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Applicability of J.N. Newman Ship Wave Integral Equation of Linear Thin Ship Theory for a Fuller Hull Form Solved by Final Root Method

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Abstract

J.N. Newman ship wave integral of a linear thin ship theory Rw is a well-known equation for analysing wave energy generated by moving ships. The equation derived on the assumption that the wave energy radiated downstream by a 3-dimensional ship is equal to the wave resistance that needs to be overcome. This wave energy is the transformation of the power or work done partially from the propulsion engines. In earlier studies, Asymptotic Method of solution was applied to solve the wave integral equation. Alternatively, Final Root Method is used to solve Rw in the present study to determine the ship wave resistance of a product tanker with a block coefficient of 0.75. The study is an extension of the previous works carried out by the main author on a Wigley hull form ship and a V-shape hull form of a naval vessel. The main objectives are to investigate and verify the applicability and validity of the J.N. Newman integral equation applied to a fuller hull form. The total resistances from the model experiments at low Froude numbers of equal to or less than 0.2 were analysed to determine the (1+k) form factor for the extraction of the wave resistance components. The calculations were performed based on the input data of the principal dimensions, hull offsets data, trial speeds and the density of the water in the towing tank. The calculated results were subsequently verified against the experimental results and compared with those results of the thinner hull forms obtained from the similar investigations performed earlier on. The Rw solved by Final Root Method as presented matched very closely with those of the experimental results. Henceforth, the J.N. Newman ship wave integral equation is remarkably reliable and indeed applicable for use in fuller hull form ships as verified in the study.

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I. INTRODUCTION

In the early days researches on ship resistance performance were much carried out by method of experimental that is by performing model experiments in experimental tanks. Through rigorous treatments, the resistance of the model and hence for the full scale ships was then predicted by law of similitude or non-dimensional analysis and other relationships. The research activities evolved and many theories related to ship resistance emerged.

Never ending works had been carried out in the past and today to calculate the ship resistance theoretically and verification by model experiments.

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Continuous activities had been conducted since many centuries back to explore other methods to determine ship resistance in particular the wave making resistance. Ship researchers are still enthusiastically seeking for more practical and accurate theoretical methods in determining ship resistance, wave making resistance and other resistance derivatives for eventual purpose of predicting the powering requirements for new and refurbished ships vis-à-vis the optimized hull form in term of resistance performance and other hydrodynamic performances. With the advent of modern computers, computation of the theoretical and experimental analysis could be performed speedily within a short period of time.

The very first study ever known devotedto describing moving bodies in water was carried out by Leonardo Da Vinci (1458-1519) [1]. In 1687 Isaac Newton pioneered thedevelopment of a theory of the resistance ofwater to a moving ship in a liquid medium. The quadratic law linked theresistance and the velocity and the relationship between tangential stressin the fluid and the dynamic coefficient of viscosity and the gradient of the velocity had provided the basis of the scientific study.

The research evolved thereon and one of the most significant happening as far as ship wave resistance research is concerned was that in 1898, an Australian Mathematical professor Michell [2] derived a mathematical method based on linear thin ship theory to calculate the wave making resistance. He formulated the wave resistance of a thin ship in motion on the surface of an ideal fluid of infinite depth. Michell obtained the complex velocity potential □□□by Fourier-integral and found the relationship between wave resistance and hull form andexpressed it as an Integral popularly known as the Michell Integral. Michell's wave resistance can be determined by integrating the normal pressure distribution over the hull surface along the length of the ship.

$$R_w = -2\rho U \iint (d\square/dx)(d\eta/dx)\,dxdz \qquad (1)$$

By differentiation the velocity potential □ with respect to x and substituting into the above equation with the integrals I and J given below we obtain the Michell ship wave resistance or Michell Integral equation;

$$R_w = (4\rho U^4/\pi g)\iiiint\!\!\int f(x,z)f(\xi,\zeta)[m^2 \exp(-m^2U^2(z+\zeta))/g]\ /[\sqrt{(m^2U^4\ell g^2-1)}]\cos m(x-\xi)\,dxdzd\xi d\zeta dm;$$
$$g/U^2 \le m \le \infty,\ 0 \le \zeta \le \infty,\ -\infty \le \xi \le \infty,\ 0 \le z \le \infty,\ -\infty \le x \le \infty$$

$$= (4\rho U^4/\pi g)\int (I^2 + J^2)m^2/[\sqrt{(m^2U^4\ell g^2 - 1)}]dm;\ g/U^2 \le m \le \infty$$

$$= (4\rho U^4/\pi g)\int (I^2 + J^2)\,\lambda^2/[\sqrt{(\lambda^2 - 1)}]d\lambda;\ 1 \le \lambda \le \infty \qquad (2)$$

$$\lambda = mv^2/g \qquad (3)$$

$$J = \iint f(x,z)\exp(-\lambda^2 gz/U^2)\sin(\lambda gx/U^2)dxdz;$$
$$-\infty \le x \le +\infty,\ 0 \le z \le \infty \qquad (4)$$

$$I = \iint f(x,z)\exp(-\lambda^2 gz/U^2)\cos(\lambda gx/U^2)dxdz;$$
$$-\infty \le x \le +\infty,\ 0 \le z \le \infty \qquad (5)$$

Further works based on Michell Integral were carried out by Wigley in many years thereon and in particular he had given the insight as how to make use of the Michell Integral in his papers [2], [3], [4], [5] and [6]. Wigley had actually made noteworthy improvements on Michell Integral and had elaborated the physical meaning more clearly and its application and the methods of solution. The improved Michell Integral on ship wave resistance by Wigley is given below:

$$R_w = (4\rho g^2/\pi U^2)\int (I^2 + J^2)\sec^3\theta\, d\theta;\ 0 \le \theta \le \pi/2 \qquad (6)$$

$$J = bd \iint (\delta\eta/\delta\xi)\exp(-dg\zeta\sec^2\theta/U^2)\sin(\ell g\xi\sec\theta/U^2)\delta\xi\delta\zeta;$$
$$-1 \le \xi \le +1,\ 0 \le \zeta \le 1 \qquad (7)$$

$$I = bd \iint (\delta\eta/\delta\xi)\exp(-dg\zeta\sec^2\theta/U^2)\cos(\ell g\xi\sec\theta/U^2)\delta\xi\delta\zeta;$$
$$-1 \le \xi \le +1,\ 0 \le \zeta \le 1 \qquad (8)$$

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The original λ identity by Michell had been substituted by secθ and converting the parameters into non-dimensional forms the limits of integration in ξ and ζ directions then become -1 to +1 and 0 to +1 respectively. In solving the ship wave equation Wigley used a symmetrical hull form forward and aft (integral I = 0) in which all the waterplanes and its vertical sections are geometrically similar and for easy handling of the integration process.

In 1931Wigley carried out investigations of wave making resistance made use of a double-wedge-shaped model with a parallel mid-body. The generated wave system he observed was found to be made up of the symmetrical surface interference, bow wave system, the forward shoulder wave system, the aft shoulder wave system and the stern wave system. Wigley then expressed the wave resistance coefficient as:

$C_w = R_w/½\rho SV^2 = V^4$ *(constant term+4 oscillating terms)* (9)

Again in 1934 Wigley further studied on the wave system of a model with parabolic waterline which comprises of five components; a symmetrical disturbance, wave system due to bow angle, wave system due to curvature of fore body, wave system due to after body and wave system due to stern angle. In 1942, Wigley managed to calculate the wave making resistance due to transverse and divergent waves which show the positions of the humps and hollows at lower Froude numbers (F_n). At higher F_n the wave resistance due to divergent waves is dominant and the last hump is clearly shown at about $F_n = 0.5$.

The main objective of the present work is to undertake a study on prediction of ship wave resistance for a fuller hull form ship by final root method in conjunction with the ship wave resistance integrals as to verify the applicability of the J.N. Newman ship wave resistance integral in an effort to search for an effective theoretical method and more accurate solution based on the present method of solutions. The results of the analysis shall be validated and compared with the experimental data.

II. THE SHIP MODEL PRINCIPLE PARTICULARS

Three ship models were used in the study, namely a Thin Ship Wigley Hull Form Model, an Offshore Patrol Vessel/LCS and a Product Tanker. The block coefficients are 0.22, 0.49 an 0.75 respectively. M.S Kamil (2014) had performed a PhD research on the first two models in A and B below [9].

A. Thin Ship Wigley Hull Form Model Particulars

Length Between Perpendiculars, L_{BP} - 1.8 m

Length Waterline, L_{WL} - 1.8 m

Draft, T 0.113 m

Beam Waterline, B_{WL} - 0.180 m

Wetted Surface Area, S at draft T - 0.482 m^2

B. Offshore Patrol Vessel / LCS Model Particulars

Length Between Perpendiculars, L_{BP} - 6.842 m

Length Waterline, L_{WL} - 6.831 m

Draft, T - 0.289 m

Beam Waterline, B_{WL} - 0.975 m

Wetted Surface Area, S at draft T - 0.6577m^2

Product Tanker UTM No 7698 Model Particulars

Length Between Perpendiculars, L_{BP} - 3.75 m

Length Waterline, L_{WL} - 3.13 m

Draft, T - 0.208 m

Beam Waterline, B_{WL} - 0.55 m

Wetted Surface Area, S at draft T - 2.5 m^2

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III. THE GOVERNING EQUATION AND THE METHOD OF SOLUTION

In 1977 there was a significant contribution made by J.N. Newman [6] in his study stated that for a constant water density the magnitude of the wave resistance is proportional to the squares of the ship's speed (U^2) and weighted integral of the wave amplitude ($|A(\theta)|^2$) and is also proportional to the cubic of the cosine of the wave propagation angle ($\cos^3\theta$) dominated by the transverse waves. In deriving the wave resistance equation, he linked up the wave resistance of a three dimensional ship to the wake energy radiation downstream. He showed connection of the integral of the wave amplitude function A(θ) to that of the Michell's linear thin ship theory. Newman expressed the ship wave resistance as follows;

$$R_w = (\pi\rho U^2/2) \int |A(\theta)|^2 \cos^3\theta d\theta; \; -\pi/2 \leq \theta \leq \pi/2 \quad (10)$$

Alternatively for a symmetrical integral, the above expression may be presented as;

$$R_w = (\pi\rho U^2) \int |A(\theta)|^2 \cos^3\theta d\theta; \; 0 \leq \theta \leq \pi/2 \quad (11)$$

$A(\theta)$ is the wave amplitude function, $\cos^3\theta$ is dominantly associated with transverse waves and θ is the wave propagation angle.

Newman's wave amplitude function $A(\theta)$ is expressed as;

$$A(\theta) = (2g/\pi U^2)\sec^3\theta \iint \eta_x \exp[v\sec^2\theta(z+ix\cos\theta)]dzdx; \quad -d \leq z \leq 0, \; -L/2 \leq x \leq L/2 \quad (12)$$

Taking the real part we have;

$$A(\theta) = (2g/\pi U^2)\sec^3\theta \iint \eta_x \exp(v\sec^2\theta z) \cos(v\sec\theta x dzdx; \; d \leq z \leq 0, \; -L/2 \leq x \leq L/2 \quad (13)$$

The study shall base on the formulation derived J.N. Newman above in which the ship wave resistance integral will be solved by Final Root method.

The coordinate system applied in the analysis is given in FIGURE 1. The study contained in this paper attempts to investigate the applicability of the shup wave integral equation by J.N. Newman applied for fuller hull form. The integral as described above based on the assumption that the wave resistance is dependent on a specific or precise maximum resultant propagation angle of the combined divergent and transverse waves of the primary wave system. This angle symbolized as θ_{pmax} would be of different magnitude depending on the hull form and speed or Froude number of the ship and this wave propagation angle sets the maximum limit of the mathematical integration of the wave resistance integral functions instead of π/2 as in the original expression by J.N. Newman. The wave resistance integral

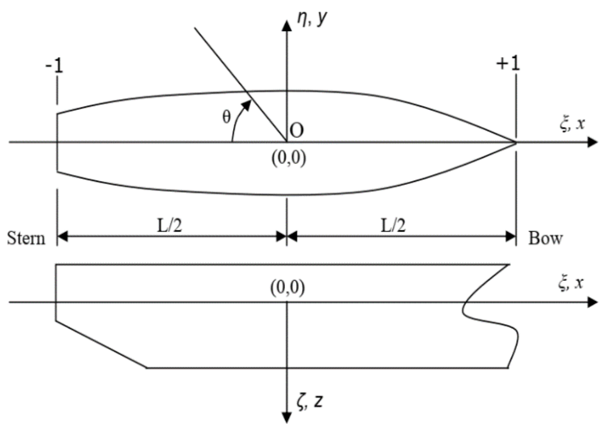

Figure 1. TheCoordinate System

unstable and in fact it is an be due to the combination of function by Newman is extremely oscillatory and very multiples of both the transverse and divergent waves propagate in different directions and superimposed to each other. Out of this combination of waves, there exists somewhat a mean or primary wave system related to the ship wave resistance or the wave amplitude functions. Each of these functions contains infinite roots of solution. The final or the last root of the solution (i.e. the precise maximum wave propagation angle θ_{pmax}) essentially corresponds to the last point of minima of the ship wave resistance or the wave amplitude function curves beyond which the value goes to infinity.

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Fundamentally, both the ship wave resistance equations are solved exactly like those of definite integral functions and this concept or methodology is implemented in the study of theoretical ship wave resistance. The original J.N. Newman ship wave resistance equation if of definite integral forms with the integration limits of $0 \leq \theta \leq \pi/2$ and $-\pi/2 \leq \pi/2$ respectively. However the deficiency of these equations is obvious that is when the equations are solved for $\theta = \pi/2$ will give results to infinity and hence divergent. The ship wave resistance or the wave amplitude functions in these cases are not easily differentiable directly to obtain the roots of the solution. The J.N. Newman ship wave resistance equations are therefore expressed respectively as follows and simply by substituting the maximum limit of integrations $\pi/2$ with θ_{pmax}. The revitalized Newman's ship wave resistance equation is of the form;

$$R_w = \pi\rho U^2 \int |A(\theta)|^2 \cos^3\theta d\theta;\ 0 \leq \theta \leq \theta_{pmax} \tag{14}$$

$$A(\theta) = (2v/\pi)\sec^3\theta \iint \eta_x \exp(v\sec^2\theta z)\cos(v\sec\theta x)\ dzdx;\ d \leq z \leq 0,\ -L/2 \leq x \leq L/2 \tag{15}$$

In implementing the computational technique, in all the cases of study the ship is divided into 10 equal spacings longitudinally along the length of the ship and divided into 10 waterline spacings vertically down from the free surface to the keel bottom. Simpson's First Rule of Integration is employed in the integration process. The integration begins at each cross-section of the η-ζ-plane of the hull followed by the longitudinal integration in the ξ-direction to calculate

the integral I with the origin is located at midship as in coordinate system. The final integration to calculate the ship wave resistance R_w is performed in θ-direction from zero up to the precise maximum wave propagation angle θ_{pmax} at an equal interval of one degree and finer spacing near θ_{pmax} and towards $\theta = \pi/2$. The calculations are readily performed in tabular formats.

IV. THE RESULTS

A. Thin Ship Wigley Hull Form Model

Table 1. Analysed results for thin ship wigley hull form model

F_n	C_wx 10^3 Experimental	C_wx 10^3 Final Root (Newman)	% Difference
0.40	2.681	2.599	3.06
0.50	3.951	3.824	3.21
0.60	4.637	4.471	3.58
0.70	4.609	4.435	3.78
0.80	4.485	4.296	4.21
0.90	4.345	4.160	4.26
1.00	4.278	4.056	5.19

B. Offshore Patrol Vessel /LCS Model

Table 2. Analysed results for offshore patrol vessel / LCS model

F_n	C_wx 10^3 Experimental	C_wx 10^3 Final Root (Newman)	% Difference
0.362	2.565	2.495	2.73
0.397	3.323	3.233	2.71
0.434	4.222	4.123	2.35
0.470	4.738	4.604	2.83
0.508	4.842	4.697	2.99

C. Product Tanker UTM No 7698 Model

Table 3. Analysed results for product tanker model

F_n	C_w x 10^3 Experiment	C_w x 10^3 Final Root (Newman)	% Difference
0.148	0.343	0.371	8.16
0.164	0.458	0.421	8.08
0.181	0.926	0.835	9.83
0.197	0.957	0.864	9.72
0.213	1.215	1.113	8.40
0.230	1.235	1.126	8.83
0.246	1.904	1.760	7.56

V. DISCUSSION

The scientific novelties of the Final Root Method applied for the prediction of ship wave resistance for mono- hull by J.N. Newman integral are obvious. The final root method had provided a

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breakthrough solution for an improper integral equation such as the J.N. Newman ship wave integral equation. The final root method had contributed to solving ship wave resistance problems more accurately and it has contributed to the development of scientific knowledge in solving the ship wave resistance of ships.

The Final Root Method is of practical significance as it could be employed in research and design activities by ship research centres, universities, shipyards, ship design consultants and relevant individuals. The fundamentals of final root method could be taught to students in marine based higher learning institutions to disseminate the new method in solving ship wave resistance. The algorithm of final root method could be turned into a computer code (computer program) for easy application by users involved in ship research and design works and for commercial application. Final root method could also be used to predict or calculate wave amplitude due to ship motion.

VI. CONCLUSION

The Applicability of J.N. Newman Ship Wave Integral Equation of Linear Thin Ship Theory for a Fuller Hull Form Solved by Final Root Method could be observed from the results of the analysis shown in TABLE 1, TABLE 2 and TABLE 3 particularly on the degree of accuracy as indicated by the percentage differences between the experimental and the theoretical solution of the J.N. Newman Integral solved by Final Root Method and also from the cross-plots of the experimental curves and those solved by Final Root Method.

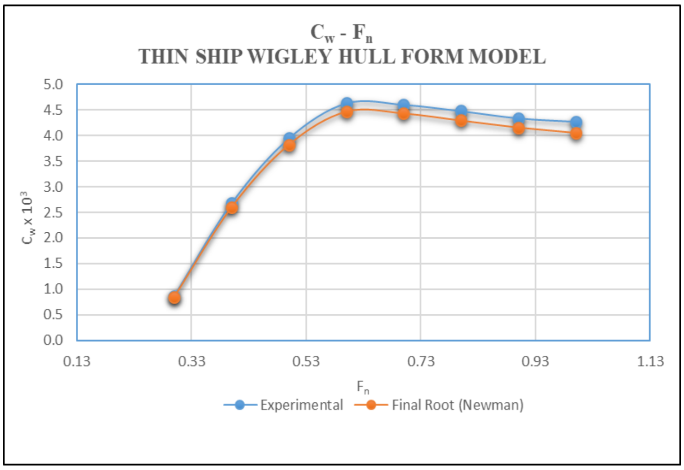

Figure 2. C_w – f_n thin ship wigley hull form model

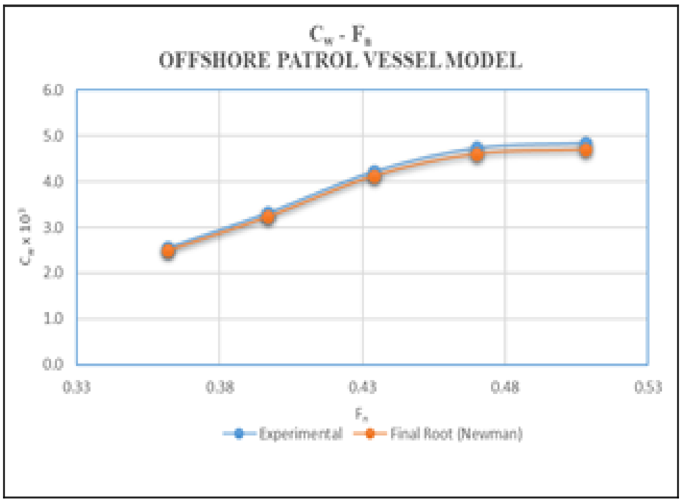

Figure 3. Cw – fn offshore patrol vessel model

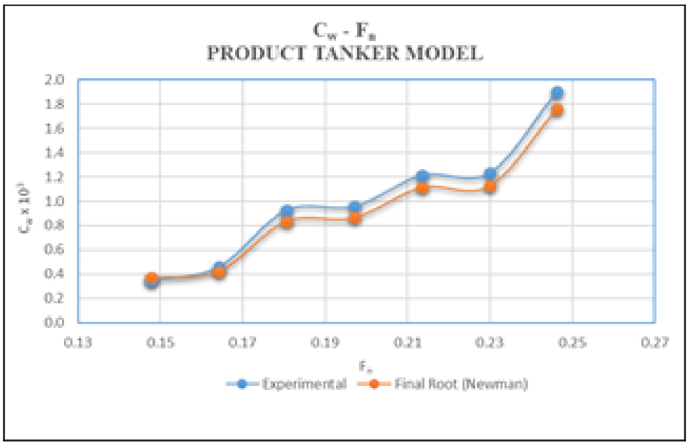

Figure 4. Cw – fn product tanker model

It could be concluded that the J.N. Newman ship wave resistance integral of the linear thin ship theory could potentially be applied for ships of fuller hull forms. Nevertheless, some corrections in relation to the hull form parameters could be further studied for better accuracy in the future. The final root method is potentially very practical and a useful engineering tool for solving ship wave resistance generated by moving ships. The method could be employed for the study in the optimisation of ship hull form in term of minimum ship wave resistance during ship design synthesis.

VII. ACKNOWLEDGMENT

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