Journal of Marine Science and Technology
DOI: 10.6119/JMST-013-0117-2

This article has been peer reviewed and accepted for publication in JMST but has not yet been copyediting, typesetting, pagination and proofreading process. Please note that the publication version of this article may be different from this version. This article now can be cited as doi: 10.6119/JMST-013-0117-2.

EFFECT OF HULL FORM COEFFICIENTS ON THE VESSEL SEA-KEEPING PERFORMANCE

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Key words: sea-keeping, waterplane area coefficient, prismatic coefficient, neural networks method and polynomial fitting method

ABSTRACT

This paper investigates the hull form of a high speed chine vessel based on a smart model, so as to observe the effect of variations in some geometrical parameters and hull form coefficients such as C_{wp} and C_p on sea-keeping response by means of numerical and experimental methods. For modeling, neural networks and polynomial fitting methods are combined to achieve sufficient accuracy in modeling. The effect of variations in C_{wp} and C_p on the hydrodynamic response, which is calculated by the modified strip theory method and Pierson-Moskowitz (PM) wave spectrum, is illustrated. The main assumption of the paper is that variations in hull form parameters are so slight that each variable can be assumed independent of other variables. Displacement, speed and angle of wave approach are considered constant for the vessel and the model in this paper. All geometrical parameters and vessel hull form coefficients affect the vessel hydrodynamic coefficients differently. Two of these mentioned parameters are the waterplane area coefficient and prismatic coefficient whose effects on the vessel seakeeping are studied. Simulation results indicate that present modeling can be applied to vessel hull form design, considering geometrical limits and the desired optimal conditions.

I. INTRODUCTION

Proper operation of a vessel in calm water and turbulent conditions is defined as seakeeping operational capability. Optimizing this ability, either analytical or non-analytical, can lead to the development of operational conditions in preliminary steps of designing new vessels.

Nowadays, optimization of hull forms so as to develop a suitable tool has turned into an important branch in technical and engineering sciences. This branch of science is also used in marine and aerospace industries to optimize the proper movement behavior of hull forms, by means of potential flow solvers, RANS solvers or other validated solvers in comparison with experimental methods and the full scale model which presents reasonable results as well.

Optimization in vessel seakeeping ability has long been of engineers' interest in naval architecture. From this viewpoint, Grigoropoulos presented a method to optimize hull form considering hydrodynamic operation in calm and turbulent water. His method was based on initial optimization of the main hull form for better seakeeping function and the optimized hull results improved for the calm water resistance. He defined the effective parameters in vessel seakeeping operation such as C_{wp}, LCF, C_B, LCB, KB, and C_p and changed these parameters according to the original vessel hull form. Then, he studied the appropriate behavior of vessels in regular head-sea wave conditions by Hooke and Jeeves optimization algorithm and created optimized hull forms according to these parameters [7].

Kapsenberg attempted to find the optimized hull form with respect to seakeeping capability through a program based on linear strip theory and managed to improve it by Lewis form expressions for his desired hull. He used the program for designing a frigate vessel and presented the final hull form. This was implemented by investigation of three hull form parameters such as beam (B), draft and Sectional area such as functions of vessel length [11].

Sener *et al.* studied the effect of different parameters on high-speed vessel seakeeping capability. In their works, hull parameters were divided into two groups: main dimensions (L, B, T) and form parameters (C_p, LCB). In their studies, a parameter was assumed as constant in each group, and the next parameter was studied: for instance, in form parameters group, 225 hull forms, derived from the main hull form, were obtained to investigate the effects of C_p and LCB on seakeeping ability. The 35 selected hull forms were studied

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and it was concluded that a decreasing in the vessel length results in a decrease in the heave amplitude but it increases the pitch amplitude. Decreasing C_p will end in heave amplitude decrease as well. However, commenting on the effect of Cp on pitch motion is impossible. Approaching LCB toward vessel aft also decreases heave amplitude but has no effect on pitch motion. It was also found out that changing the main dimensions of vessel is more effective than changing form parameters in heave amplitude [12].

Another study was conducted by Aranda *et al.* considering the constant speed of high-speed vessel in regular sine wave conditions. Their experimental and analytical results had a very good match in a vast domain of sea conditions. They studied heave, pitch, and roll dynamic motions in the encounter angles between 90 degrees and 180 degrees. Their method was based on genetic algorithm and nonlinear optimization algorithm, and their initial data was obtained through system identification [2].

E. Sarioz calculated 2-D damping and added mass coefficients using Frank Close-Fit method, and by his method he could investigate effects of some geometrical and hull form coefficient on seakeeping criteria[15].

Combining of seakeeping related theories for ship design is done completely by Faltinsen and Svensen in 1990. Whole seakeeping theories for ships are introduced and strip theories, at least in preliminary design stage, are considered as the best and most practical method (by ignoring some limitations) for calculating ship motions in waves [10].

The most recent studies are carried out by Trincas et al. (2001), Alkan *et al*. (2003), Nabergoj *et al. (*2003), and Sayli *et al.* (2010) among which Trincas proposed an inverse problem solution of optimal hull forms and the others worked on the base of statistical analysis using a large amount of ship motion data related to various parameters in multi-linear models. [16]

Tomasz Cepowski presented a method which makes it possible to determine optimum hull form of passenger car ferry with regard to selected sea-keeping qualities and added resistance in waves. In the first phase of investigations, a hull form characterized by the highest qualities was selected from the list of similar ships. Next, its optimum dimension ratios were determined. Design criteria were formulated by using a method based on deterministic scenarios, but objective functions of partial targets were determined in the form of artificial neural networks. For selection, the best design variant elements of fuzzy logic were used, which made it possible to show merits of the design by means of linguistic variables. Such approach made it possible to find the best hull form and its dimensions from the point of view of all considered criteria simultaneously [3].

In another paper, Tomasz Cepowski presented the modeling of a car passenger ferry ship design parameters with respect to these design criteria such as sea-keeping qualities and additional resistance in waves. In the first part of the investigations, the approximations of selected statistical parameters of design criteria of ferry ship were elaborated with respect to ship design parameters. The approximation functions were obtained with the use of artificial neural networks. In the second part of the investigations, design solutions were searched for by applying the single and multi-criteria optimization methods. The multi-criteria optimization was performed by using Pareto method. Such approach made it possible to present solutions in such a form as to allow decision makers (ship owners, designers) to select the most favorable solutions in each individual case [4].

Tomasz Cepowski researched to elaborate design guidelines which could make it possible to improve sea-keeping qualities of passenger-car ferries. The investigations for design guidelines were prepared in the form of regression functions as well as artificial neural networks on the basis of the results obtained from calculations with the use of numerical methods based on the theory of planar flow around a body [13].

David Winyall describes ongoing research to develop a flexible 3D hullform design process and modules with associated performance models, and integrate these modules into an existing ship synthesis model (SSM) in a multi-objective optimization approach to perform Naval Ship Concept and Requirements Exploration (C&RE). Effectiveness is initially based on seakeeping indices and resistance, and then extended to a multi-objective genetic optimization of an Offshore Patrol Vessel (OPV) total ship design. Overall Measure of Effectiveness (OMOE) used in this process which is based on expert opinion and pair wise comparison. In this method cost and risk considered beside use of relatively simple and traditional parametric hull form model and design variables (LBP, B, D, T, Cp, Cx, Crd) with performance based on parametric resistance algorithms (Holtrop 1984) and seakeeping indices (Bales 1980). [18]

One parameter or *one* variable cannot be used in order to evaluate and define seakeeping ability; rather *a group of* variables and parameters is required for evaluation. Here, eight parameters and variables, such as heave motion, pitch motion, relative speed, absolute acceleration and roll motion are considered.

The quality of a vessel seakeeping is defined as staying in the sea at all times. In sailing a vessel and all responses in the six states, it is assumed that the vessel does not lose its rigidity. Initial study of the vessel response in ideal long waves without considering the motion interactions is not correct due to the force distribution; motion-like heave generates pitch motion.

II. MODELING CALCULATION METHOD BY COMBINATION OF NEURAL NETWORKS AND POLYNOMIAL FITTING METHODS

One of the applications of neural networks is modeling the nonlinear relations of the systems. Neural networks (NN) are in fact non-parametrical methods which are based on data which does not possess many of the restricting assumptions in respect of data.

The back-propagation algorithm is the most important algorithm for the supervised training of NN, it derives its name from the fact that error signals are propagated backward through the network on a layer-by-layer basis. The neural network is three layers in this study. The network consists of input, hidden and output layers. The network converts the inputs according to the connection weights. These weights are adjusted during the learning process to minimize sum of the squared errors between the desired output and the network output [1]. A simple neural network is represented in Figure (1).

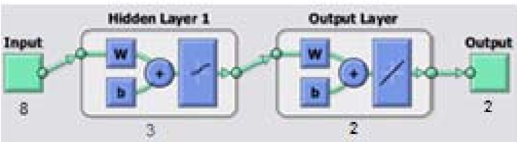

Figure (1): Neural network diagram

The output layer is given by

$$net_j = \sum_{j}^{i} w_{ji} o_i + \theta_j \qquad (1)$$

where w_{ji} represents the weight between hidden node j and input node i. The output of unit i in the hidden and input layers are represented by O_i.

The total error energy, E_p, is obtained by,

$$E_p = \frac{1}{2} \sum_{j-output} (t_{pj} - O_{pj})^2 \qquad (2)$$

Where t_{pj} is the desired output and o_{pj} is actual output. If a sigmoid transfer function is used in the operation element then

$$O_{pj} = \frac{1}{\sum_i 1 + e^{-w_{ji} o_{pi} + \theta_j}} \qquad (3)$$

Using equations (1) and (3), the activity of each unit is propagated forward through each layer of the network. Error for each unit is calculated.

$$\delta_{pj} = o_{pj}(t_{pj} - o_{pj})(1 - o_{pj}) \qquad (4)$$

A hidden layer error is back propagated as follow,

$$\delta_{pj} = o_{pj}(1 - o_{pj}) \sum_k \delta_{pk} w_{kj} \qquad (5)$$

The change in each weight is calculated. This rule for the adaptation of the weights is known as the generalized delta rule.

$$\Delta_p w_{jt}(t+1) = \alpha \delta_{pj} o_{pt} + \varepsilon \Delta_p w_{jt}(t) \qquad (6)$$

Where α is a constant which determines the learning rate of the back propagation algorithm, ε determines the effect of previous weight changes on the current direction of movement in weight space. The learning rate has used between 0.01 to10 [1].

In this paper, two neural networks are applied to vessel modeling. The first network is so trained that it models the relation between vessel independent parameters and height variations. This network is a two-layer network with sigmoid transfer function in the first layer and linear transfer function in the output layer. There are 3 Neurons in each layer and the training repeat steps are 20 times.

%% Define the Input and Target Vectors for Neural Network_1 Training

% Input Vectors are Independent Variables: L/B, B/T, CB, Cp, Cwp, Cm, KB, L/LCF. We have used some values of these parameters

% Output vectors are Hull Forms (Height: y)

Where:

LCF: Distance between center of waterplane area and mid-ship section

C_B: Block coefficient

Cm: Midship section area coefficient

T: Draft of vessel

KB: Height of buoyancy center of vessel

The second network is applied to model the relation between vessel height and beam variations. This network is a two-layer network with sigmoid transfer function in the first layer and linear transfer function in the output layer. There are 2 Neurons in each layer and training repeat steps is 50 times.

%% Define the Input and Target Vectors for Neural Network_2 Training

% Input Vectors are calculated Offsets (x) (Hull Forms) used in above section (8values)

*% Output vectors are Hull Forms (Height) through all positions (7*8 Matrix)*

In this method, using the data presented in table (3), a polynomial of minimum degree (polynomial of degree 5 selected in simulations) is used for modeling the body lines, and body line variations are studied due to independent parameters variations.

In this section, vessel's body line for aft ship (vessel transverse section in aft ship), which is obtained through the combination of neural networks method and polynomial fitting method, is drawn and the modeling error is indicated in both charts (error is determined according to the chart obtained from main vessel body lines). Using the above combination method C_{wp} and C_p variations of smart model are obtained as in Figures (2) and (3). By this process, the vessel body lines can be drawn for all transverse sections.

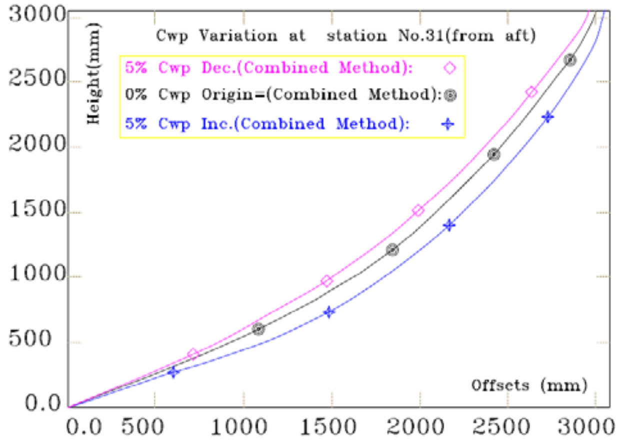

Figure (2): difference between Cwp in three cases

In Figure (4) where the combination method (neural network method with polynomial fitting method) is used, both curves coincide with each other; this indicates a higher accuracy in the combination method in comparison with neural networks method.

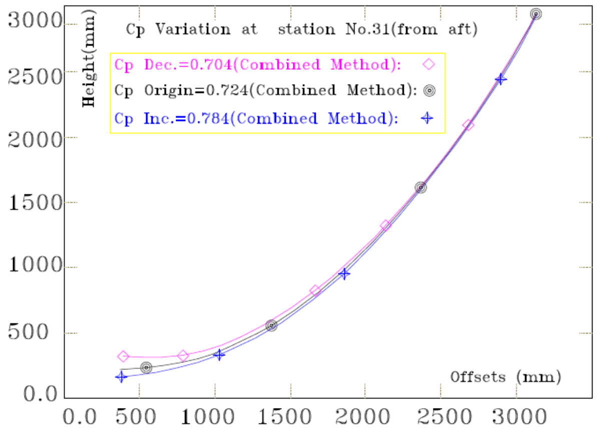

Figure (3): difference between C_p in three cases

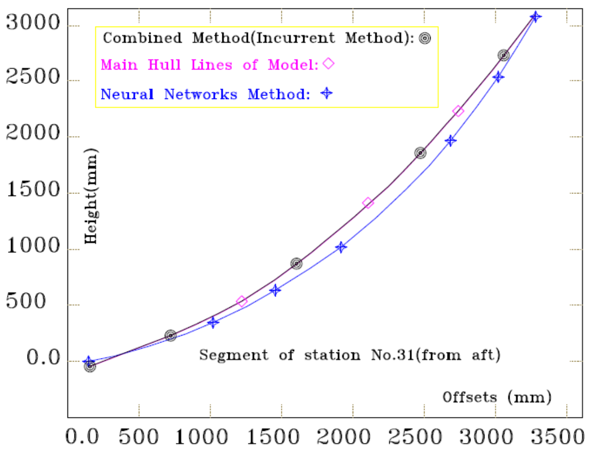

Figure (4): difference of modeled vessel transverse section by combined method (neural networks method and polynomial fitting),main hull lines form and neural networks method

Thus, combination method is selected for vessel modeling and two procedures are used for its evaluation for this paper. One is by model experiment and the other is by comparison with modeled vessel in reference [12].

III. TEST CONDITIONS IN LABORATORY

Laboratory, as shown in tables (1) and (2), possesses geometrical and hydrodynamic properties for testing the vessel model: this can be considered as test condition assumptions (Figure (5)).

Table 1: main properties and assumptions of model puller in laboratory

Parameter	**Amount**
Min. speed (m/s)	0.05
Max. speed(m/s)	6
Acceptable speed(m/s)	10
Speed accuracy (%)	0.1
Time for reaching the max. speed(s)	4
Engine type	DELTA
Gearbox type	AE05 007
Engine power(kw)	15
Model max. pulling force(N)	Min 500
Max. Capacity(Persons)	4
Wheel diameter(cm)	50
Wagon dimensions(m)	3*4
Max. model length(m)	2.5

Table 2: main properties and assumptions of model pulling system control

Control systems	System type	Manual	By manual volume
		Automatic	PLC: control: speed time, time, distance, acceleration time, stop time, Positioning and orientation
	Control type	By crew	By HMI located on the wagon
		Auto pilot	By HMI located on control room door (radio modem system)
Safety systems	Software system	PLC	Control: speed, time, distance, acceleration, location
	Brake	Mechanical	Lent viral Brake
		Electrical	By changing engine

			rpm
	Micro switch	Beginning and end of rails	
	damper	Spring foam	

1. Laboratory equipment for model test:

1. Model holder equipped with 3 degrees of freedom dynamometer
2. Possibility of measurement of the force exerted to the model in 3 directions
3. Possibility of 6 degrees of freedom for the model
4. Ease of installation of surface and subsurface models
5. Ability to lock and release the model in any desired direction
6. Ability of easy replacement of load cells to achieve the desired accuracy
7. Ability of recording and playback of model images
8. Ability to send images simultaneously to the control room
9. Ability of remote zoom and to focus on the model

Figure (5): vessel model installed in lab.

IV. AREA WAVE CONDITIONS FOR MAIN VESSEL

Waves are of the most important sea phenomena and due to their complicated and random nature, they are considered as one of the most difficult research and engineering problems. Marine engineers design a vessel according to its operational conditions: therefore, identification and review of incident's wave spectrum are important. In order to investigate vessel motion spectrum a wave spectrum must be considered according to the main vessel operational area. The selected wave spectrum which is applicable for Persian Gulf area is Pierson-Moskowitz (PM) and test conditions must be according to this spectrum. This spectrum is one of the statistical spectrums of energy distribution relative to frequency and was obtained in north Atlantic sea in 1964 and its formula is as follows [14]:

$$S_{PM}(\omega) = \frac{\alpha g^2}{\omega^5}\exp\left[-\beta\left(\frac{g}{\omega U_{19.5}}\right)^4\right] \quad (7)$$

$\alpha = 0.0081, \beta = 0.74$ and g is gravity acceleration $U_{19.5}$. is the wind speed in the height of 19.5 m from the sea level, $\omega = 2\pi f$ in which f is wave frequency. In other words, if this spectrum is written in terms of significant wave height (H_S) and crest wave period (T_p), then we have [14]:

$$S_{PM}(\omega) = 5\pi^4\frac{H_S^2}{T_p^4}\cdot\frac{1}{\omega^5}\exp\left[-\frac{20\pi^4}{T_p^4}\cdot\frac{1}{\omega^4}\right] \quad (8)$$

Linear superposition principle in random waves was applied by Denis and Pierson (1953) who assumed that sea random waves can be stated as the sum of regular waves with definite height and phase. According to this principle, motions of a vessel in random waves can also be stated as the sum of its motions in regular waves. This principle allows a general problem to be simplified into two sub-problems as predicting vessel response in regular waves and indicating random waves and random vessel motions as wave spectrum and response spectrum [15].

1. Equations of forces

Viscosity and surface tension can be ignored in the equations due to their little effects in comparison with those of wave and pressure especially in vertical motions. Vessel hydrodynamic forces can be defined as a linear boundary value problem in the potential flow. By assuming the motion responses to be linear or those they can at least be linearized and harmonic, vessel motion equation in waves can be stated as the following general formula [15]:

$$L_{kj}(H,\omega,V)\eta_j = F_k, \qquad k,j = 1,2,\ldots,6 \quad (9)$$

Where H defines the hull geometry, ω is wave frequency and V is vessel speed. L_{kj} function is typically defined as below:

$$L_{kj} = -\left(M_{kj} + A_{kj}\right)\omega^2 - iB_{kj}\omega + C_{kj} \quad (10)$$

Where M is mass matrix, A and B are respectively added mass and fluid damping matrices related to stimulated forces/moments in kth mode so that in jth mode motion is slow and *C* is hydrostatic restoring matrix. *j* degrees of freedom are according to Surge, Sway, Heave, Roll, Pitch and Yaw which are respectively indicated as 1-6. Hydrodynamic coefficients and hydrostatic restoring forces of the model hull form are stated as below [15]:

$$\begin{aligned} A_{kj} &= A_{kj}(H,\omega,V) \\ B_{kj} &= B_{kj}(H,\omega,V) \\ C_{kj} &= C_{kj}(H) \end{aligned} \quad (11)$$

Exciting wave force F_k is also a function of wave heading.

$$F_k = F_k(H,\omega,V,\beta) \quad (12)$$

Added mass, damping coefficient, restoring force and wave's exciting force terms can be calculated by proper numerical estimation methods. In order to decrease the calculation time the modified linear strip theory is applied. In Sarioz's [15] work, damping coefficient and added mass are calculated through the known method of Frank Close-Fit.

Final transfer functions "η_j", which are called Response Amplitude Operators (RAOs), are also functions of hull form, heading speed, wave heading and frequency:

$$\eta_j = \eta_j(H, \omega, V, \beta) \tag{13}$$

Transfer functions present vessel responses in regular sine waves. The considered frequency range is related to the sea state where in the vessel operates. Thus, sea state properties must be taken into consideration in seakeeping equations. In order to make the optimization problem more real, it is assumed that random sea waves are presented by statistical methods based on the two main wave parameters, significant wave height H_s and wave modal period T_m. Thus if waves or seaways are defined as bellow [15]:

$$S_\xi = S_\xi(\omega, H_s, T_m) \tag{14}$$

Response spectrum S_ξ for jth response can be defined as bellow:

$$S\eta_j(\omega, H_s, T_m, H, V, \beta) = S_\xi(\omega, H_s, T_m) \times |\eta_j(H, \omega, V, \beta)|^2 \tag{15}$$

And j^{th} response variance (rms) will be:

$$\sigma_j = \int_0^\infty S\eta_j(\omega, H_s, T_m, H, V, \beta)\, d\omega \tag{16}$$

Thus, for the considered incident speed, wave heading parameters and sea state, an optimization problem can be created by reducing vessel responses in a seaway. Generally vessel seakeeping capability in a sea state cannot be simply presented by single motions. A general seakeeping criterion which calculates all the critical motions including obtained responses such as slamming and vertical accelerations is a real objective function of the reverse design problem.

The modified strip theory method applied in this paper is a computational method by which motions and forces exerted to a three dimensional floating body can be defined using two dimensional potential theory results. Merging the theories related to seakeeping for ship design was performed by Faltinsen and Svensen in 1990. Modified Strip theory is planned based on the potential flow theory, and damping effect of viscosity on the transverse rolling is taken into account by empirical formulas. For high-speed vessels divergent unsteady wave systems are important which are ignored in strip theory [5]. Based on modified strip theory, wave forces exerted to the vessel X'_{wj} and uncoupled 2D potential hydro-mechanical loads X'_{hj} in the desired direction j are defined as follows [8]:

$$X'_{wj} = \frac{D}{Dt}\left\{\left(M'_{jj} - \frac{i}{\omega_e}N'_{jj}\right)\cdot \dot{\zeta}^*_{wj}\right\} + X'_{FK_j} \tag{17}$$

$$X'_{hj} = \frac{D}{Dt}\left\{\left(M'_{jj} - \frac{i}{\omega_e}N'_{jj}\right)\cdot \dot{\zeta}^*_{hj}\right\} + X'_{rs_j} \tag{18}$$

This formula is applied in this paper as it is a proper method when the vessel has forward speed. In the modified strip theory formula M'_{jj} و N'_{jj} are 2D potential coefficients of mass and damping. X'_{FK_j} is 2D Froude-Krylov force or moment which is calculated by integrating directional pressure gradient in regular waves on the surface of each 2D hull section. Directional components of water particle acceleration and rotational speed $\dot{\zeta}^*_{wj}$ are also calculated through Froude-Krylov forces and are used for calculating waves diffraction forces and moments [9].

Forces $\vec{F}$ and moments $\vec{M}$ are calculated by integrating pressure p on the total vessel submerged surface (S):

$$\vec{F} = -\iint_S \left(p \cdot \vec{n}\right)\cdot dS \qquad \vec{M} = -\iint_S p \cdot \left(\vec{r} \times \vec{n}\right)\cdot dS \tag{19}$$

In this relation, $\vec{n}$ is surface (dS) normal vector, and $\vec{r}$ is surface (dS) location vector in $O(x, y, z)$ coordinate system. Pressure is also obtained from linearized Bernoulli equation and potential as follows [8]:

$$p = -\rho\frac{\partial \Phi}{\partial t} - \rho g z = -\rho\left(\frac{\partial \Phi_r}{\partial t} + \frac{\partial \Phi_w}{\partial t} + \frac{\partial \Phi_d}{\partial t}\right) - \rho g z \tag{20}$$

Φ_r Is radiation potential, Φ_W is regular wave field potential and Φ_d is diffraction potential [8].

V. SEMI-DISPLACEMENT HULL FORM

Main vessel and tested model properties are presented in table (3) for evaluating the effect of geometrical parameters and hull form coefficients on the vessel seakeeping criteria and degree of variables as the program output are illustrated in table (4).

Main vessel/ model body lines are indicated in Figure (6). As illustrated before, vessel has longitudinal step.

By varying the 8 variables such as C_{wp} ,LCF, C_B, KB, C_p ,L, L/B, B/T in the modeling process, different forms of vessel body lines can be obtained. For instance, model body lines with 5 percent increase and decrease in C_{wp} are shown in Figure (7). On the other hand, number of variations for each variable is infinite; it means that a great number of hull forms can be obtained for a variable such as C_{wp} or C_p.

Table (3): main properties of model and vessel for experimental test

Parameters	Model	Variable /Constant
Overall length (m)	2.67	Variable
Length between perpendiculars (m)	2.50	Variable
Beam (m)	0.40	Variable
Depth (m)	0.2216	Variable
Draft (m)	0.11	Variable
Weight (kg)	48.97	Constant
Coefficients		Variable

Speed (m/s)	3.6565	Constant
encounter wave angle (Degree)	135,180	Constant
Lab. Temp. (Deg.)	25	Constant
Density (Kg/m^3)	1025	Constant
τ (Deg.) (Trim)	0	Constant
GM(m)	1	Constant
MSI		Variable

Problematic limitations for varying the hull form will be considered based on the following two assumptions:

1. Weight or underwater volume of vessel/model is always constant.
2. Density of fluid and environment temperature and pressure where the model floats are always constant.
3. Speed / Froude number (0.9) is always constant

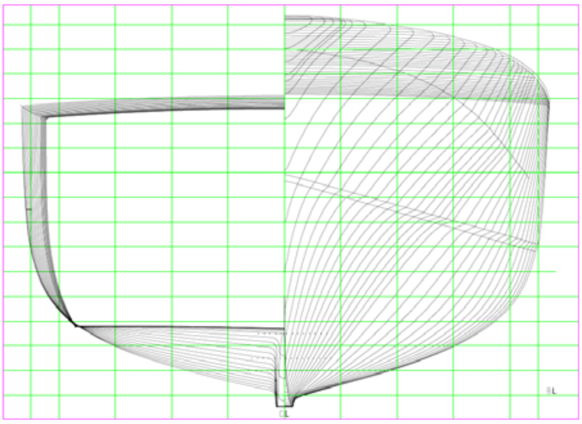
Figure (6): vessel model body lines

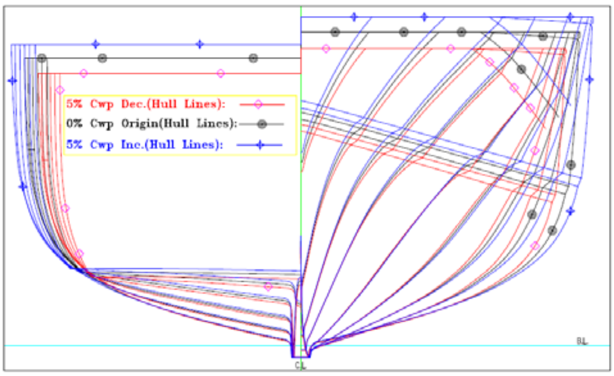

Figure (7): main vessel bodyline variations due to increasing and decreasing C_{wp} 5 and 5 percents respectively

1. FROUDE NUMBER EFFECT

The results of test show that the amount of Froude number plays a significant role in vessel motion response; in other words, some values of the above 8 variables might be optimum in a specific Froude number while the same values of variables are not optimum in another Froude number.

Also as observed in the model test, model pitch amplitude increases as wave length increases. Vessel motion will be constant in longer wave length and it lends toward the amount of incident wave amplitude.

Table 4: variation amounts of 8 analyzed parameters in the program output

Independent Variables							
Cp	CB	Cm	Cwp	KB/T	B/T	L/B	L/ LCF
0.707	0.510	0.725	0.817	0.627	2.764	6.466	2.311
0.719	0.519	0.725	0.825	0.623	2.756	6.485	2.296
0.721	0.521	0.726	0.826	0.623	2.755	6.488	2.295
0.724	0.522	0.726	0.827	0.623	2.755	6.488	2.293
0.726	0.524	0.725	0.829	0.622	2.755	6.487	2.290
0.727	0.525	0.725	0.829	0.622	2.755	6.487	2.289
0.728	0.526	0.725	0.830	0.621	2.755	6.487	2.288
0.729	0.526	0.726	0.830	0.621	2.755	6.487	2.287
0.730	0.527	0.726	0.831	0.620	2.755	6.487	2.286
0.730	0.527	0.726	0.831	0.620	2.756	6.487	2.285
0.738	0.533	0.725	0.838	0.620	2.755	6.487	2.269
0.750	0.541	0.724	0.846	0.622	0.617	6.481	2.254
0.761	0.549	0.726	0.853	0.614	2.762	6.472	2.240
0.774	0.558	0.726	0.862	0.612	2.759	6.479	2.224
0.791	0.570	0.725	0.873	0.610	2.755	6.488	2.203
0.800	0.577	0.725	0.879	0.607	2.755	6.487	2.192
0.824	0.595	0.725	0.894	0.602	2.758	6.481	2.163

Another term which affects the eight mentioned parameters is wave length. Like Froude number, each variable can have an optimum amount in a specific wavelength which is not optimum in another wavelength. According to the above two principles, Froude number and wave length must be determined for defining optimum amount of each of the above eight mentioned variables.

Motion amplitude increases as vessel speed increases. This amplitude increment is due to encounter frequency increment. In waves with smaller wave lengths, encounter frequency increment results in a decrease in encountered wave period; thus, the vessel has fewer motions. But when wave length increases, motion amplitude increases with a lower rate. In a specific wave length which motion amplitude is maximum, motion amplitude has higher amounts in higher speeds [2] [9] [17].

Many model tests were performed in different speeds and wave heights in towing test. Among these tests, vessel motion amplitude has increased a lot more than the previous cases (with increasing Froude numbers). This increment shows approaching of encountered wave frequency to the vessel motion natural frequency.

As nonlinear behavior occurs in large incident wave amplitudes, tests were performed in wave amplitudes which do not cause the nonlinear behavior of the vessel. Results are illustrated in non-dimensional charts whose vertical axis shows RAO operator that is the input amplitude divided by vessel response (output amplitude) and the horizontal axis shows the non-dimensional parameters such as input wave length to vessel length ratio and also input wave heights to draft ratio. Non-dimensional charts make it possible to use the results of real vessels and also similar vessels with different lengths and drafts [6].

As observed in test results, increasing vessel motion amplitude, in small wave lengths, increases as input wave amplitude increases; while in large wave lengths, by increasing input wave amplitude, vessel motion amplitude decreases; in very large wave lengths relative to ship length in each three amplitudes, wave amplitude converge reaches the same amount (Figure 8).

When input wave height increases, as observed in the results, by increasing input wave amplitude, the number of wave lengths for which vessel motion amplitude has the maximum amounts increases accordingly. In smaller amplitudes, the number of points (wave lengths) for which vessel motions have the maximum amount is one wave length. But in higher amplitudes, there are two wave lengths; in other words, two resonance encounter frequencies occur (Figure 9).

When investigating the effect of wave length on vessel motions, model speed and wave amplitude are considered constant.

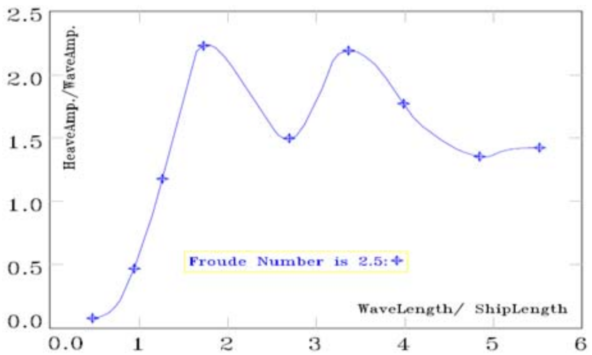

Figure (8): vessel heave amplitude in wave amplitude of 2 cm

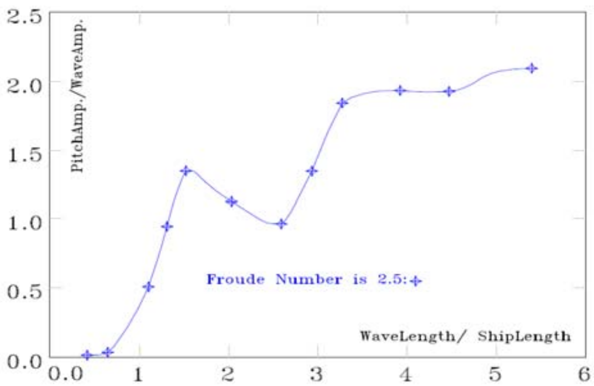

Figure (9): vessel pitch amplitude in wave amplitude of 2 cm

VI. VARIATIONS OF THE COEFFICIENT C_{wp} AND C_p

The coefficients C_{wp} and C_p have a relative effect on vessel seakeeping. Nevertheless, it is worth to note that when the optimum amount of these coefficients is calculated in an encounter angle, this amount is not necessarily optimum in all encounter angles. The optimum amount is related to the encounter wave direction. The effect of prismatic coefficient (C_p) on heave, roll, pitch RAOs and vertical acceleration are indicated in Figures (10-13), respectively.

Heave motion effective restoring force coefficient, multiplication of 5 coefficients, is defined as below, and the effect of vessel length and beam as well as the waterplane area coefficient (C_{wp}) are shown:

$$C\,(\text{restoring force coefficient}) = \rho\, g\,.\,L\,.\,B\,.\,C_{wp} \tag{26}$$

where ρ, L and B are respectively water density, vessel length and breadth.

Roll added mass coefficient, according to the present relations, is directly related to waterplane area coefficient and prismatic coefficient and is, on the other hand, inversely related to vessel length, beam and draft [10]:

$$\alpha = I_{xx} + \delta I_{xx} = \frac{\Delta}{g}\left(k_{xx}^2 + k_{xx}'^2\right) = \frac{\Delta}{g} k_{xx}''^2 \tag{27}$$

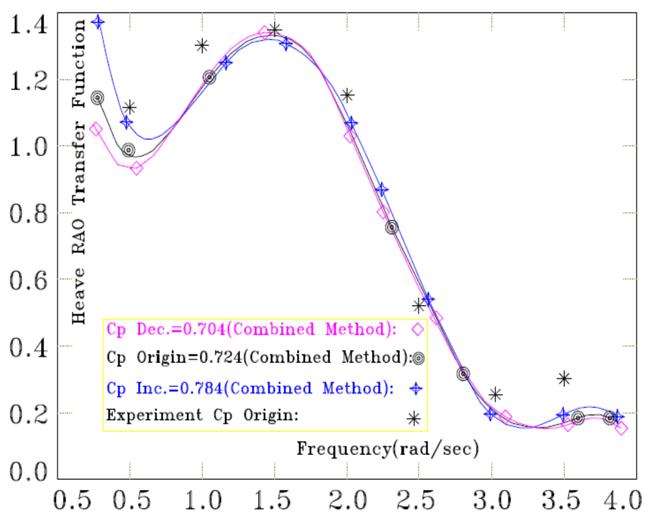

Figure (10): effect of C_p variation on vessel heave motion in different frequencies

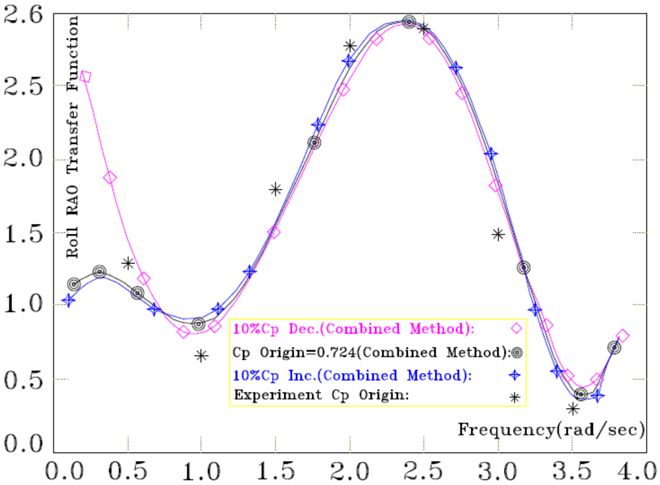

Figure (11): effect of C_p variation on vessel roll motion in different frequencies

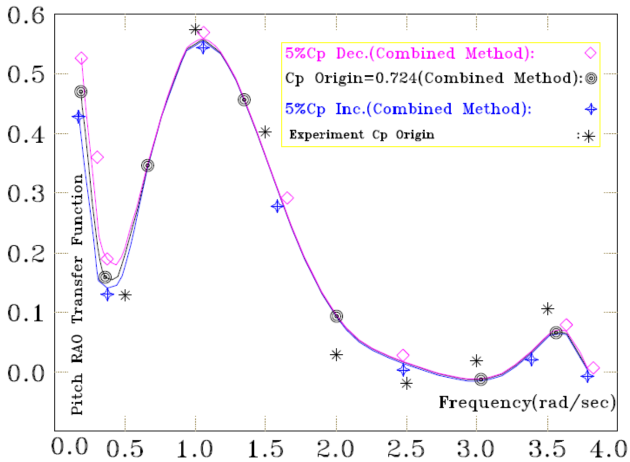

Figure (12): effect of C_p variation on vessel pitch motion in different frequencies

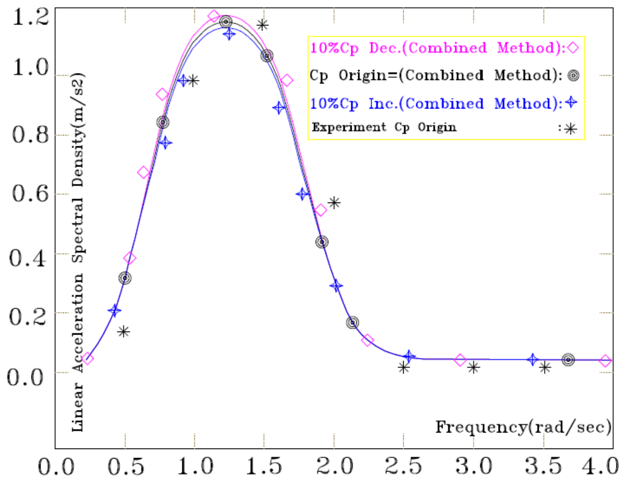

Figure (13): effect of C_p variation on vessel pitch motion in different frequencies

VII. CHINE HULL FORM

Here, another hull form is employed by the present method. This hull form is chine hull form and it is almost similar to the planing hull form. Ozum *et al*. [12] calculated seakeeping performance of this model. The body plan is shown in Figure (14). We determined the effect of waterplane and prismatic coefficients on this model as well. Figure (15) shows the comparison of C_p variation effects on the vessel heave motion for 8% increase, 8% decrease and main model with C_p maintained from Ozum et al. [12]. As observed in Figure, the heave motion amplitude increases as C_p increases, and the results are in good agreement with Ozum et al. [12] results. The all calculations carried out at Froude number 0.5 for this model as well.

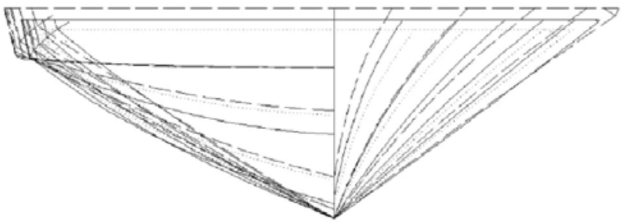

Figure (14): body line analyzed by method presented in [12]

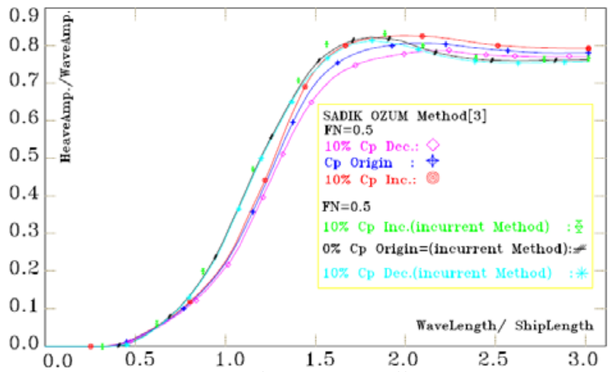

Figure (15): comparison of C_p variation effects on the vessel heave motion for 8% increase, 8% decrease and main model with C_p maintained from Ozum et al. [12] method.

Variations of 1 to 10 percent (decreasing and increasing) of the waterplane area coefficient are performed by the combined method (neural network method and polynomial fitting) and its effects on vessel hydrodynamic coefficients are indicated. Figures (16-19) are presented the effect of waterplane area coefficient (C_{wp}) on vertical acceleration, heave, pitch and roll RAOs. The results show that when the coefficient (C_{wp}) increases, heave and pitch RAOs decrease.

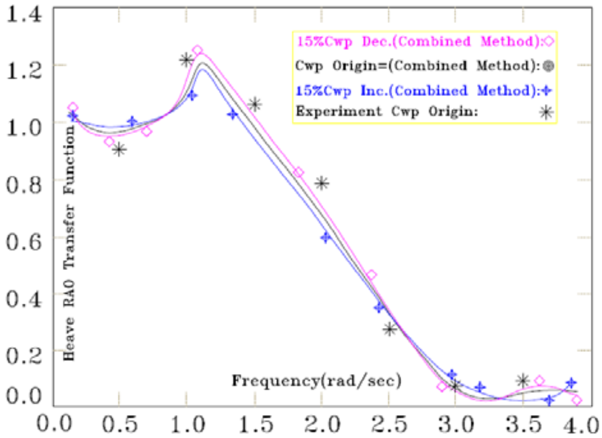

Figure (16): effect of C_{wp} variation on heave motion in different frequencies

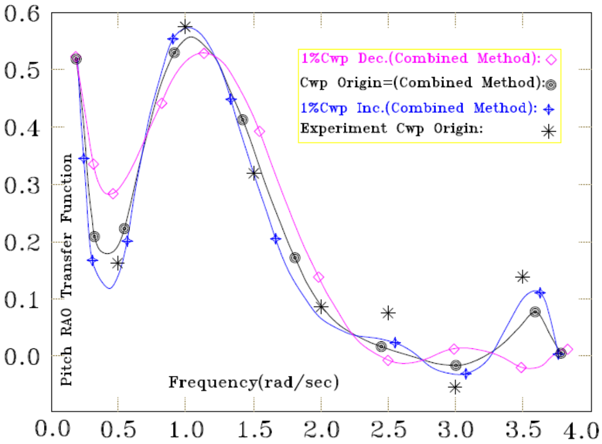

Figure (17): effect of C_{wp} variation on pitch motion in different frequencies

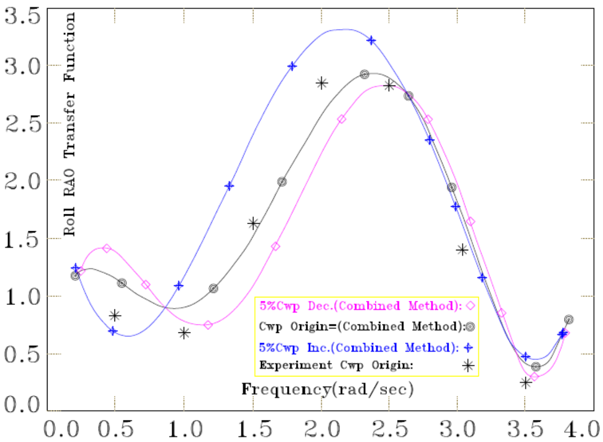

Figure (18): effect of C_{wp} variation on roll motion in different frequencies

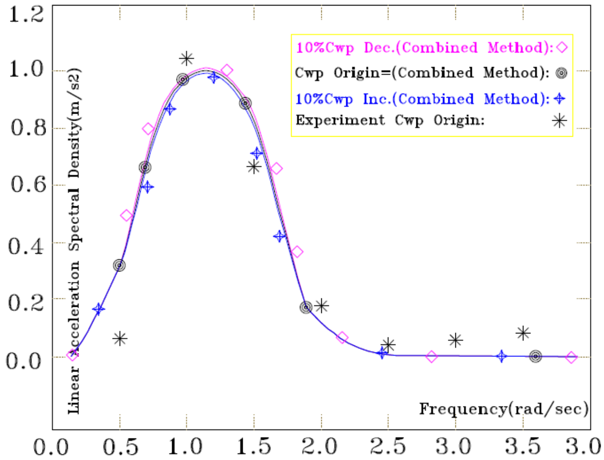

Figure (19): effect of C_{wp} variation on vertical acceleration in different frequencies

VIII. CONCLUSIONS

Simulation results indicate that the performed modeling can be employed in a vessel hull design regarding the geometrical limitations or the desired optimization conditions. The significant point is that, as variation of a parameter such as waterplane area coefficient (C_{wp}) or prismatic coefficient (C_p) affects the other coefficients, the effect of ship hull variations on the seakeeping criteria cannot be stated as a general law.

The following results are concluded from the program and performed tests to investigate the effect of dimensional variations and hull form coefficients on seakeeping parameters:

1- Combination method has a great accuracy for vessel modeling and seakeeping survey;
2- Decreasing or increasing C_{wp} in the fore of vessel can reduce deck wetness and increase slamming;
3- Decreasing or increasing C_{wp} in roll motion is totally related to the relative frequency and cannot be studied independent of it;
4- Decreasing C_{wp} results in a decrease in roll amplitude while increasing it leads to its increase;

Acknowledgements

The authors would like to express their sincere appreciation for the respectable editor Dr. Chung-Ru Ho, who directed this paper so that it can be presented in the best standing. The authors would also like to thank the reviewers for their helpful points and directions.

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