Jurnal Mekanikal
December 2008, No. 26, 129 - 140

THE PREDICTION OF WAKE WASH IN THE TOWING TANK

Mohamad Pauzi Abdul Ghani[1*], M.N. Abdul Rahim[2]

[1]Faculty of Mechanical Engineering,
Universiti Teknologi Malaysia,
81310 UTM, Skudai,
Johor

[2]PETRONAS,
KLCC, Kuala Lumpur

ABSTRACT

The wash or ship-generated waves from high speed craft has become a common subject in research and development of marine transportation. Since some time now the wake wash of high speed craft has become a problem in particular on inland or confined waterways. This wake wash has an impact on safety and environment such as bank/shoreline erosion, risk to people on shore and small boats in harbors and changes in the local ecology. This paper describes the results of model test of a high speed patrol, together with theoretical prediction of wake wash.

Keywords: *Ship-generated waves, wake wash*

1.0 INTRODUCTION

Ship moving through the water generates two sets of waves, *divergent waves* which move out at an angle from the centerline of travel and *transverse waves*, which move out from the stern perpendicular to the centerline of travel. These are easily noticed when viewed from above in an airplane or from a bridge as a vessel passes beneath [1]. They are illustrated in Figure 1.

The generation of the divergent waves is a function of hull form (prismatic coefficient), angle of entry, speed, and speed-length ratio $V/(L_s)^{0.5}$ and is significant in the development of the height and energy of the wave train, particularly at low or intermediate speeds. The transverse wave form is usually negligible at low speeds but increases with speed up to a length Froude Number of about 0.6 and at higher speeds the transverse wave disappears in the range of $0.6 \leq F_n \leq 1.0$ leaving a bow divergent wave and a stern divergent wave [2].

The angle α in salt water develops to be 19.46° initially for all ships but the angle of obliquity β, varies with hull form and speed, being lower at higher speed length ratios (4°-10°) and higher for lower speed length ratios and fuller hull forms (20°-30°).

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[*] Corresponding author: E-mail: pauzi@fkm.utm.my

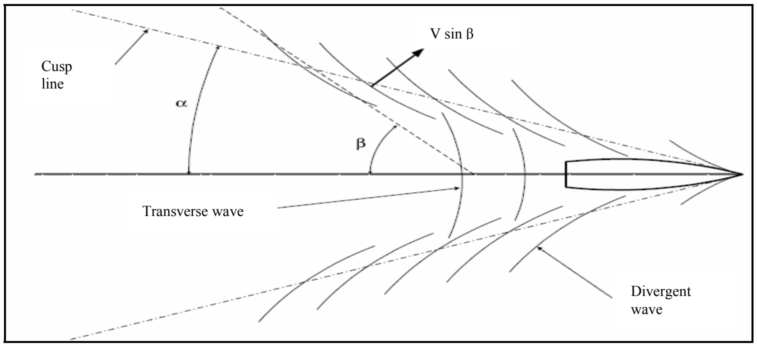


Figure 1: Ship-generated waves [2]

The significance of the angle of obliquity (β), is that the direction of the movement of the energy front will be as shown in figure 1 and the wave length (L) and wave period (T) will be affected by the angle of wave generation. In general, the finer the bow entry, the smaller the angle β and thus the smaller the wavelength and period. This smaller wavelength results in a lower energy density for a vessel's wash [3].

2.0 SHIP WAKE WASH PATTERNS

The best measure of deep water for vessel generated waves is the Depth Froude Number, given by [4]:

$$F_{nh} = \frac{V}{\sqrt{gh}} \tag{1}$$

where

V is vessel speed,
g is the gravitational constant,
h is the water depth

For the purpose of wash comparison, vessels may be considered to be free of shallow water effects when h/L_{wL} exceeds 1.

The Depth Froude Number is critical in determining wash characteristics in shallow water, just as the Length Froude Number is in determining wash characteristics in deep water. However, the influence of the critical value of F_{nh} is much more visible, dramatic and well defined than that of the Length Froude Number. The Length Froude Number is given by [4]:

$$F_{nl} = \frac{V}{\sqrt{g(LWL)}} \tag{2}$$

The main categories are as follows;

- sub-critical, $F_{nh} < 1$
- critical , ship speed = maximum wave speed , $F_{nh} = 1$

- super-critical , ship speed > maximum wave speed , $F_{nh} > 1$
- high speed sub-critical similar to sub-critical but recognizes that high speed ships in deep water can produce divergence waves with or without the transverse wave component depending on the length Froude number (the ratio of ship velocity to a function of waterline length),
- trans-critical or near-critical depth Froude numbers between 0.85 and 1.1.

Below the critical value of $F_{nh} = 1.0$ the wash pattern for a vessel with a F_{nl} less than about 0.9 appears as shown in Figure 2.

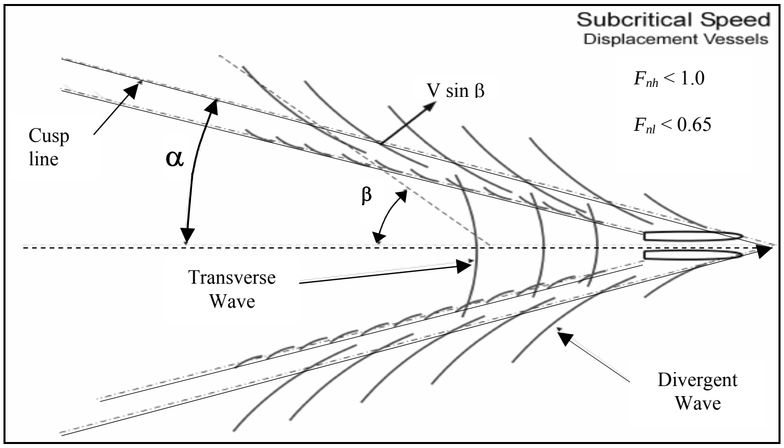


Figure 2: Sub-critical wash pattern for displacement vessels [4]

If a vessel is transiting from deep water to shallow water at constant speed, at F_{nl} values less than about 0.9, and we cross this critical depth in relation to that speed, the direction of wave propagation will be seen to change from that shown in Figure 2 to the pattern shown in Figure 3.

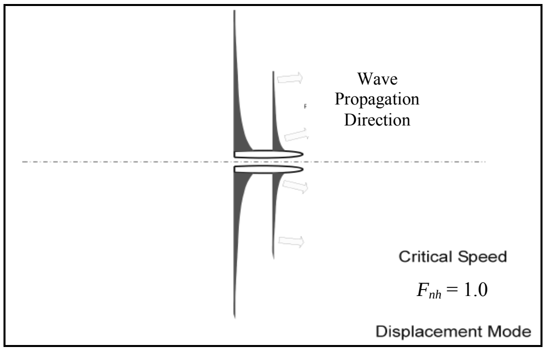


Figure 3: Critical wash pattern for displacement vessels [4]

For vessels with a value of F_{nl} approaching and exceeding 1.0, the wash pattern will be the standard pattern depicted in Figure 4, and will not produce the critical wave shown in Figure 3.

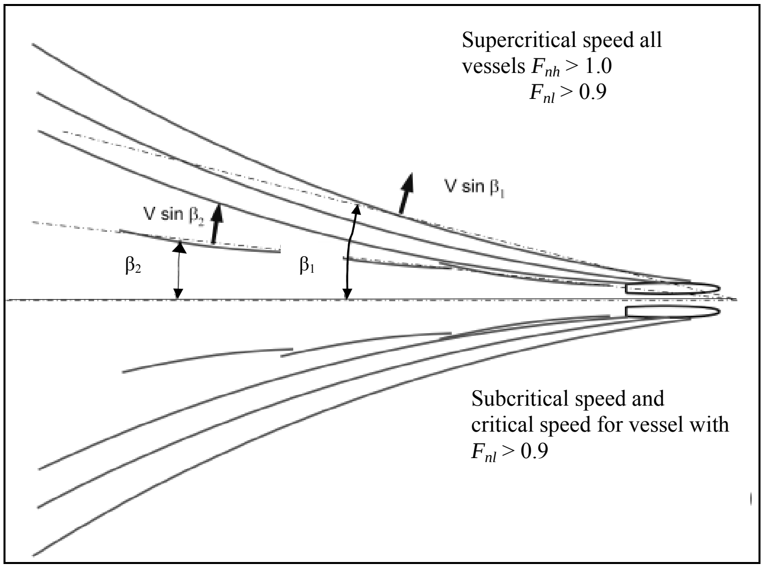


Figure 4: Wash pattern for supercritical operation and vessels at speeds above $F_{nl} = 0.9$ [4]

For vessels that are somewhere below $F_{nl} \approx 0.9$ but not in the region below the hump ($F_{nl} < \sim 0.65$), the wash pattern will be somewhere between the two conditions of Figure 4 and Figure 2. All of this can be quite important in predicting the character of the wash and where it will reach a given beach.

3.0 EFFECT OF WATER DEPTH

In shallow water, the pressure gradient on the hull, and therefore the wave pattern generated by the vessel is influenced by the waves reflecting from the sea bottom. When a wave is propagating in water having a depth of less than approximately half the length of the wave, the wave induced water particle motion reaches the bottom and the water depth affects wave characteristics. In shallow water the wave speed (celerity) of a gravity wave is given by[5],

$$C = \frac{L}{T} = \sqrt{gd} \tag{3}$$

The ratio of the vessel speed to the maximum wave celerity in shallow water is often used to classify the wash produced by a vessel. This ratio, called the Depth Froude Number is defined as follows [5];

$$F_{nh} = \frac{V}{\sqrt{gh}} \tag{4}$$

At $F_{nh} = 1$, the wave speed increased to its physical maximum of $\sqrt{gd}$. Normally the transverse wave will travel at the same speed as the vessel, however

since it physically cannot go any faster, the wave gets much larger, and the ship resistance increases dramatically.
In deep water the vessel length Froude number,

$$F_{nl} = \frac{V}{\sqrt{g(LWL)}} \tag{5}$$

is used to classify wash. At a critical value of F_{nl} ~ 0.4 to 0.55 the wavelength of the transverse waves equals the ship length giving a condition similar to the critical condition in shallow water.

For most displacement vessels, in normal speed ranges, there is no strong wave bottom interaction if the water depth to draft ratio, d/T, is greater than 3 to 5. The d/T ratio will most often be less than 3 for the displacement vessels being studied, thus F_{nh} has been used in analysis.

Vessel generated wake wash in shallow water is usually classed in three categories. Those produced by vessels that travel at sub critical Froude numbers, those produced at the critical Froude number of 1, and those produced by vessels that operate at supercritical Froude numbers such as planning craft and multi hulls. Normally the cruise ship operates at sub critical Froude numbers whereas the patrol vessel generally operates at supercritical speeds and is treated separately [6].

4.0 EXPERIMENTAL STUDY

4.1 Model Testing

Experiment to investigate wake wash from patrol craft were conducted in calm water over a wide range of speeds corresponding to a range of depth Froude numbers F_{nh} 0.6 to 1.4 in towing tank 120 m x 4 m x 2.5 m of Marine Technology Laboratory UTM. During the model tests to measure the wash, resistance, heave and trim were also recorded by D.A.A.S at towing carriage. The wash or wave cuts was measured by 4 wave probes and recorded by LabView software which integrates with wave probes, signal conditioning unit and computer as shown in Figure 5.

For this experimental study a model of Harbor Patrol Boat (MTL 0029) with 8.75 scale ratio as shown in Figure 8 was used for wake wash investigations. The principal particulars of the model and ship are shown in Table 1.

Table 1: Ship and model particulars

Item	Ship	Model
Length Overall L_{OA}, m	15.0	1.71
Length Between Perpendicular, m	12.6	1.44
Breath B, m	4.2	0.48
Trim, m	0.063	0.0072
Draught Forward T_f, m	1.038	0.119
Draught Aft T_a, m	0.911	0.104
Volume Displacement ∇, m^3	19.60	0.0293
VCG or KG, m	1.948	0.223
LCG from AP	5.385	0.615
Block Coefficient, C_B	0.392	0.392
Midship Coefficient, C_p	0.709	0.709

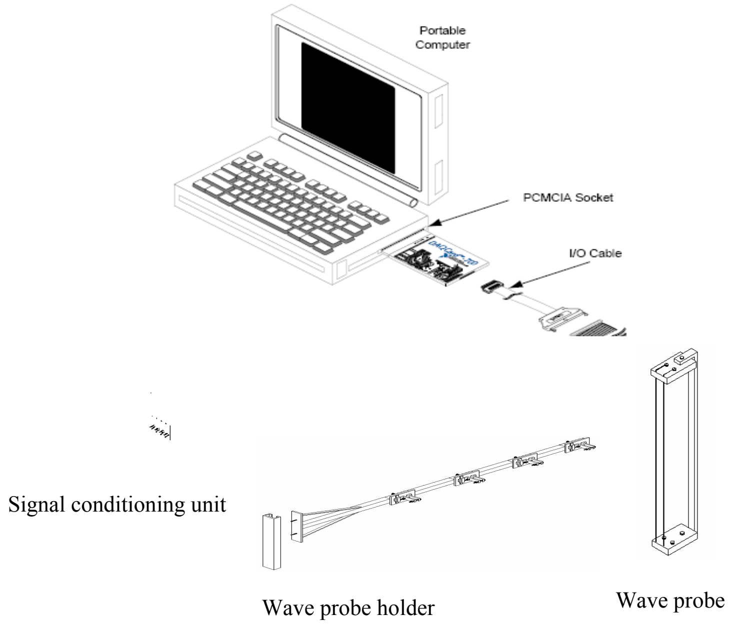


Figure 5: Wash measurement apparatus [6], [7]

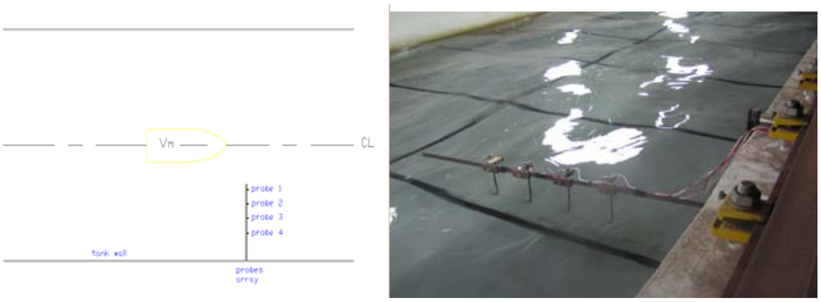


Figure 6: Wave probe arrangement [7]

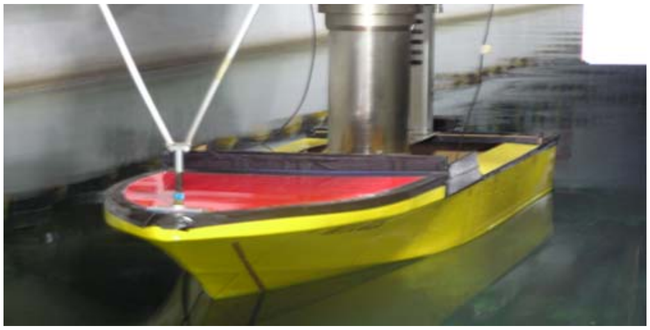


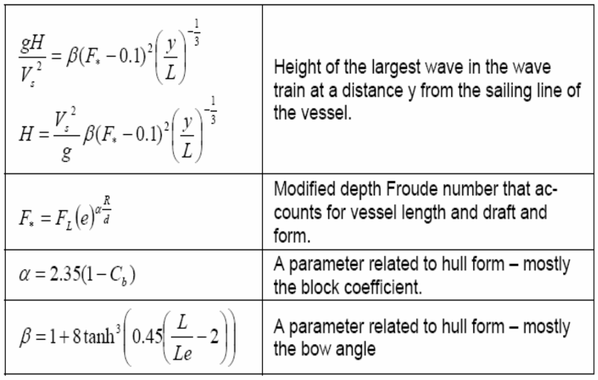
Figure 7: Model ready for testing [7]

5.0 THEORETICAL APPROXIMATION

The values of ship generated wave heights were predicted using a recently published regression model produced by Kriebel, Seelig, and Judge [8]. The equations are developed from regression analyses of data collected by the authors with adjustments to satisfy some theoretical considerations. The model also is based upon a regression analysis of ship generated wave data from model tests of a wide variety of vessels include patrol craft.

The formulas they provide are mostly a modification and combination of those produced by Sorensen and Weggel, [9] and Gates and Herbich [10]. The vessels in the data set were only tested at F_{nh} up to 0.8, with most of the data points in the 0.3 to 0.8 range. So formulas are only relevant for F_{nh} up to 0.8, and those predictions below F_{nh} of 0.3 will be less accurate.

Table 2: The formulas proposed by Kriebel *et. al* [8]



$\frac{gH}{V_s^2} = \beta(F_* - 0.1)^2 \left(\frac{y}{L}\right)^{-\frac{1}{3}}$ $H = \frac{V_s^2}{g} \beta(F_* - 0.1)^2 \left(\frac{y}{L}\right)^{-\frac{1}{3}}$	Height of the largest wave in the wave train at a distance y from the sailing line of the vessel.
$F_* = F_L (e)^{\alpha \frac{R}{d}}$	Modified depth Froude number that accounts for vessel length and draft and form.
$\alpha = 2.35(1 - C_b)$	A parameter related to hull form – mostly the block coefficient.
$\beta = 1 + 8\tanh^3\left(0.45\left(\frac{L}{Le} - 2\right)\right)$	A parameter related to hull form – mostly the bow angle

where

H	Maximum ship generated wave height, m
C	Celerity, m/s (wave speed)
F_L	Length based Froude number
F_d	Depth based Froude number
F_*	Modified depth based Froude number
L_{BP}	Ship length between perpendiculars, m
d	Water depth, m
R	Ship draft, m
C_b	Ship block coefficient
Le	Bow entrance length, m
Vs	Ship Speed, m/s
α	Coefficient related to hull form – used in wave height regression analysis
β	Coefficient related to bow shape – used in wave height regression analysis
y	Distance from sailing line, m
Lw	Wavelength, m
θ	Angle between sailing line and line perpendicular to direction of diverging waves

6.0 RESULTS AND DISCUSSION

There are several methods which can be used to analyze the measured data. The first approach utilizes the wave energy method, i.e the calculation of the energy of the wave system at the measuring position. The second approach is based on the maximum and minimum amplitude of the generated wave (or to find the highest wave in the measured data). This study only covers the second approach and the results are tabulated in Table 3. This table shows the maximum wave height for the model as function of F_{nh} at 4 different probe locations. It is obvious from this table that the largest waves are produced at depth Froude number is near the so-called critical Froude number, $F_{nh} \approx 0.9$. The result was validating with theoretical approach equation in Table 2 suggested by Kriebel, Seelig and Judge [8]. However, these formulas are only relevant for F_{nh} up to 0.8, and the predictions below F_{nh} of 0.3 will be less accurate. Table 4 shows the theoretical results of maximum wash height by using formula as suggested by Kriebel et. al.

Figure 8 shows the total model resistance plotted against depth Froude number and model. It can be seen that model resistance rising rapidly as the shallow water critical speed was approach. In this figure also, it can be seen that there was an increase in resistance in shallow water at sub-critical speeds, rising to a peak just below the depth Froude number, $F_{nh} = 1.1$, but at super critical speeds a reduction in resistance was obtained when compared with the value in deep water at the same speed.

Figures 9 and 10 show the heave and pitch in shallow and deep water respectively. From these figures, it can be concluded that when ship achieve critical speed it try to plan as a planning craft characteristic and this condition will influence the length to beam ratio (L_{WL}/B) simultaneously wash height because wash height are inversely proportional to length to beam ratio. Figure 11 shows the relationship between the divergence of the leading wave crest and the depth Froude number. The correlation with the experimental is quite good.

Table 3: Experimental maximum wash height

	probe 1 y/L = 0.53	probe 2 y/L = 0.66	probe 3 y/L = 0.79	probe 4 y/L = 0.93
F_{nh}	Hmax (mm)	Hmax (mm)	Hmax (mm)	Hmax (mm)
0.6	9.86	9.18	7.65	6.19
0.7	18.78	17.26	15.21	13.32
0.8	31.49	29.62	27.25	23.34
0.9	44.72	42.43	39.23	35.14
1.0	35.27	33.13	30.88	26.75
1.1	33.15	31.02	27.53	23.97
1.2	35.86	32.84	29.97	25.83
1.3	36.83	33.58	30.34	26.36
1.4	36.97	35.84	34.86	32.92

Table 4: Theoretical maximum wash height

	probe 1 y/L = 0.53	probe 2 y/L = 0.66	probe 3 y/L = 0.79	probe 4 y/L = 0.93
F_{nh}	Hmax (mm)	Hmax (mm)	Hmax (mm)	Hmax (mm)
0.6	12.94	12.03	11.33	10.73
0.7	25.91	24.09	22.68	21.48
0.8	46.77	43.47	40.94	38.77

Table 5: Experimental divergent angle

F_{nh}	Divergent Angle, θ
0.6	32.13
0.7	31.73
0.8	30.75
0.9	25.37
1.0	12.86
1.1	24.38
1.2	32.48
1.3	35.82
1.4	41.37

Table 6: Theoretical divergent angle

F_{nh}	Divergent Angle, θ
0.6	34.98
0.7	34.30
0.8	32.07
0.9	24.64
1.0	0.00
1.1	24.62
1.2	33.56
1.3	39.72
1.4	44.42

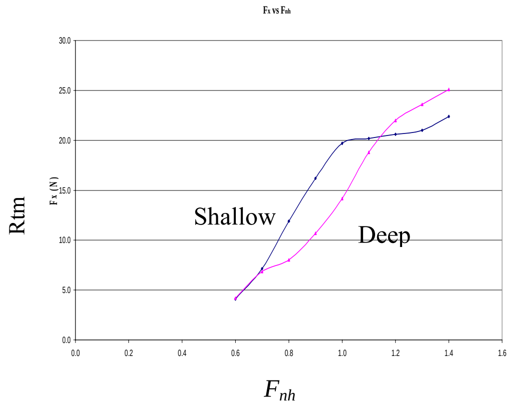


Figure 8: Total model resistance against depth froude number

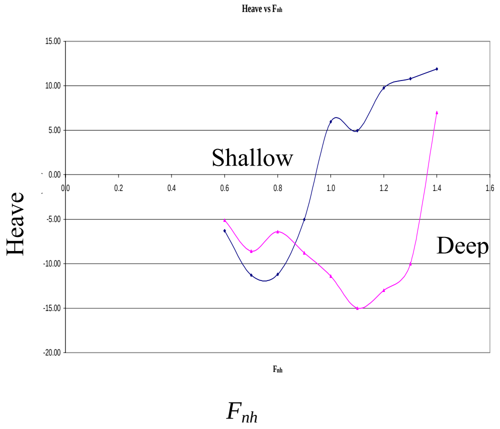


Figure 9: Experimental maximum heave against depth froude number

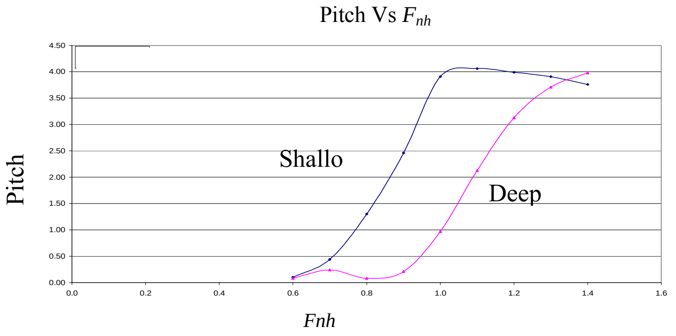


Figure 10: Experimental maximum pitch against depth froude number

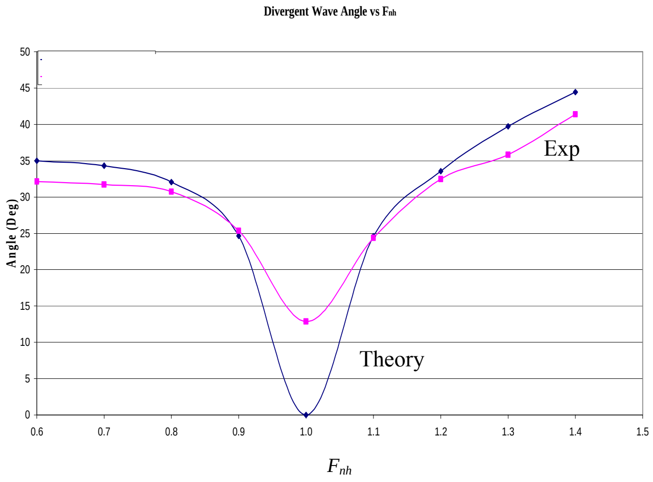


Figure 11: Angle of divergent against depth froude number

7.0 CONCLUSION

It should be noted that, all results mentioned are based on preliminary investigation of wake wash done in the Marine Technology Laboratory UTM. The wash measurement was done by using in-house developed wave probe and Labview Software. The pattern of the wash wave system has been measured for different depth and length Froude numbers and compared with theoretical predictions. It can be concluded that;

i) The agreement between the theoretical and experimental curve pattern is reasonably good.
ii) Wake wash characteristic generated by traveling vessel is largely dependent on the depth Froude number.
iii) The hump speed was achieve at depth Froude number, $F_{nh} \approx 0.9$

This study has quantified and analyzed the characteristics of the wake wash generated by the Harbor Patrol Craft but there are still room left for improvements. The following recommendations are made for further study and for better improvement:

i) As the towing tank facility in the Marine Technology Laboratory is limited by several aspects such as shallow water platform too short, so that when vessel transiting from deep water to shallow water wash disturbance occurs during measurement especially at higher depth Froude number. This will contributes to measure exact wake wash.
ii) Using computer program such as ship flow to validate all the result collected from experiment.
iii) Improve the instrumentation developed to reduce noise as low as possible.

ACKNOWLEDGEMENTS

The authors would like to thank the Marine Technology Laboratory technicians for their assistance in conducting the model tests.

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