IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X,
PP 42-48
www.iosrjournals.org

Study of Hydrodynamic Flow around A Vessel for Powering and Wave Pattern

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***Abstract** : One of the most critical issues in ship powering is the reduction of resistance offered by different components such as wave, frictional etc. To meet these reductions it is important to study different components and ways to reduce this effect. For high speed ships, as the speed increases wave resistance dominates and frictional resistance lessens, hence it is important to minimize wave resistance by hull form modification.*
Computational fluid dynamics (CFD) techniques are used in all engineering field where complex flow problems exists especially around ships which is highly turbulent region. CFD methods are accepted as a viable approach to simulate the complex flows and analyse this physical process. CFD results permit us rapid hull form modifications so that a comparative study of results can be done within hours. Towing tank experiments were conducted on a bench mark model R/V Athena and the data being compared and evaluated using mat lab code which was written using Fourier transformation method for wave resistance calculation. In this paper the results of a comparative study on resistance of high-speed transom stern R/V Athena hull form using CFD techniques, and experimental results are presented.
***Keywords -** Froude Number, R/V Athena, Towing Tank, Wave Heights, Wave Resistance*

I. Introduction

Minor changes to the hull form can have a reduction in required engine power and leads to save in fuel consumption. Hence it is important that hydrodynamic optimization of the hull is a necessary process in the development of a ship. A ship in forward motion has resistance in various kinds. The engine power is calculated as per the resistance at the desired speed and thereby the fuel consumption which is one of the important factors which determine the economy of the ship. So it is important to reduce the ship resistance which is vital in ship design. A considerable resistance component roots from the steady ship wave system even when ship sailing in relatively calm water. Almost 50% of installed power is used to overcome wave resistance for fast displacement ships. Also the wave generated causes an adverse effect to the shores as wash hits or hits to other vessels. Therefore it is important to reduce the wave making as much as possible.

CFD flow simulations can provide clear trends in hydrodynamic design aspects and allow a much more cost effective and detailed optimization of ship hulls than large series of model tests [1]. Still Tank testing is the traditional method of predicting vessel performance. Numerous ships have already been computed at model scale giving an estimation of the total resistance with an accuracy of about three to five percent [2].

II. Experimental Set-Up

2.1. Model Description

Model 5365 is a 1/8.25 scale model of the R/V Athena. The R/V Athena is a converted PG-84 Asheville-class patrol gunboat which is operated out of Naval Surface Warfare Center - Panama City Division as a high speed research vessel [3]. Hull form characteristics of model 5365 and full scale(R/V Athena) are shown in **Table 1**, [4].

Table .1 Model 5365 and Full-Scale (R/V Athena) Hull Form Characteristics

Hull Form Particulars		Ship		Model	
		feet (ft)	meters(m)	feet (ft)	meters(m)
Length Between Perpendiculars	LBP	154	46.94	18.67	5.69
Length Overall	LOA	164.5	50.14	19.94	6.08
Maximum Beam	B	22.6	6.87	2.73	0.83
Displacement	Δ (tons/kg)	260 tons		458 kg	
Wetted Surface Area	S (ft^2/m^2)	3100	315.9	49.95	4.64
Draft	T	5.58	1.7	0.676	0.206
Mean Scale Ratio	λ	8.25		1	

2.2. Wave Profiles

Table 2 presents the non-dimensional wave profile heights along the hull for Model 5365 from David W Taylor Naval Ship Research and Development Center (DTNSRDC) in the free to sink and trim condition. The measured wave heights are non-dimensionalised by $U^2/2g$, [5].

Table 2. Wave Heights

ζ(wave heights)												
Port							CL	Starboard				
x distance	y distance	0.76246	0.60883	0.4552	0.30726	0.15363	0	0.15363	0.30726	0.4552	0.60883	0.76246
5.87777		0.004	0.031	0.049	0.052	0.052	0.05	0.056	0.037	0.049	0.031	0.007
6.0314		0.003	0.031	0.045	0.047	0.047	0.047	0.073	0.053	0.051	0.033	0.007
6.18503		0.008	0.037	0.053	0.046	0.045	0.044	0.049	0.034	0.046	0.032	0.007
6.33866		0.013	0.019	0.031	0.048	0.042	0.037	0.051	0.049	0.034	0.019	0.015
6.49229		0.012	0.012	0.016	0.037	0.035	0.035	0.039	0.019	0.019	0.014	0.015
6.64023		0.015	0.012	0.018	0.03	0.034	0.035	0.034	0.032	0.017	0.015	0.015
6.81662		0.015	0.011	0.013	0.018	0.024	0.026	0.034	0.019	0.015	0.013	0.017
6.94749		0.016	0.01	0.007	0.003	0.021	0.023	0.027	0.012	0.012	0.012	0.015
7.04422		0.015	0.01	0.008	-0.004	0.012	0.016	0.015	0.007	0.012	0.017	0.015

2.3. Resistance Data

The total, residuary and wave pattern resistance coefficients [6] for Model 5365 (DTNSRDC) free to sink and trim as a function of length Froude number are shown above in **Table 3**. Measurements of the wave elevations of **Table 2** were made on Model 5365 in the captive mode at a Froude number of 0.48.

2.4. Measurement System

Longitudinal wave cuts (LWCM) were obtained using a modified and strengthened capacitance wave probe system, developed and constructed at Naval Surface warfare center (NSWC). These wave cuts resulted in four off-body wave time-histories for each chosen speed. The data from the outer most probes was used to calculate wave pattern resistance [7]. The wave profile is measured in a fluid region reasonably free from vorticity, this makes LWCM consistent with the separation between viscous and wave resistance, while for instance in transverse cut method the wave profile is also measured inside the viscous wake [8]. The present optimization approach aims at the minimization of the wave pattern resistance which is determined by a longitudinal wave cut analysis. In case of flows symmetric to the ship center plane, a single infinitely long wave cut parallel to the ship suffices to perform the whole analysis. The longitudinal wave cut method is preferred to other wave analysis methods since it is comparatively fast, relatively robust in application and it has a broad application range [9].

Table 3. Coefficient of Total Resistance, Residuary Resistance, Wave Resistance for R/V Athena

Froude Number (F_N)	**Coefficient Of Total Resistance (C_T*1000)**	**Coefficient Residuary Resistance (C_R *1000)**	**Coefficient Wave Resistance (C_{WP} *1000)**
0.28	5.531	2.655	0.465
0.312	5.357	2.53	0.7
0.351	5.344	2.52	0.985
0.412	5.03	2.26	1.546
0.448	5.498	2.8	1.912
0.484	5.774	3.145	2.192
0.521	5.629	3.033	2.083
0.57	5.347	2.79	1.851
0.653	4.924	2.42	1.407
0.8	4.387	1.963	0.931
1	4.008	1.666	0.325

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e-ISSN: 2278-1684,p-ISSN: 2320-334X,
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www.iosrjournals.org

III. Theory of Free-Wave Spectrum

3.1. The Ship Wave System

A complex wave system of ship consists of both transverse waves and diverging waves which we often say it as kelvin wave pattern. The development of a hull form with a minimum of wave resistance involves a good understanding of the theory of waves, the origins of wave generation by the ship and experience on effective procedures to minimize the energy transferred by the ship to its generated wave system [10]. Out of the double infinite manifold of all possible plane progressive waves, varying both in wavenumber *k* and in component wave direction θ, it is only a single infinite set of so called free waves which contribute to the wave pattern resistance. These free waves satisfy conditions i.e., wavenumber and wavelength of each component of the free wave system are determined one-to-one by its wave direction. Furthermore, outside a confined region around the disturbance by the ship it is the free waves which constitute the wave pattern whereas, the local disturbance arising from the presence of non-free waves vanish with the square of the reciprocal distance from the disturbance [11].

Expression (1) shows a resistance Function which measures the wave energy distribution along the components of the ship wave system for infinite water depth [12],

$$R_{WP} = \frac{\pi}{2}\rho V_S^2 \int_{-\pi/2}^{+\pi/2} \left|A(\theta)\right|^2 \cos^3(\theta)\, d\theta \,, \tag{1}$$

From the wave pattern resistance coefficient, we get the expression (2),

$$C_{WP} = \frac{R_{WP}}{\frac{1}{2}\rho V_S^2 S_{ref}} = \int_{-\pi/2}^{+/2} C_{WP}(\theta)\, d\theta \tag{2}$$

The amplitude square of the complex free-wave spectrum in Equation (1) can be the summation of its sine A_S (θ) and cosine A_C (θ) components.

3.2. Free Surface Elevation

The free surface wave elevation ζ can generally be expressed [13] according to linear theory as the superposition of plane progressive waves of varying amplitudes, with wave numbers k and wave directions θ at a fixed point in space by the expression (3)

$$\zeta(X, Y, t) = \Re \int_{-\pi/2}^{+\pi/2} \int_{0}^{+\infty} A(\omega, \theta) \exp\left[-ik(\omega)(X\cos\theta + Y\sin\theta) - i\omega t\right] d\omega\, d\theta \tag{3}$$

The integrals in Equation (3) are double-Fourier integrals, with the property that the Fourier inversion formulas can be applied to convert between the wave elevation and wave amplitude spectrum, A (ω , θ). Equation (3) can be used to analyze the ship wave system in terms of the wave amplitude spectrum, A (ω , θ), but may also be used to represent ocean waves. The wave number k and circular wave frequency ω in Equation (3) are mutually-dependent parameters that are linked by the dispersion relation and yield the following for infinite water depth,

$\omega^2 = kg$ (Dispersion relation), $V_p = \omega / k$ (phase velocity), $\lambda = 2\pi / k$ (wave length), $T = 2\pi / \omega$ (wave period)

In a Langrangian reference system that steadily moves with the ship, the ship waves appear as a stationary wave system. Hence, Equation (1) must be independent of time. This implies a restriction on the phase velocity and wave number. As a consequence, there exists for each wave propagation angle a unique wave number or circular frequency. Hence, the ship or Kelvin wave system represents a single-dispersion curve in wave angle and wave number. The steady wave elevation in the ship-fixed reference system simplifies to the time-independent equation (4),

$$\zeta(x, y) = \Re \int_{-\pi/2}^{+\pi/2} \int_{0}^{+\infty} A(\omega, \theta) \exp\left[-ik(\omega)(x\cos\theta + y\sin\theta)\right] d\omega\, d\theta \tag{4}$$

Equation (4) is a general description of the linear ship wave system, [14] since it comprises both the near-field (or local) ship wave system and the far-field wave system. Out of the double infinite manifold of all possible plane-progressive waves, varying both in wave number and in component wave direction, θ , it is only a single infinite set of so-called free waves which constitute the far-field or free-wave pattern. Whereas, the local disturbance (e.g., the local wave system, also referred to as the Bernoulli wave), is bound to the vicinity of the ship and does not interact with the far-field wave system. Moreover, the local ship waves vanish with the square of the reciprocal distance from the disturbance and, hence, do not radiate energy outward. This gives rise to a drop in the contribution of the local waves in Equation (5) thus, considerably simplifying the complex equation.

$$\zeta(x, y) = \Re \int_{-\pi/2}^{+\pi/2} A(\theta) \exp\left[-ik(\theta)(x\cos\theta + y\sin\theta)\right] d\theta \tag{5}$$

The free-wave spectrum A(θ) is a pure function of the hull shape and the ship speed, and can be utilized to compute the (linear) wave resistance or to readily calculate the far-field waves at any arbitrary location in the ship's wake.
The free-wave system is derived from Equation (5) with the sine, A_S (θ) and cosine, A_C (θ) components of the wave spectrum in terms of below expression (6),

$$\zeta(x, y) = \int_0^{\pi/2} \left[A_S(\theta)\sin(k_x x + k_y y) + A_c(\theta)\cos(k_x x + k_y y)\right] d\theta \tag{6}$$

Alternatively, Equation (6) can be written in terms of the longitudinal wave number, k_X ($k_X = k\cos\theta$)

$$\zeta(x, y) = \int_{k_0}^{\infty} \left[A_S(\theta)\sin(k_x x + k_y y) + A_C(\theta)\cos(k_x x + k_y y)\right] \frac{d\theta}{dk_x} dk_x \tag{7}$$

The Fourier transformation is realized by applying the continuous Fourier integral to transform between the longitudinal wave cut and the related free-wave spectrum, as follows

$$\zeta(x, y) = \frac{1}{\pi} \int_{k_0}^{\infty} \left[S(k_x)\sin(k_x x) + C(k_x)\cos(k_x x)\right] dk_x$$

With the Fourier transforms,

$$S(k_x) = \int_{-\infty}^{\infty} \zeta(x, y)\sin(k_x x)\,dx$$
$$C(k_x) = \int_{-\infty}^{\infty} \zeta(x, y)\cos(k_x x)\,dx \tag{8}$$

Where S and C denote the sine (odd) and cosine (even) components, respectively, of the Fourier transforms. The wave elevation ζ(x, y = const.) in Equation (8) represents a longitudinal wave cut that may be determined either from a CFD simulation or from wave-probe measurements in a towing tank (EFD).The longitudinal wave cut is given in practice as wave elevation samples along varying *x*-positions, for a constant transverse cutting plane or off track position with y = constant [10].
Now by introducing the weighted Fourier transforms, expression simplifies as follows,

$$A_S(\theta) = \frac{k_x}{\pi}\left[S_{WFT}(k_x)\cos(k_y y) + C_{WFT}(k_x)\sin(k_y y)\right]$$

$$A_C(\theta) = \frac{k_x}{\pi}\left[-S_{WFT}(k_x)\sin(k_y y) + C_{WFT}(k_x)\cos(k_y y)\right]$$

S_{WFT} and C_{WFT} denote the sine and cosine components. Above expressions shows the components of the free-wave spectrum are pure functions of the hull shape and the ship speed, yielding a direct measure of the wave energy distribution along the components of the ship's wave system. This is why they are extremely valuable for determining ship hull optimization.

IV. Results and Discussions

A literature study on the flow around a ship, resistance of a ship and CFD cases that deal with similar examinations has been studied. Tutorials in SHIPFLOW were made, to get to know the software better in advance of the investigation. A mat lab code was written using Fourier transformation for wave pattern resistance and analyzed using towing tank result from David W Taylor Naval Ship Research and Development Center (DTNSRDC). Existing results from model tests in towing tanks for the R/V ATHENA vessel has been studied. The analysis of the wave resistance has been made mainly by CFD-calculations using SHIPFLOW. Wave resistance were analyzed for a range of different Froude numbers and compared to model test results. After running computations for different Froude numbers results are compared to each other as diagrams and tables.

Table 4. Coefficient of Wave Pattern Resistance

No.	Froude Number(F_N)	Coefficient of Wave Resistance C_{WP}*1000 (Experiment)	Coefficient of Wave Resistance C_{WP}*1000 (Ship flow)	% Variation
1	0.28	0.465	1.659	-71.97
2	0.312	0.7	1.411	-50.38
3	0.351	0.985	1.233	-20.11
4	0.412	1.546	1.729	-10.58
5	0.448	1.912	1.997	-4.25
6	0.484	2.192	2.165	1.24
7	0.521	2.083	2.122	-1.83
8	0.57	1.851	1.922	-3.69
9	0.653	1.407	1.58	-10.94
10	0.8	0.931	1.184	-21.36
11	1	0.325	1.07	-69.62

Experimental data for model scale was available for wave resistance which has been performed on ship model with the scale factor of around λ = 1:8.25. Ship model has been free to sink and trim during the tests. **Table 4** shows some of the necessary results of computed wave resistance of ship model using ship flow and experimental values obtained from towing tank with its variation in percentage.

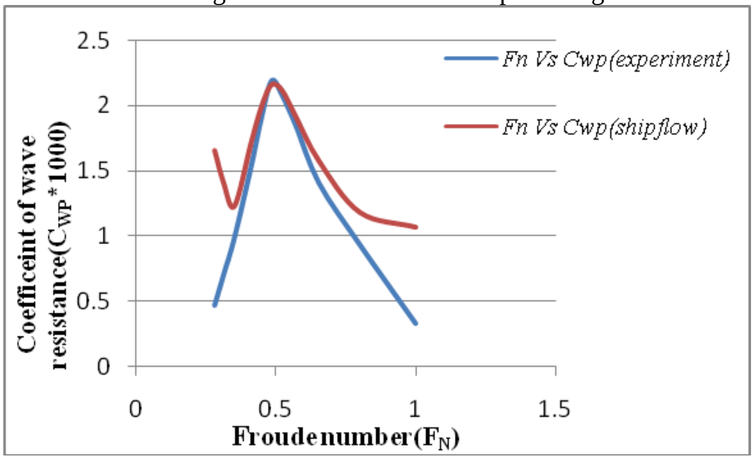

Fig. 1. Coefficient of wave resistance(C_{WP}) from experiment and shipflow over a range of froude number(F_N)

The **Figure 1** shows the numerical values of the wave resistance coefficient, C_W, from XPAN, a brief description will be given about abilities and strength of SHIPFLOW which is used in this study as a CFD software to analyze the flow around ship hull [15] for R/V Athena. In **Figure 1**, C_W using longitudinal wave cuts (LWCM) for Froude numbers (0.28 to 1) from the model test and the calculated values of the wave resistance coefficients are plotted together for comparison. **Figure 2 and 3** shows free surface elevation contours for ship model bare hull for a range of Froude numbers.

Computed results which are in the tabulation illustrate an acceptable agreement with test results which are shown above. Consequently it is observed that computed results in model scale are very close to the reported data from the tests. Therefore it is concluded that computation results for model scale are reliable with a reasonable accuracy. The shape of the curve follows same as that of the experimental values. There is still a small difference between the values for lower Froude numbers and higher Froude numbers.

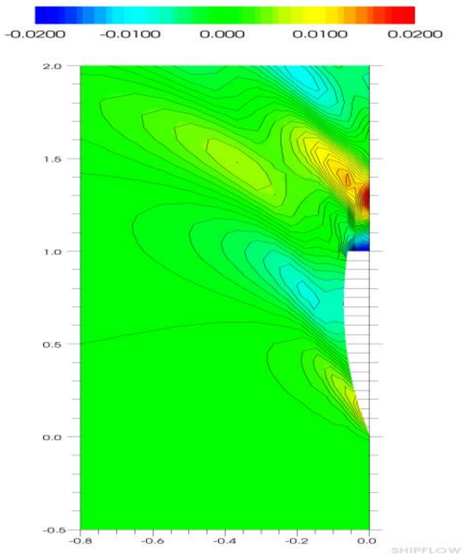

Fig. 2. Free surface elevation for F_N, 0.44

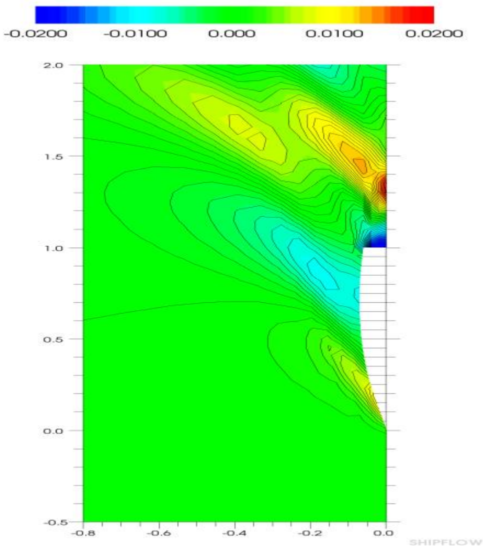

Fig. 3. Free surface elevation for F_N, 0.48

Table 5. Validation of Mat lab Code

Methods	**Total Coefficient Wave Resistance (C_{WP} *1000)**
Mat lab Code	2.20
Model Testing (Literature)	2.192
CFD (Ship flow)	2.165

Table 5 shows the Mat lab code for the calculation of total wave pattern resistance using Fourier transformation method for Froude no 0.48 and being compared with model testing data (DTNSRDC) as well as CFD result using ship flow. From **Table 4** and **figure 1,** for above Froude number (F_N) - 0.48, wave breaking and spray generation increase with increasing F_N, in this high F_N range, the values of C_{WP} drop off at a faster rate than do the C_R values, as F_N increases. It appears that wave breaking and spray resistance add resistance to the ship, and this resistance increase is not reflected in the measured-wave-pattern resistance obtained with the longitudinal wave-cut.

V. Conclusion

The wave pattern resistance given by DTNSRDC for R/V ATHENA is having agreement with mat lab code which was written using Fourier transformation method in which longitudinal wave cut method is used for wave height measurement and numerical calculation using ship flow, i.e., components of ship resistance have studied using CFD software named ship flow and analyzed using published literature.

Acknowledgment

The author sincerely acknowledges the valuable support extended by Prof. S.C Misra (former Director, IMU, Visakhapatnam) and Mr. U.S Ramesh of IMU Visakhapatnam campus. The author thanks Mrs. C.H Revathi, Mr. Avinash Godey for the support.

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