Utilization of Wave Energy to Improve Propulsive and Seekeeping Performances of a Ship in Rough Weather

Hroshi Isshiki

IMA (Instiute of Mathematical Analysis, Osaka, Japan)
Osaka-Sayama, Japan
Email: isshiki [AT] dab.hi-ho.ne.jp

ABSTRACT— ***According to IMO's Energy Efficiency Design Index (EEDI), the CO2 emission of a ship must be cut 30% in 2025. This would invite serious speed drop of a ship in rough seas and deteriorate the safety of a ship drastically. The present paper discusses to utilize wave energies abundant in rough seas to overcome the danger. A very small hydrofoil fixed to the ship bow could reduce the ship motion and generate thrust enough to counter the speed drop mentioned above and make a ship much safer.***

Keywords— EEDI, Hydrofoil, Wave energy utilization, Reduction of speed drop, Riding comfort increase

1. INTRODUCTION

According to IMO's Energy Efficiency Design Index (EEDI), the CO2 emission of a ship must be cut drastically in ten years to come [1-3]. The definition of EEDI and a formulae related to EEDI are given by Eqs. (1) and (2)

$$EEDI\left(g/(ton\cdot mile)\right)=\frac{Conv.\ coefft.\ to\ CO_2\times Fuel\ Consump.(g/kWh)\times Eng.\ Pow.(kW)}{DWT(ton)\times Velocity(mile/h)}, \tag{1}$$

$$Attained EEDI \le Required EEDI = Reference\ EEDI = Reference(a\times DWT^{-C})\times\left(1-\frac{X}{100}\right). \tag{2}$$

The examples of reference line in Eq. (2) is given below

$$Reference(a\times DWT^{-C})=\begin{cases}961.79\times DWT^{-0.477} & \text{for a bulk carrear}\\ 1218.80\times DWT^{-0.488} & \text{for a tanker}\end{cases}. \tag{3}$$

The CO2 emission is reduced 10% in 2015, 20% in 2020 and 30% in 2025 with 2013 as the basis. The example in case of a bulk carrier is shown in in Fig. 1. Roughly speaking, the main engine output becomes 30% smaller. This is a very serious situation for ship designers.

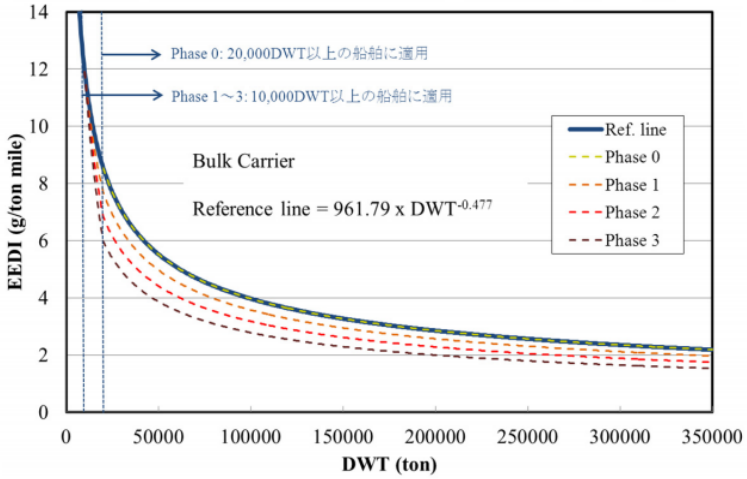


Figure 1: Reference Line and EEDI (Bulk Carrier) (NK Tech. Ref. [2])

In order to satisfy EEDI, we must increase the propulsive efficiency in calm water to reduce the main engine power. However, if the engine power is much reduced, the ship speed is much reduced under rough weather, and the safety of a ship is considerably lowered. So, we must manage to increase the safety of a ship under rough weather condition. The present paper discusses the possibility of utilizing wave energy which exists abundantly in rough seas to ship propulsion

and overcome the speed drop [5-22]. Specifically, we could use a small hydrofoil fixed to the ship bow because of high waves. The hydrofoil reduces the ship motion, and it decreases the resistance increase of a ship in waves. Furthermore, the hydrofoil generates thrust. We can reduce the speed drop of a ship in waves using these two gains of the hydrofoil and can increase the safety of a ship under rough weather.

The reason why the foil size could be small is given below. We aim to reduce the speed drop of a ship in head seas of Beaufort 10. The one third significant wave height $H_W^{1/3}$ and wave length λ are $9m$ and $206.3m$, respectively. Hence, the wave energy is very big. Even a small hydrofoil could produce big force enough to reduce the ship motion and generate big thrust. The image of the bow foil might be given by a hammerhead shark (https://en.wikipedia.org/wiki/Hammerhead_shark). According to an estimation discussed below, the increase of the wetted surface due to the hydrofoil is less than 2% of the total wetted area of the ship hull. On the other hand, according to rough estimation by Prof. K. Sasa of Kobe University, the probability of a bulk carrier encountering the rough weather worse than Beaufort 8 is about 8%. This suggests us that the resistance increase in calm water due to the hydrofoil could be paid enough by the gain obtained by the hydrofoil in rough weathers.

Recently, Yasukawa et al [4] have conducted a very interesting research on the effects of a small bow fin having squid head shape. The object was to reduce the vertical acceleration at the bridge of a domestic container with length 80m. Eventually, the tank test results showed clearly the considerable decrease of the resistance increase in waves. Furthermore, if there is a wave with wave height higher than 1.2m, the resistance increase due to fin is compensated by the decrease of the resistance increase in waves.

2. ROUGH ESTIMATION ON SPEED DROP IN ROUGH WEATHER

2.1. Research Conducted Past

Until 25 years ago, we did series of research at Hitachi Zosen Corporation including experiment of a ship with a hydrofoil on sea [20]. In the preliminary research, we conducted self-running test of a model ship with length 2m in a small wave tank with breadth 1m, depth 0.8m and length of the measuring part 20m. The experimental tank and the model ship with a hydrofoil attached to the bow are shown in Figs. 2 and 3.

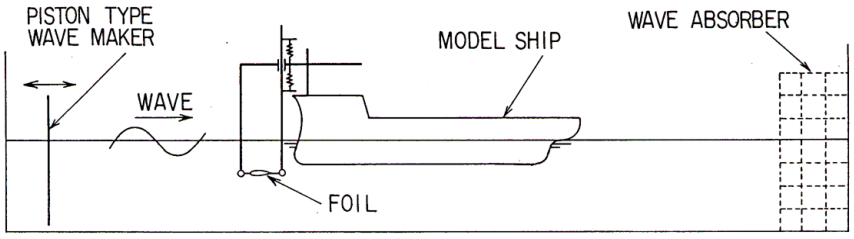


Figure 2: Self-Running Test of a Model Ship with a Foil in Waves

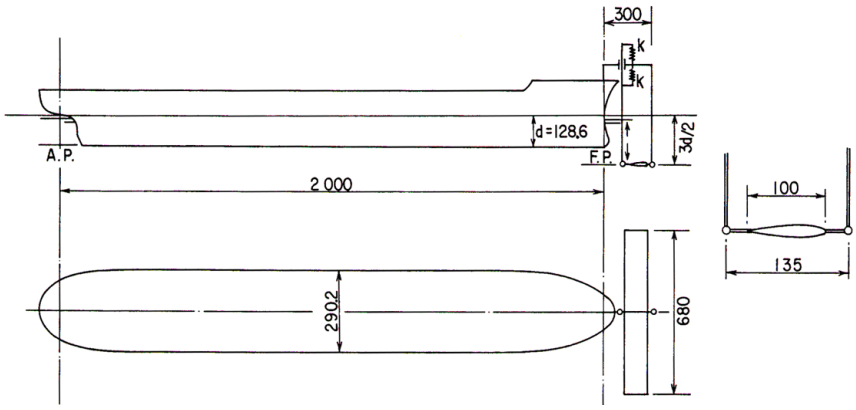


Figure 3: A Model Ship with a Foil

When we conducted this experiment, we aimed to use the wave power as the primary power of the propulsion. Hence, we used a rather big foil. Since a big foil increases considerably the resistance of a ship in calm water, the foil must be extracted from the sea when navigating in cal seas. This invites a serious difficulty to apply the technology to real ships. However, if we use the technology as a countermeasure to EEDI, the foil size is reduced drastically and not required to extract from water in calm seas. So, the possibility becomes very high.

The results of the self-running tests are shown in Figs. 4 and 5. Very interestingly, the model ship runs forward not only in head seas but also in following seas. Generally speaking, the ship runs to the direction of the foil leading edge.

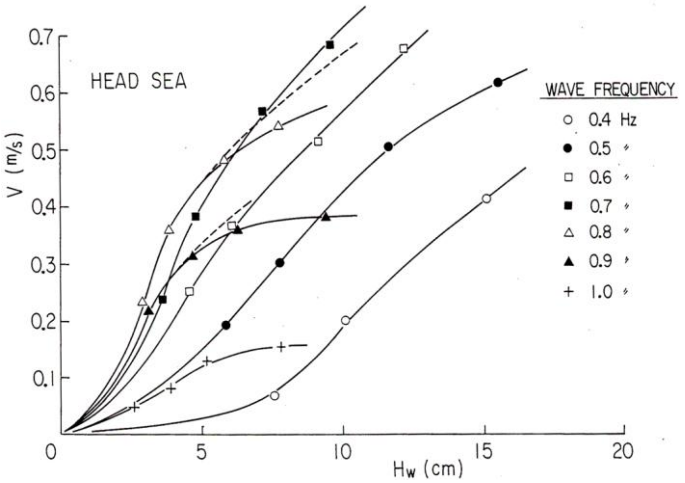


Figure 4: Self-Running Test Results in Head Seas

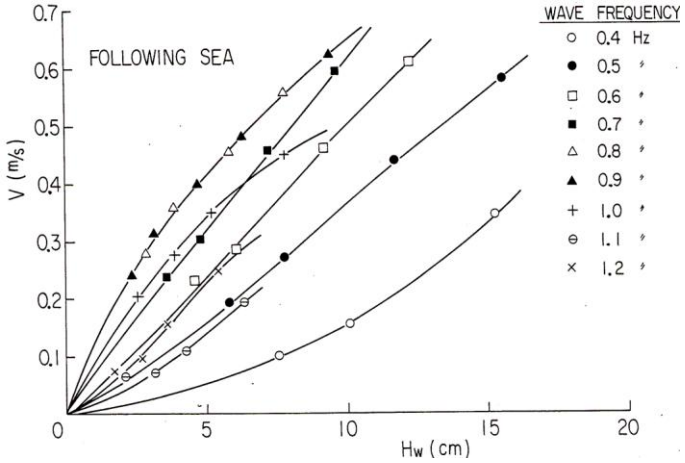


Figure 5: Self-Running Test Results in Following Seas

We used the self-running test results in Fig. 4 to estimate the propulsive performance of a SR108 container ship with length 80m in a wave with wave length $\lambda = 99.8m$ and one third significant wave height $H_W^{1/3} = 3.13m$. The particulars of the ship and foil are shown in Table 1. The effective horse power EHP is shown in Figure 6. The lines with circles, triangles and crosses are EHP of a ship without foil in calm water, a ship without foil in wave and a ship with foil in wave, respectively. The bare hull resistance in wave is significantly large. On the other hand, the resistance of a ship with foil becomes surprisingly small. In this experiment, the full span of the foil is 27.2m, that is, more than double of ship breadth.

Table 1: Particulars of ship and foil

		MODEL	SHIP
SHIP	LENGTH (P.P.) (m)	2.000	80.000
	BREADTH (M^{LD}) (m)	0.290	11.608
	DEPTH (M^{LD}) (m)	0.176	7.040
	DRAFT (m)	0.129	5.144
	BLOCK COEFFICIENT	0.5658	0.5658
FOIL	SECTION OF FOIL	NACA 0015	NACA 0015
	CHORD LENGTH (m)	0.100	4.000
	SPAN LENGTH (m)	0.680	27.200
	DRAFT (IMMERSION) (m)	0.193	7.716

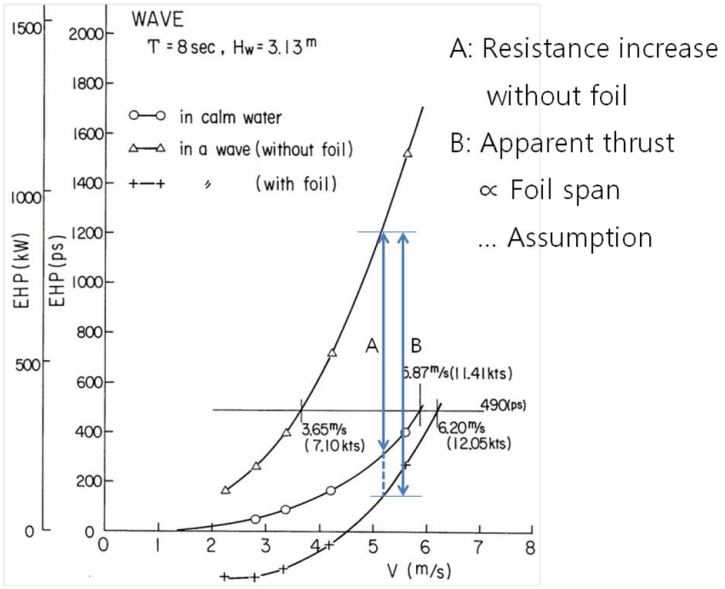


Figure 6: Estimatied *EHP* of a SR108 Container Ship with Length 80m in Waves

2.2 Rough Estimation of Speed Drop of a Target Ship in Rough Sea

SHOPERA (energy efficient SHip OPERAtion) is an EC-funded collaborative project involving several stakeholders in the maritime industry, tasked with improving ship safety while achieving the required reduction in carbon emissions due to EEDI. The Japanese Society of Naval Architects and Ocean Engineers is also conducting similar research and will also report its findings to IMO [3]. The Japanese task force has selected two types of big ships to investigate the safety in adverse conditions. One of them is a tanker KVLCC2 with length 320.0m, displacement 313,000m^3 and block coefficient 0.81 in full. The other is a bulk carrier HandyMax B/C with length 178.0m, displacement 47,500 m^3 and block coefficient 0.715. In the present paper, we selected HandyMax B/C as a target ship.

The sea states are shown in Table 2 below. We consider the most severe condition to the ship operation. Namely, we study how to reduce the speed drop in head seas of Beaufort 10.

Table 2: Sea states

Beaufort	$H_{1/3}$ (m)	T_{Wave} (s)	λ (m)	P (kNms^{-1})	P_{head} (kNms^{-1}) at V=8ms^{-1}	U_{Wind} (m/s)
6	3.0	6.69	69.82	58.964	149.369	12.35
7	4.0	7.72	92.97	120.963	281.683	15.55
8	5.5	9.05	127.8	268.095	571.956	19.0
9	7.0	10.2	162.3	489.453	981.658	22.65
10	9.0	11.5	206.3	912.216	1725.861	26.5

We estimate the propulsive performance of Target Ship (TS), HandyMax B/C using the data of Refeence Ship (RS) SR108. Namely, we obtain the performance of RS having the same ship length with TS under Beaufort 10 and estimate the performance of TS very roughly. In the following, we use the name HandyMax B/C* to distinguish it from original HandyMax B/C. For the appropriate estimation, we must match the wave condition. The (wave length)/(ship length) λ/L for RS is $99.84/80.0 = 1.25$ and that for TS is $206.3/178.0 = 1.16$ is almost same. The other parameter (wave height)/(ship length) $H_W{}^{1/3}/L$ is $3.13/80.0 = 1.0/25.6$ and that for TS is $9.0/178.0 = 1.0/19.8$. Hence, we must increase $H_W{}^{1/3} = 3.13m$ for RS to $H_W{}^{1/3} = 4.04m$. This means the wave force must be multiplied by $(4.04/3.13)^2 = 1.29^2$.

Let V be ship speed in Fig. 6. A/V is the difference between the resistance of a ship without the foil in waves and that of the ship without foil in calm seas. B/V is the difference between the resistance of a ship without the foil in wave and that of the ship with foil in waves. We call A/V as the resistance increase ΔR of a ship without foil and B/V as the apparent thrust T_F of the foil. Then, the necessary or externally applied thrust T_{Ext} to maintain the specified ship speed is give by

$$R_H + \Delta R - T_F = T_{Ext}\,, \tag{4}$$

where R_H is the resistance of the ship in calm seas.

From Fig. 6, we can obtain the bare hull resistance R_H in calm seas, resistance increase ΔR of bare hull and apparent thrust T_{Ext} of foil. They are shown in Fig. 7.

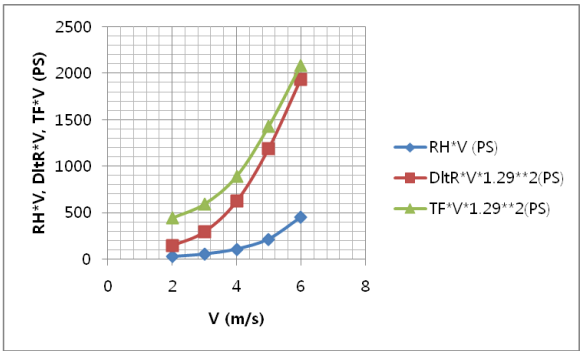


Figure 7: The Bare Hull Resistance R_H in Calm Seas, Resistance Increase ΔR of Bare Hull and Apparent Thrust T_{Ext} of Foil (SR108; T=8s, $H_W{}^{1/3}$=4.04m, Ship Length=80m, Foil Span=27.2m)

3. A STUDIES ON FOIL SIZE

If we assume that the apparent thrust in Fig. 6 is proportional to the full span b of the foil, we could estimate the effects of the span on the propulsive performance of the ship in waves. In Table 3, we show a series of span selections. The foil span of HandyMax B/C* is scaled up according to

$$b_{HandyMax\,B/C*} = \left(L_{HandyMax\,B/C*} / L_{SR108}\right) \times b_{SR108}\,. \tag{5}$$

Table 3: Selection of foil span

Ratio	1/12 span	1/6 span	1/3 span	1/2 span	1/1 span
SR 108	2.27m	4.53	9.07	13.6	27.2
HandyMax B/C*	5.05m	10.08	20.18	30.26	60.52

The effective horse power $EHP = T_{Ext}V$ at the ship speed V for SR106 in the wave with one third significant wave height $H_W{}^{1/3} = 3.13 \times 1.29m = 4.04m$ and period $T = 8\sec$ is estimated by

$$T_{Ext}V = \left[R_H + \left(\Delta R - Ratio \times T_F\right) \times 1.29^2\right]V \tag{6}$$

and is shown in Fig. 8.

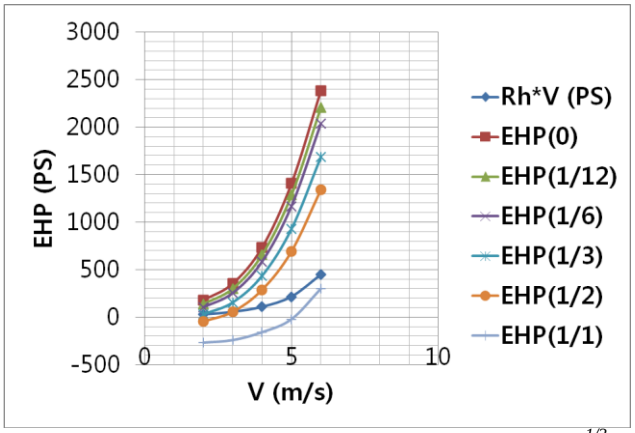


Figure 8: Effects of Foil Span on EHP (SR108; T=8sec, $H_W{}^{1/3}$=4.04m)

From Fig. 8, we can obtain the self-navigating ship speed at the EHP of 490PS and is shown in Table 4. According to this results, if we use "1/6 span", it might be enough as a countermeasure to the 30% reduction of the main engine output due to EEDI.

Table 4: Effect of foil span on ship velocity (Beaufort 10 for Handymax B/C*)

	0 span	**1/12 span**	**1/6 span**	1/3 span	1/2 span	1/1 span
SR 108	**3.4 m/s**	**3.6**	**3.8**	4.15	4.6	6.3
Handymax B/C *	**5.1**	**5.4**	**5.7**	6.23	6.9	9.45
$(V/V_0)^3$	**1**	**1.19**	**1.40**	1.82	2.48	6.36

The foil size in case of 1/6 foil, we show the increase of the wetted area is less than 2%. The wetted area of the ship hull is given by

Wetted area of the ship hull = Wall + Bottom ≒ 178m×11.57m×2+32.26m×178m=9861m^2, (7)

Wetted area of the foil ≒ 10.08m×8.9m×2=13.8m×6.51m×2=179.6m^2, (8)

The ratio of wetted area of the foil to that of the ship hull= $179.6m^2/9861m^2=0.0812$, (9)
Since the ratio is very small, there is no need to extract the foil from water in calm seas.

4. ESTIMATION BY STRIP METHOD

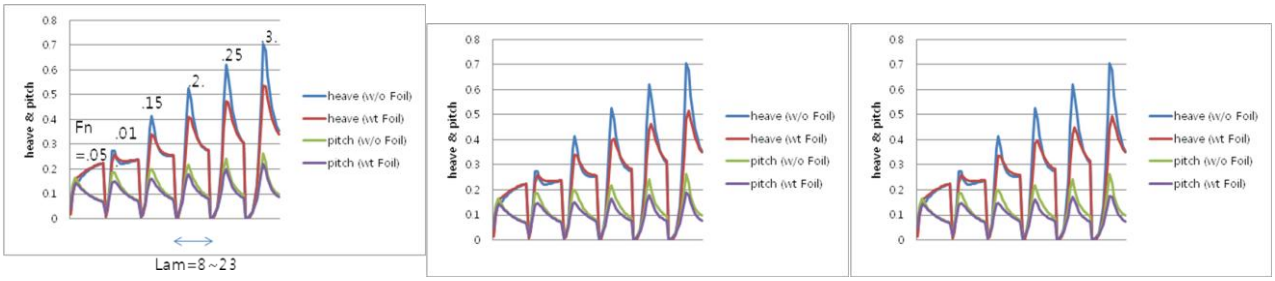
Estimations using strip method was also conducted for a ship with a foil attached to the bow. For convenience, we use a model ship with length 1m having Wigley hull form. The hull and foil particulars are given in Table 5:

Table 5: Particulars of hull and foil

Hull		Foil	
Hull form	Wigley	Section	NACA0015
Length L	1m	Half span s	0.03875m
Breadth B	0.181m	Cord c	0.0366m
Draft d	0.065m	Half area	$0.001418m^2$
Block coefficient Cb	0.715	Center of gravity to pivot l_s	0.5m
Long. radius of gyration/ Ship length	0.25	Pivot to foil geometric center l_1	0.0183m
		Pivot to lift center l_2	-0.0915m
		Foil spring constant k_p	1kgf.m/rad

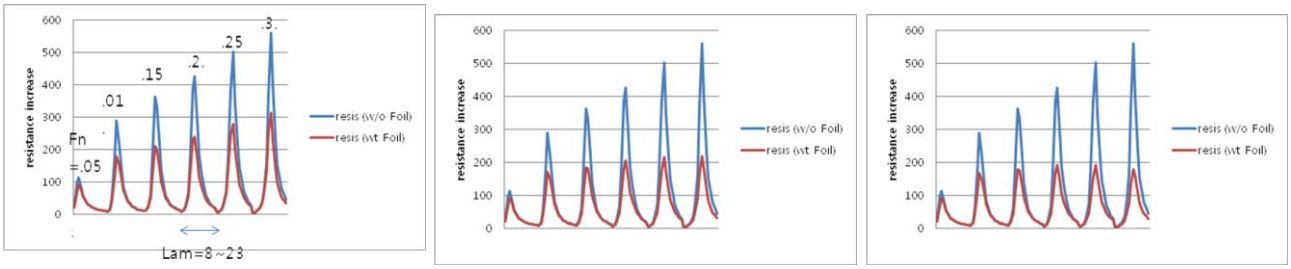
Scale up to the results with ship length $L \neq 1\text{m}$ can be conducted very easily, since the force is proportional to L^3 and velocity to $\sqrt{L}$. Although the hull form is Wigley, the particulars are chosen same to those of HandyMav B/C.

First, we study the effects of the foil spring using a ship with length $L = 10\text{m}$. The results are shown in Figs. 9-12. According to the results, the ship pitch both in amplitude and phase coincides with the foil pitch in case $k_p = 1000\text{kgf.m/rad}$. Hence, the foil is fixed to the ship hull when $k_p = 1000\text{kgf.m/rad}$. The gain of using foil consists of the decrease of the resistance increase and the generation of the thrust by the foil. The gain in case $k_p = 1000\text{kgf.m/rad}$ is almost equal to that in $k_p = 100\text{kgf.m/rad}$.



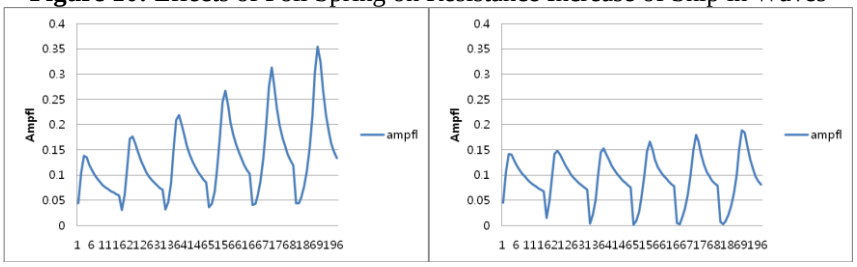
(a) k_p=10 (b) k_p=100 (c) k_p=1000

Figure 9: Effects of Foil Spring on Heave and Pitch of Ship in Waves



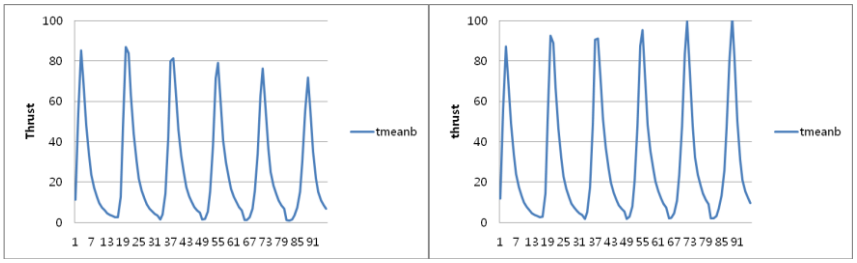
(a) k_p=10 (b) k_p=100 (c) k_p=1000

Figure 10: Effects of Foil Spring on Resistance Increase of Ship in Waves



(a) k_p=100 (b) k_p=1000

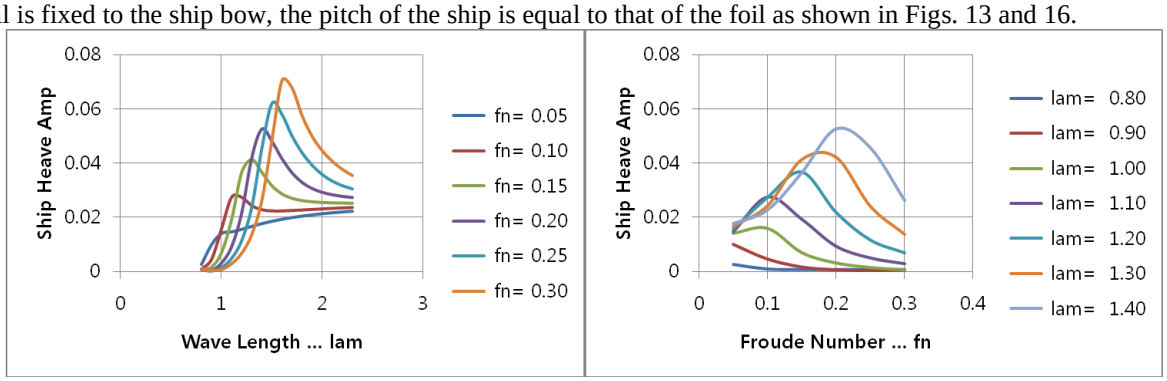
Figure 11: Effects of Foil Pitch in Waves



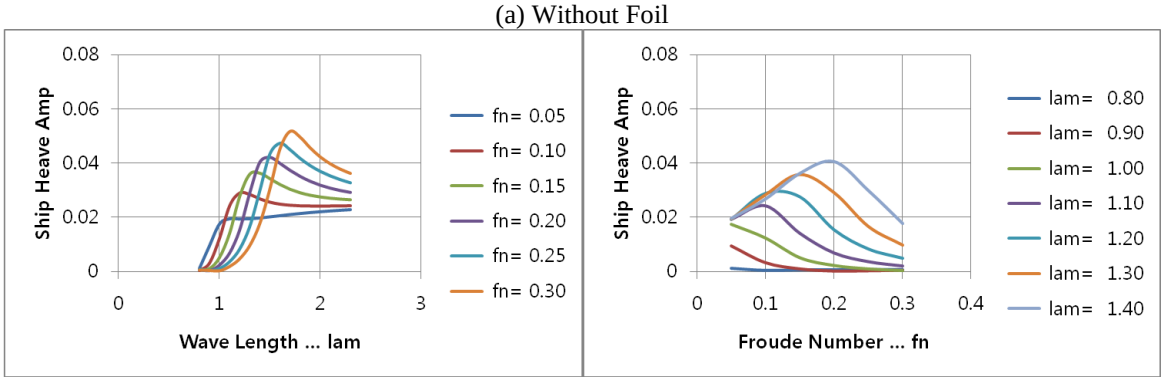
(a) k_p=100 (b) k_p=1000

Figure 12: Effects of Foil Thrust in Waves

We also conducted similar calculations for a ship with $L=1\text{m}$. In this calculation the foil is fixed to the bow because of the reason mentioned above. Namely, we used $k_p=1\text{kgf.m/rad}$. The results are shown in Figs. 13-17. If we attach a foil to the bow of the ship hull, big decrease of ship motions and ship hull resistance increase are observed. Hence, the bow foil could be very effective as the counter measures to the serious speed drop under rough weather. Since the foil is fixed to the ship bow, the pitch of the ship is equal to that of the foil as shown in Figs. 13 and 16.

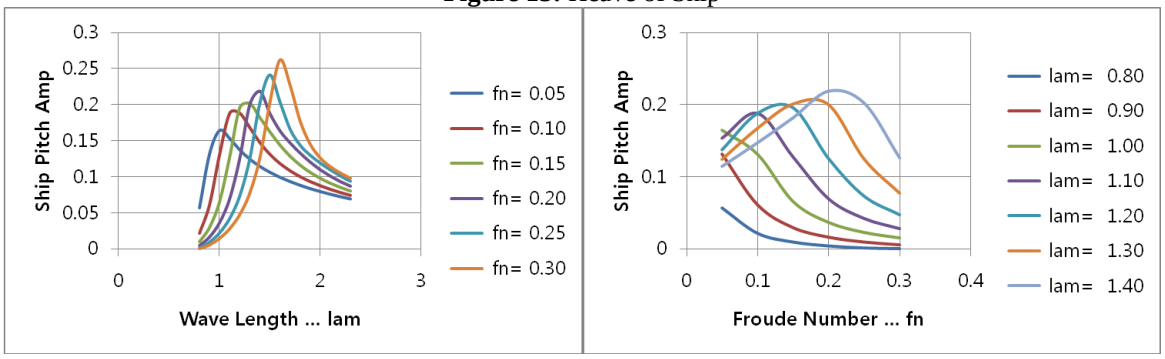


(a) Without Foil

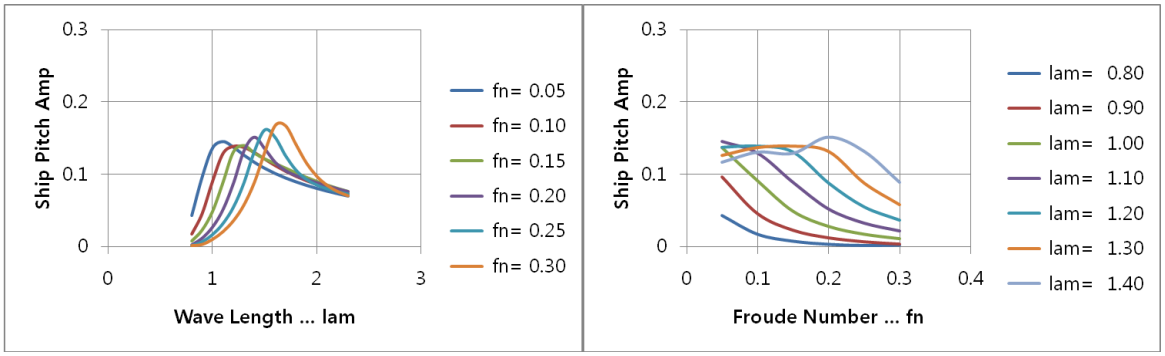


(b) With Foil

Figure 13: Heave of Ship

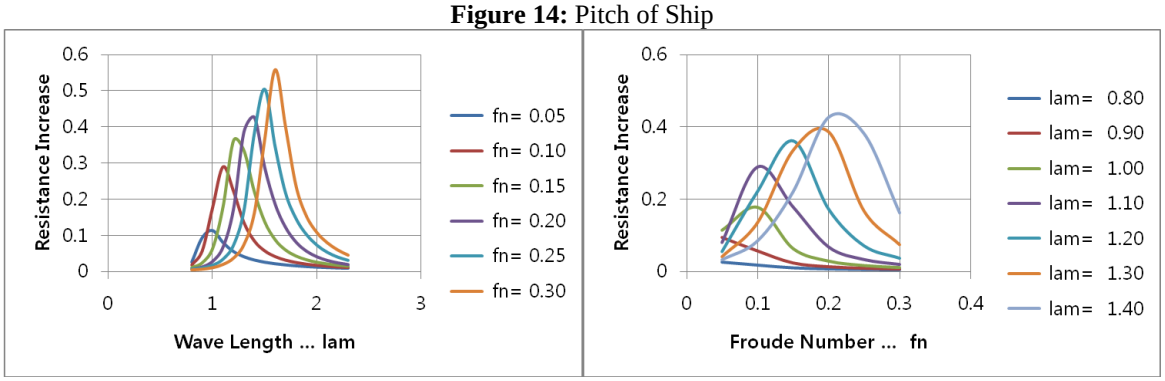


(a) Without Foil

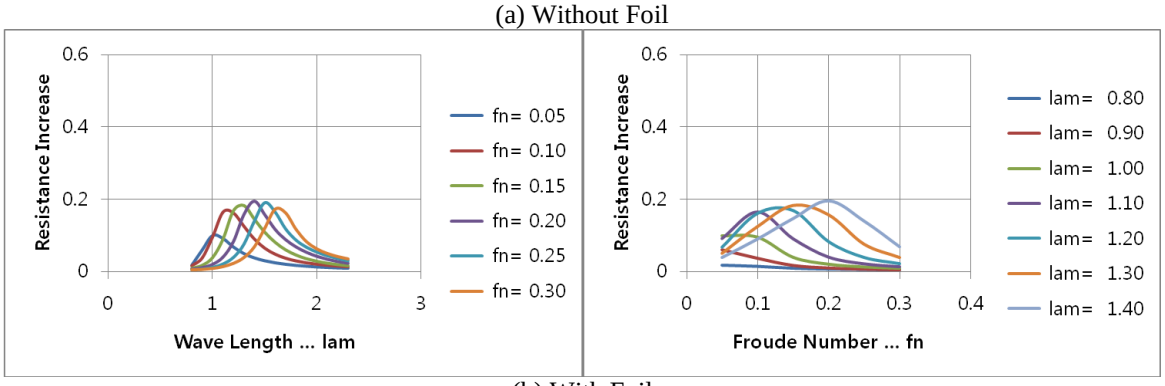


(b) With Foil

Figure 14: Pitch of Ship



(a) Without Foil



(b) With Foil

Figure 15: Resistance Increase of Ship Hull

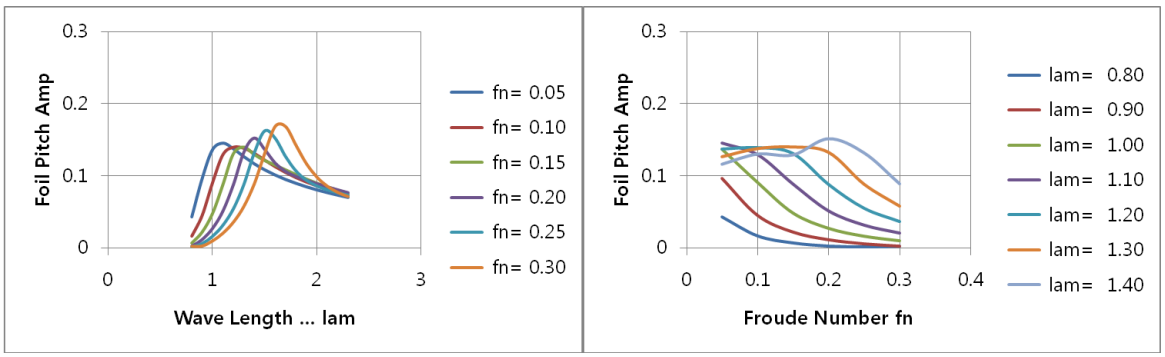


Figure 16: Pitch of Foil

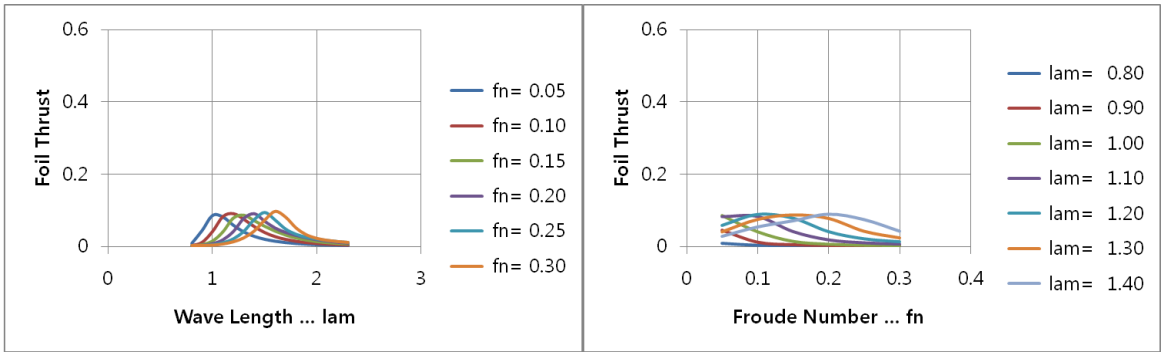


Figure 17: Thrust Generated by Foil

5. CONCLUSIONS

We studied in the present paper the possibility of decreasing the serious speed drop in very rough seas. We proposed the utilization of the natural energy existing abundantly in rough seas. A small hydrofoil attached to the bow could be very effective as the counter measure to the serious speed drop in rough seas due to the possible 30% decrease of engine output due to EEDI. Hence a small bow foil would increase the safety of ships in rough seas sufficiently. Furthermore, since the foil can reduce ship motion considerably, the riding comfort would also be improved significantly.

Wave energy might be better than wind energy, since wave energy is denser than wind energy. Furthermore, a hydrofoil is more suitable to reduce the ship motion in waves than a wind turbine. However, a wind turbine can be used to generate thrust when there is not sufficient wind. In case of a hydrofoil, we must extract the foil out of water in calm seas. However, in the present application of a hydrofoil, there might be no need to extract it from water in calm seas, since the foil is very small and the gain obtained in rough weather can compensate the resistance increase due to the foil in calm seas.

More detailed and precise calculations should be conducted in future before applying the technology to real ships. Researches from different viewpoint such as maneuverability and strength should also be conducted.

6. ACKNOWLEDGEMENTS

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