

# ***Hull-Vane® Submerged-Elevation Optimization for Improved Seakeeping Performance: A Case Study of an Orela Crew Boat***

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**Abstract:** Effects of the Hull Vane®'s submerged elevation on seakeeping performance are studied. As a case study, the Orela planning-hull crew boat is considered. Three foil's submerged elevations are investigated:  $h/T = 1.5, 1.0$  and  $0.75$ , where  $h$  is the submerged elevation and  $T$  is the design draft. Model tests were done and the experimental data were verified using results of numerical simulation. In all cases, the Hull Vane® results in a decrease of both the heave and the pitch responses. For a sailing boat with 22-knots speed ( $Fr = 0.57$ ) in sea state 4 head seas, the decrease of heave rms reaches 18.9% and the decrease of pitch rms reaches 20.4%. Furthermore, for the same ship speed, the shallower the foil's submerged elevation, the smaller the decrease of the heave response but the larger the decrease of the pitch response, compared to the case without foil.

## **1. Introduction**

Hull Vane® is a fixed hydrofoil attached to a ship at the stern below the transom with the purpose to reduce the ship resistance and to improve the seakeeping performance. Hull Vane® was invented by van Oossanen in 1992 and patented in 2002. The mechanism of the Hull Vane® is described in [1]. Due to the ship resistance reduction and seakeeping characteristic improvement, the application of a Hull Vane® results in a reduced fuel consumption and a higher comfort level for the crew and passengers.

For relatively large vessels, effects of the Hull Vane® on the motions of ferries and RoPax vessels (167 m Norbank) are reported in [2]. Seakeeping tests (167 m container vessel Rijnborg) were performed at MARIN, Wageningen, and The Netherlands, measuring the heave response amplitude operator (RAO), pitch RAO and required thrust. They reported the pitch RAO was reduced but the heave RAO was on the contrary increased (particularly at lower frequencies) with the application of

a Hull Vane<sup>®</sup>. Furthermore, numerical simulation results show that the pitch amplitude decreases approximately 4.9%, which is much smaller than that observed in smaller ships (up to 20%). The Hull Vane<sup>®</sup> clearly reduced the pitch motion but its effect on the heave motion was suggested to depend on the wave frequency and the resulting phase shift between the pitch and the heave motions.

Studies of seakeeping-performance improvement due to the application of a Hull Vane<sup>®</sup> utilizing computational fluid dynamics (CFD) were reported in [3, 4].

In [3], effects of the Hull Vane<sup>®</sup> on fuel consumption and seakeeping performance applied to a 108 m Hollands-class ocean-going patrol vessel (OPV) of the Royal Netherlands Navy was reported. At the speed where most fuel was consumed (17.5 knots), the fuel saving reached 15.3 % when a Hull Vane<sup>®</sup> was attached. On yearly basis, a reduction of 12.5% fuel consumption was achieved. Furthermore, the vertical acceleration (calculated on the helicopter deck) and the pitching motion were reduced, consistent with [2].

In [4], the performances of Hull Vane<sup>®</sup>, interceptors, trim wedges and ballasting were compared. Regarding the Hull Vane<sup>®</sup>, five foil placements were considered, varying in the longitudinal and vertical directions. In all the Froude-number ranges being considered ( $0.2 < Fr < 0.8$ ), the Hull Vane<sup>®</sup> reduced the bow-up running trim. The Hull Vane<sup>®</sup> was the most efficient device in reducing the pitch motion. However, the effects of varying foil's submerged elevation on the pitch motion (seakeeping) were not elaborated.

Assuming the Hull Vane<sup>®</sup> will work for all types of ship, some practical questions are arisen, which have not sufficiently been explored:

- i. What type and size of foil are the most optimum ones for a certain ship (or a certain type of ship with similar dimension)?
- ii. What is the most optimum foil's placement relative to the ship hull, both in the longitudinal and vertical directions?

Although in [4] the importance of foil's placement has been recognized in affecting the ship resistance and seakeeping performance, a systematic investigation into this matter is still lacking.

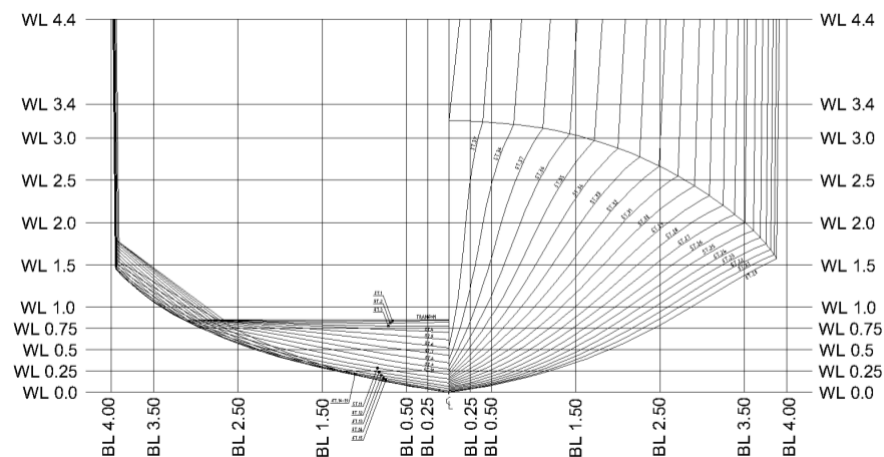


Figure 1. Body plan of the crew boat.

The purpose of the present study is to systematically investigate the effects of foil's submerged elevation on the seakeeping performance. Three variations of foil placement in the vertical direction are investigated:  $h/T = 1.5$ ,  $1.0$  and  $0.75$ , where  $h$  is the foil's submerged elevation and  $T$  is the design draft. The same placement in the longitudinal direction is considered in all cases, namely, the foil's leading edge is precisely below the transom.

As a case study, the Orela crew boat is considered, which is a semi-planing boat with a target top speed of 28 knots (Froude number  $Fr = 0.73$ ). Figure 1 shows the body plan of the boat. The boat's principal particulars are summarized in Table 1.

The optimum foil size with maximum lift-to-drag ratio was obtained from CFD-simulations of foil alone [5]. The used foil's type is NACA 64(1)212 and the struts are NACA 0010 symmetrical foil. In the simulations, the foil's span was kept the same as the boat's beam (8.0 m). It was found that the optimum chord length was 1.2 m with foil's aspect ratio of 6.67. The optimum foil's angle of attack was  $2^\circ$ . The foil is attached to the ship's hull using two struts with the chord length equals that of the Hull Vane<sup>®</sup>.

Table 1. Principal particulars of the crew boat.

Length overall ( $L_{OA}$ )	40.00 m
Length between perpendiculars ( $L_{BP}$ )	39.90 m
Beam ( $B$ )	8.00 m
Height ( $H$ )	4.40 m
Draft ( $T$ )	1.70 m
Displacement ( $\Delta$ )	242.72 t

## 2. Methods

### 2.1. Experiments

Experiments were performed at the Hydrodynamics Laboratory of the Faculty of Marine Technology, ITS Surabaya, Indonesia. The towing tank is 50 m long and 3 m wide. The water depth is 2 m.

A scaled model of the boat with foil and struts was designed and manufactured with a scale of 1:40. The ship hull was made from fibre-glass reinforced plastics (FRP). The ship model was coated with paint and resin. The stern foil and the struts were first made from brass material. Later, they were replaced by those from mica. Measurement results have shown that the foil and strut material, either using brass or mica, has a negligible effect on the experimental results. The ship model with stern foil attached to the hull using two struts is shown in Figure 2.

To measure the heave and pitch motions, two sensors (linear variable differential transformer; LVDT) were placed respectively at the bow and the stern of the model measuring the ship's vertical displacements. Before performing a measurement, the LVDT's were calibrated by pulling a string 5 cm distance and simultaneously measuring the corresponding voltage. The heave and pitch motions were derived from the recorded ship displacements at the bow and the stern.

Tests in regular head waves were conducted to determine the heave and pitch RAO's of the boat with zero speed and with 22-knots speed ( $Fr = 0.57$ ). Seven wave periods were tested ( $T = 3.16, 4.43, 5.69, 6.96, 8.22, 9.49$  and  $10.75$  s), each with wave amplitude of 0.48 m (full scale).

For tests with a sailing boat, the frequency encounter is calculated as follows:

$$\omega_e = \omega \left( 1 - \frac{\omega V_s}{g} \cos \mu \right) \quad (1)$$

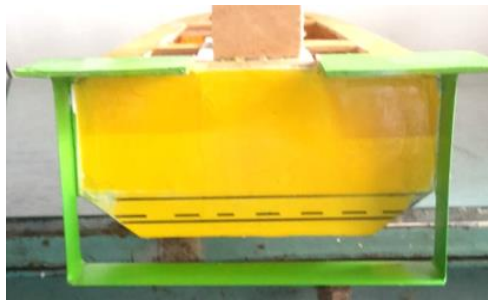
Where  $\omega_e$  is the encounter frequency,  $\omega$  is the wave frequency,  $V_s$  is the ship speed,  $g$  is the gravitational acceleration and  $\mu$  is the wave heading ( $180^\circ$  in the present case).

## 2.2. Numerical Simulations

The experimental heave and pitch RAO's are compared with those obtained from numerical simulations based on radiation/diffraction theory [6, 7]. To ensure independency of the results from the number of cells (elements) being used in the simulations, tests were performed to comply with the grid-independence criterion. This is defined as that the difference between two subsequently calculated area under the RAO curve is less than 2% where the number of cells in the latter simulation is approximately twice of that in the former; cf. [8].



(a)



(b)

Figure 2. Model of the crew boat with stern foil attached to the hull using two struts (scale 1:40): side view (a) and aft view (b)

To determine the ship response in irregular waves, the following relation is used:

$$S_{rr}(\omega) = (RAO)^2 S_{\zeta\zeta}(\omega) \quad (2)$$

Where,  $S_{rr}(\omega)$  is the response spectrum,  $S_{\zeta\zeta}(\omega)$  is the wave spectrum and  $RAO$  is the response amplitude operator.

The root mean squared (rms) values of the heave and pitch responses are calculated utilizing the response spectrum as follows:

$$\text{rms} = \sqrt{m_{0,r}} \quad (3)$$

Where,  $m_{0,r}$  is the area under the response spectrum [9].

## 3. Results and Discussions

### 3.1. Heave and Pitch RAO's

Figure 3 shows the experimental heave RAO's for zero speed for the cases  $h/T = 1.5, 1.0, 0.75$  and without stern foil. In Figure 3, the numerical simulation result for the case without foil is also

shown. Overall, the numerical result underestimates the experimental data. Looking at the experimental data, the application of a stern foil decreases the heave RAO (compared to the case without foil). The submerged elevation  $h/T = 1.0$  seems to have the largest response compared to the cases  $h/T = 1.5$  and  $0.75$ . To ascertain a definite conclusion, the response spectra will be calculated together with the response rms-values in Subsection III B below.

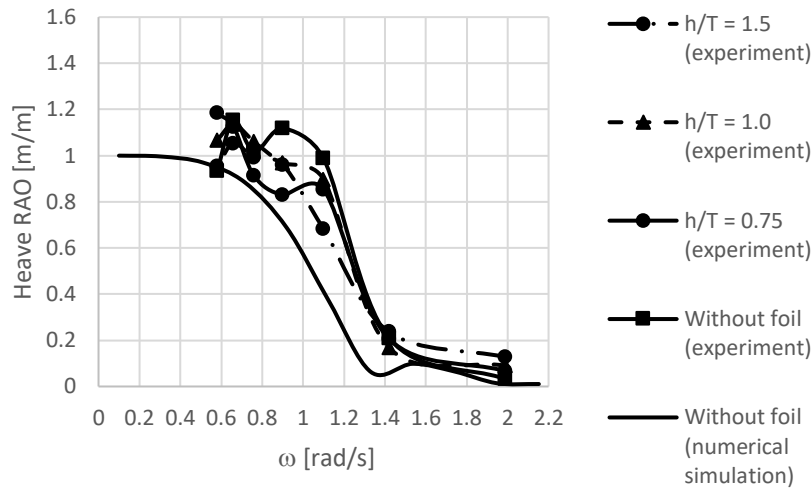


Figure 3. Heave RAO's for zero speed obtained from experiments and numerical simulation.

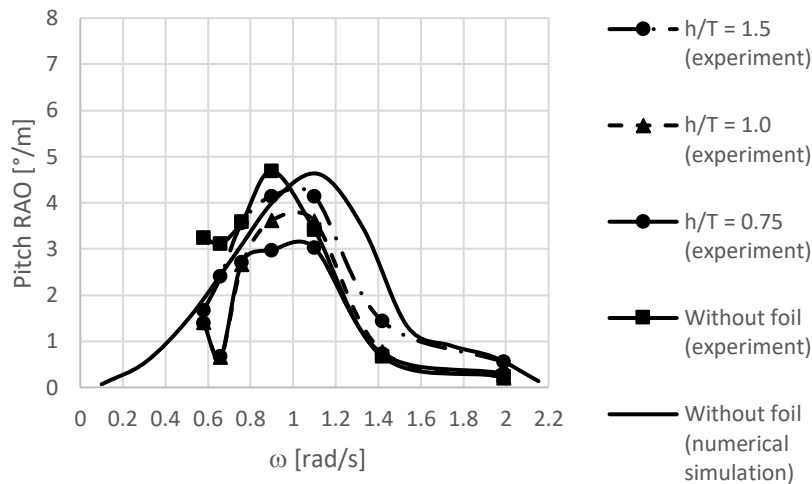


Figure 4. Pitch RAO's for zero speed obtained from experiments and numerical simulation.

Figure 4 shows the experimental pitch RAO's for zero speed for the cases  $h/T = 1.5$ ,  $1.0$ ,  $0.75$  and without stern foil. In Figure 4, the numerical simulation result for the case without foil is also shown. Looking at the experimental data, the case with  $h/T = 0.75$  (the shallowest submerged elevation) gives the lowest pitch response.

Figure 5 shows the experimental heave RAO's for 22-knots speed ( $Fr = 0.57$ ) for the cases  $h/T = 1.5$ ,  $1.0$ ,  $0.75$  and without stern foil. In Figure 5, the numerical simulation result for the case without foil is also shown. In general, the numerical result underestimates the experimental data as for the zero-speed case (Figure 3). Looking at the experimental data, the application of a stern foil decreases the heave response. The case with  $h/T = 1.5$  gives the lowest response compared to the cases  $h/T = 1.0$  and

0.75. In addition, due to the ship sailing in head waves ( $Fr = 0.57$ ), the magnitude of the heave RAO increases and the frequency range with significant response becomes broader compared to the zero-speed case (larger response, as expected).

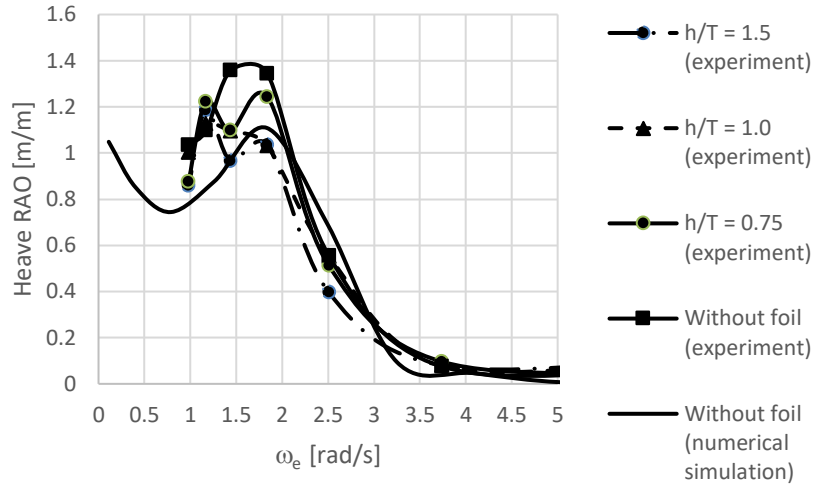


Figure 5. Heave RAO's for 22-knots speed ( $Fr = 0.57$ ) obtained from experiments and numerical simulation

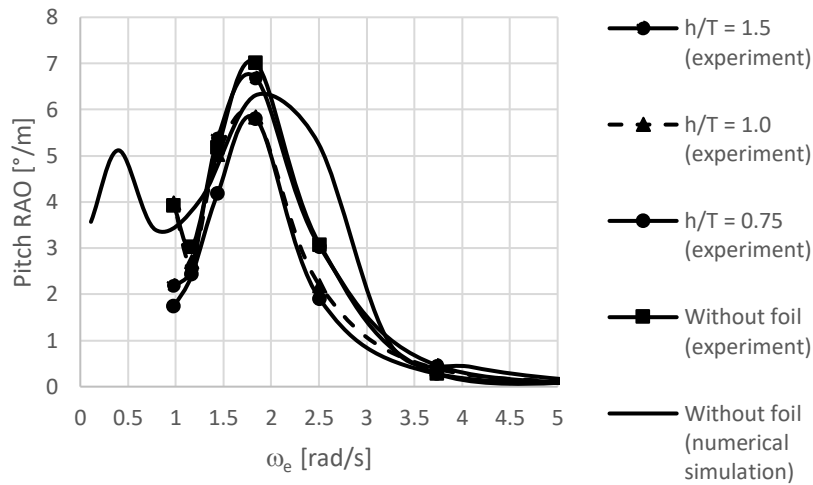


Figure 6. Pitch RAO's for 22-knots speed ( $Fr = 0.57$ ) obtained from experiments and numerical simulation.

Figure 6 shows the experimental pitch RAO's for 22-knots speed ( $Fr = 0.57$ ) for the cases  $h/T = 1.5, 1.0, 0.75$  and without stern foil. In Figure 6, the numerical simulation result for the case without foil is also shown. Considering the experimental data, the application of a stern foil decreases the pitch response, with the lowest response resulted from  $h/T = 0.75$  (the shallowest submerged elevation).

### 3.2. Heave and Pitch Spectra

From the observations of heave and pitch RAO's presented above, the application of the stern foil results in a decrease of heave and pitch RAO's. To make a clearer interpretation of the results, the response spectra will be calculated in this subsection using (2). For that purpose, the response spectra in sea state 4 head seas are considered, for which the ITTC spectrum is utilized [9].

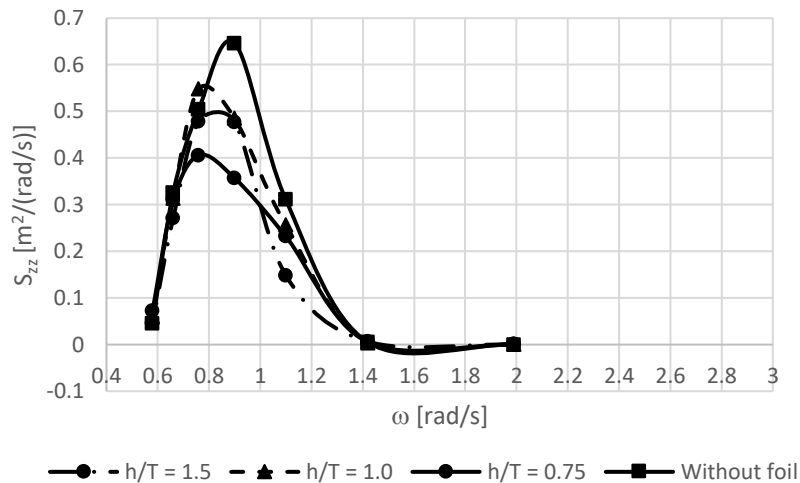


Figure 7. Heave spectra for zero speed in sea state 4, obtained from experimental heave RAO's and utilizing ITTC wave spectrum.

Figure 7 shows the heave spectra and Figure 8 the pitch spectra for zero speed, utilizing the experimental heave and pitch RAO's, respectively. Similar plots as shown in Figure 7 and 8 can be presented for the heave and pitch spectra at 22-knots speed (not shown). Figure 7 and 8 clearly show that utilizing a stern foil decreases the heave and pitch responses.

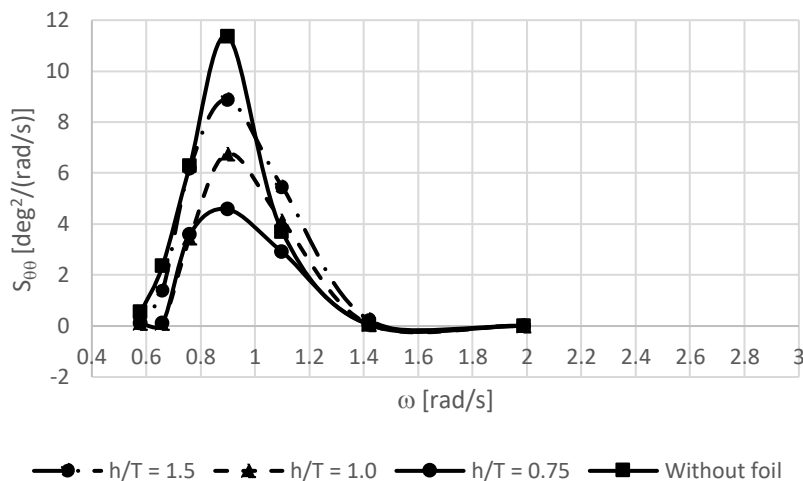


Figure 8. Pitch spectra for zero speed in sea state 4, obtained from experimental heave RAO's and utilizing ITTC wave spectrum

To evaluate which foil's submerged elevation will give the smallest response, the root mean squared (rms) values of the responses are calculated, as summarized in Table 2. For the zero-speed case, the submerged elevation  $h/T = 0.75$  consistently gives the lowest heave and pitch rms. The

decrease of heave rms is approximately 15.5% and that of pitch rms is approximately 28.2 % compared to the case without foil.

Table 2. Root mean squared (rms) values of heave and pitch in sea state 4.

	Zero speed		22-knots speed	
	Heave [m]	Pitch [°]	Heave [m]	Pitch [°]
$h/T = 1.5$	0.494	2.16	0.561	2.87
$h/T = 1.0$	0.542	1.79	0.590	2.64
$h/T = 0.75$	0.492	1.55	0.633	2.38
Without foil	0.582	2.16	0.692	2.99

For the 22-knots speed ( $Fr = 0.57$ ), the submerged elevation  $h/T = 0.75$  also gives the lowest pitch rms. The decrease reaches 20.4%. However, for the heave response, the submerged elevation  $h/T = 1.5$  gives the lowest rms value. The decrease reaches 18.9%. For the submerged elevation  $h/T = 0.75$ , the decrease of the heave rms is only approximately 8.5%.

Results from tank tests performed at the Wolfson unit on the 42 m yacht *Alive* show a decrease of pitch rms of 4.6% [2], which is much smaller than that observed in the present study. Furthermore, in [4], considering a sailing ship ( $Fr = 0.6$ ) in regular head waves, they reported a decrease of pitch amplitude of 20.9% when applying a Hull Vane<sup>®</sup>, comparable to the present observation.

The present results show a consistent decrease of heave and pitch responses when a Hull Vane<sup>®</sup> is applied. Considering the pitch response, the present results are consistent with [1-4]. However, considering the heave RAO, [2] reported a frequency-dependent result whether a decrease or an increase of RAO would take place, which was ascribed to the resulting phase shift between the pitch and the heave motions. Further studies are necessary to interpret the results presented above.

#### 4. Conclusions

The application of a Hull Vane<sup>®</sup> to the Orelia crew boat results in a decrease of the heave and pitch responses for all three foil's submerged elevations considered:  $h/T = 1.5$ , 1.0 and 0.75, where  $h$  is the submerged elevation and  $T$  is the design draft. For a sailing boat ( $Fr = 0.57$ ) in sea state 4 head seas, the decrease of heave rms reaches 18.9% and the decrease of pitch rms reaches 20.4%. Considering the pitch response, the present results are consistent with previous studies [1-4]. However, regarding the heave response, [2] reported a frequency-dependent result whether a decrease or an increase of response would take place, which was ascribed to the resulting phase shift between the pitch and the heave motions. Experimental results from the present study show that, for a sailing ship ( $Fr = 0.57$ ) in head waves, the shallower the foil's submerged elevation, the smaller the decrease of heave response but the larger the decrease of pitch response, compared to the case without foil. Further studies are necessary to interpret the results of the present study.

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