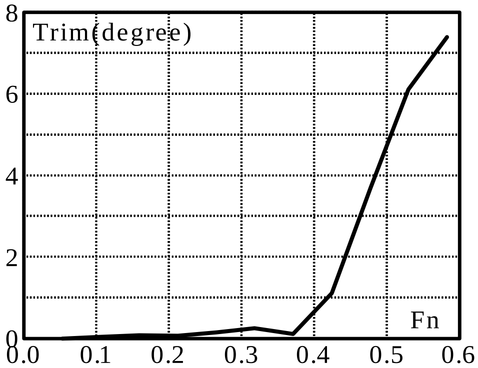


Figure 3 Relationship between ship speed and trim angle in calm water

## 4. THEORETICAL PREDICTION

From the experimental results, bow-diving occurs when the bulwark top at bow dived into water during transient surf-riding under intermediate propelling power. On the other hand, the bulwark top in higher propelling power did not submerge. Since the encounter frequency of a ship in surf-riding to waves was almost zero, heave and pitch motions can be approximated by tracing a static balance. Therefore, we can calculate a relative vertical distance between bulwark top at bow end and water surface using the static balance calculation to determine whether the bow bulwark top submerges or not.

In the previous paper, we calculated heave and pitch motions in waves from the static balance calculated by the linear Froude-Krylov assumption with running attitude for the ship forward velocity corresponding to the wave celerity. However the model experiments mentioned above for several Froude numbers show that occurrence of bow-diving depend on the propeller revolution. Here ship speed itself was increased by waves from that in still water, however it is difficult to estimate ship speed and attitude during bow-diving accurately. In the experiment, bow-diving occurred before settling down into a steady state of running attitude because ship speed is drastically increased and the bow plows into a wave up-slope immediately. Therefore, in the calculation, we use the experimentally obtained ship attitude at the ordered propeller revolution in calm water. In addition, the nonlinear Froude-Krylov calculation that the wave pressure is integrated up to the wave surface with free heave and pitch is used because wave elevation changes significantly in steep waves where bow-diving could occur. The coordinate systems used in the calculation are shown in Fig.4.

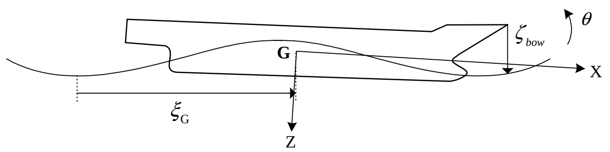


Figure 4 Coordinate Systems

The relative vertical distance between the bulwark top at bow end and the wave surface, $\zeta_r$, can be calculated as follows: (Matsuda et al., 2004)

$$\zeta_r = \zeta_G - x_{bow}\sin\theta - \zeta_{W\,bow} \tag{1}$$

$$\zeta_{W\,bow} = \zeta_a \cos k(x_{bow}\cos\theta + \xi_G) - \frac{1}{2}k\zeta_a{}^2 \cos 2k(x_{bow}\cos\theta + \xi_G) \tag{2}$$

Here $\zeta_G$ is heave including the sinkage due to running, $\zeta_{W\,bow}$ is the wave height at the bow edge, $\zeta_a$ is the wave amplitude, $x_{bow}$ is the horizontal distance between the bow edge and the centre of ship gravity, $\theta$ is the pitch angle including the trim due to running, $k$ is the wave number and $\xi_G$ is the longitudinal position of centre of gravity from a wave trough. If $\zeta_r$ is larger than bull work top height to the still water surface, $\zeta_{still}$ , bow submergence is occurred. Therefore the relative water level of the bulwark top, $\zeta_{bow}$ , is calculated as follows:

$$\zeta_{bow} = \zeta_r - \zeta_{still} \tag{3}$$

If $\zeta_{bow}$ is less than zero, the bulwark top is below the wave surface, which means bow-diving occurs.

$\zeta_{bow}$ at Fn=0.454 is shown in Fig.5. Minimum $\zeta_{bow}$ is just zero around $\xi_G / \lambda$ of 0.9. On the other hand, minimum $\zeta_{bow}$ at Fn=0.464 is positive. This result agrees with the experimental results shown in Table.2. All results of calculation are shown in Table.3. The results agree well with the experimental results. By the way, at the lower propelling power area, experimental results were broaching-to. It might be because that the lower propelling power could not make enough rudder force against yaw moment acting on the hull, then she could not keep her course.

Table 3 Comparison between experimental and calculated results

| Fn | Experiments | Calculations |
|---|---|---|
| 0.492 | Stable surf-riding | Stable surf-riding |
| 0.482 | Stable surf-riding | Stable surf-riding |
| 0.471 | Stable surf-riding | Stable surf-riding |
| 0.464 | Stable surf-riding | Stable surf-riding |
| 0.454 | Bow-diving | Bow-diving |
| 0.445 | Bow-diving | Bow-diving |
| 0.435 | Stable surf-riding | Bow-diving |
| 0.425 | Broaching-to | Bow-diving |
| 0.415 | Broaching-to | Bow-diving |
| 0.405 | Periodic | Bow-diving |

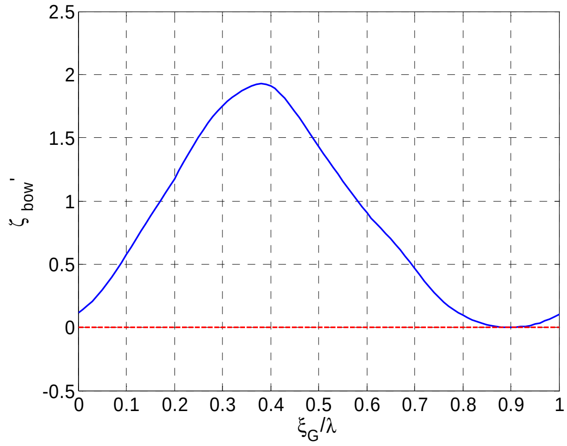


Figure 5 Relative height between bulwark top at bow end and wave surface at Fn=0.454, λ/L=1.392 and H/ λ=0.107

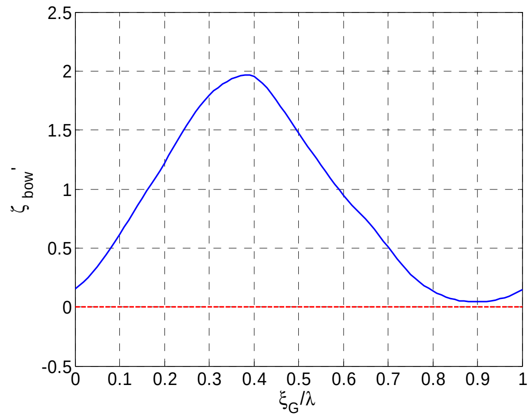


Figure 6 Relative height between bulwark top at bow end and wave surface at Fn=0.464, λ/L=1.392 and H/ λ=0.107

## 5. INVESTIGATION FOR OTHER TYPES OF FISHING VESSELS

We attempt to apply the new calculation method using the speed-dependent ship attitude to the other three types of fishing vessels which are a 80 gross tonnage Japanese purse seiner (Ship A), a North European purse seiner (Ship B) and a fishing vessel for set nets (Ship C). The general arrangements of these ships are shown in Figs.7-9. Principal particulars of these ships are shown in Table 4. Ship A is one of the typical Japanese purse seiners, which experienced some capsizing accidents in recent years. Ship B is an European purse seiner having much larger freeboard. Ship C is a semi-planing boat having large beam to depth ratio.

Free running model experiments had been conducted by the authors before for the three ships. From the experiment results, Ship A and Ship C suffered bow-diving and capsizing, but Ship B had not suffered bow-diving but stable surf-riding in similar wave condition as the 135GT Japanese purse seiner. The detail of these experimental results including time series can be found in the literature. (Matsuda et al., 2004) We carry out the comparison between free running model experiments for these three additional ships and theoretical calculations based on the new theoretical method mentioned in this paper.

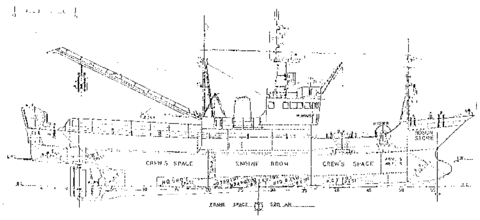

Figure 7  General arrangement of Ship A

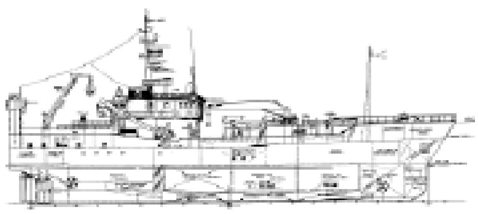

Figure 8  General arrangement of Ship B

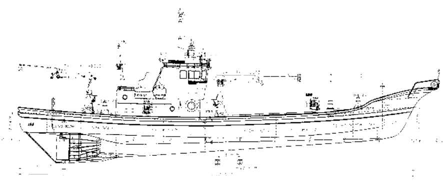

Figure 9  General arrangement of Ship C

From these results, we can conclude that the new theoretical prediction method reasonably explains the speed-dependence of the bow-diving observed in the free running model experiment for the Japanese 135GT purse seiner, and can predict the bow-diving occurrence for the displacement type of 80GT Japanese purse seiner and European purse seiner, but cannot predict for the semi-planing vessel which is not categorized into the ordinary displacement type ship.

Table 4. Principal particulars of the ships

| Ship | A | B | C |
|---|---|---|---|
| Length between perpendiculars: $L_{pp}$ | 29.0m | 55.0m | 21.2m |
| Bredth: $B$ | 6.80m | 12.0m | 4.82m |
| Depth: $D$ | 2.60m | 7.60m | 1.26m |
| Mean draught: $d_m$ | 2.30m | 5.25m | 0.99m |
| Block coefficient: $C_b$ | 0.577 | 0.657 | 0.657 |
| Model scale | 1/12.6 | 1/25 | 1/8 |

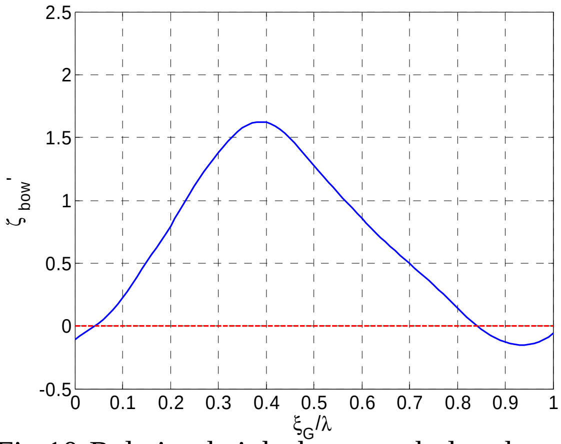


Fig.10 Relative height between bulwark top to wave surface at bow (Ship A) with H/λ= 0.111 and λ/L=1.41

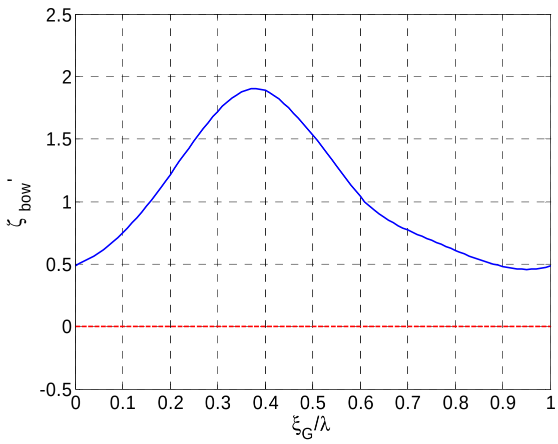


Fig.11 Relative height between bulwark top to wave surface at bow (Ship B) with H/λ= 0.106 and λ/L=1.39

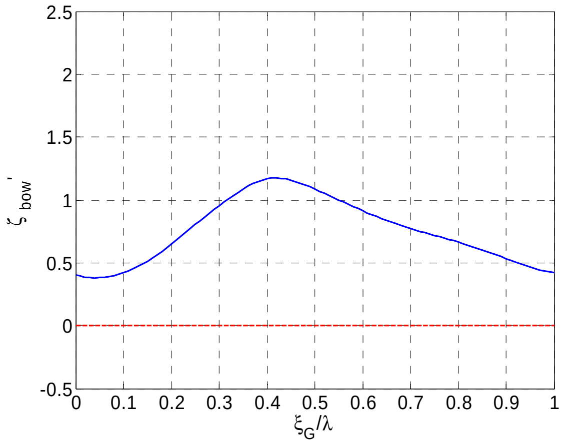


Fig.12 Relative height between bulwark top to wave surface at bow (Ship C) with $H/\lambda= 0.11$ and $\lambda/L=1.38$

## 6. CONCLUSIONS

Following conclusions are obtained from this experimental and theoretical research on new capsizing mode of bow-diving:

1) Free running model experiment for a 135 gross tonnage Japanese purse seiner demonstrates that bow-diving occurred with intermediate propeller power, i.e. 0.44~0.46 of the Froude number.

2) The calculation of relative height between bulwark top at bow and wave surface with the experimentally obtained speed-dependent running attitude in calm water could reasonably estimate the threshold of bow-diving for the 135 gross tonnage Japanese purse seiner.

3) The calculations based on the proposed theoretical prediction method agree also well with free running model experiments for the 80 gross tonnage Japanese purse seiner and European purse seiner.

4) The proposed theoretical prediction method for bow-diving could be applicable for displacement type vessels but not for non-displacement type ones.

## 7. ACKNOWLEDMENTS


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