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Development of Preliminary Ship Motion Prediction Tool for Coupled Heave and Pitch

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ABSTRACT: *Seakeeping analysis has been one of the most important, yet rigorous phases of ship design. Modern seakeeping tools such as SEAKEEPER and VERES have been developed by commercial firms, which are mostly based on frequency domain. This study aims at developing a motion prediction program with the aid of JAVA programming language in time domain. By the application of potential wave theories and basic ship motions relationships together with numerical solutions incorporating Runge-kutta fourth order Algorithm, an effective tool for predicting seakeeping qualities for ships in coupled heave and pitch modes of motion have been developed. Attempts made to validate the developed software against proven seakeeping software such as those from CBT and VERES using the popular S175 ITTC container vessel showed strong correlation. Further analysis showed strong feasibility in the application of this tool for the prediction of ship seakeeping performance at the preliminary design stage. However, it must be cautioned that use of the developed program be limited to stationary vessels in water since sectional added mass and damping were only computed for a stationary vessel in water. In reality, the vessel is practically not stationary due to waves therefore; a computational approach that would compute real time non-stationary vessel's hydrodynamic properties should be applied to provide a better prediction of vessel responses.*

KEYWORDS*: pitch, heave, added mass, damping, pitch-added mass, excitation force, restoring force, Froude-krylov force, unified modelling language, responses*

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I. INTRODUCTION

The motion prediction analysis is an important phase of ship design process since this impacts on the operational ability of the vessel and the crew in realistic sea state.

Seakeeping analysis is 'the seaworthiness' of a vessel in calm and disturbed seaway conditions as the vessel goes through the seaways[1]. This analysis has had its challenges ever since the design of ships was proposed along the design stages. The common ways of predicting seakeeping analyses were either through experiments or some adapted designs approach of old varying results. Increasingly, experiments actually produce more accurate results but its time consuming and a lot of resources and energies directed towards it. On the other hand, the analytical methods and tools used in producing the same prediction has yielded a lot closer values with experiments which saves a lot of time and energy for the naval architects and ship project engineers in making design decisions. All thanks to the fast super computers we have these days. Some approaches have been proposed for the prediction of these motions amongst which are the popular panel method, and strip theory[2]. The strip theory, has given some realistic results over the years in the entire circle of ship motion computations ranging from the computations of the sectional hydrodynamics added masses and damping and its restoring coefficients.

Other considerations were with regards to the domain of computations, which are further subdivided basically into the frequency domain and time domain. While the former explore the computations of the response amplitude operators and makes of the frequency dependency techniques, it has produced fairly accurate results and the computation time is fairly fast. The frequency domain on the other hand has its shortcomings as it does not cover non-linear effects and real time analysis of these floating structures. These deficiencies are made up for much more with the time domain approach, which tries to capture the non-linear effects and gives a historic time motion of a vessel with regards to a given time [3].

With regards to the vessels linear dimensions, considering the length along the longitudinal section, beam and depth, the motion of a vessel tends to express its two degree of freedom of linear and rotational motions respectively along their linear directions of the length. Along the longitudinal length, we have the linear and rotational motion about that axis which is the popular surge and roll motion respectively[4],[5],[6]. Also, along the beam we have the linear motion of sway and rotational motion of pitch respectively. The popular linear heave and rotational yaw motion are along the depth of direction of the vessel. In broad divisions, the motion of the vessel is divided into two due to coupling effects, which are vertical and horizontal motions. The vertical motions are heave, pitch and roll, surge and yaw makes the horizontal motion. The figure 1.1 below depicts a typical ship motion in all six degrees of motion.

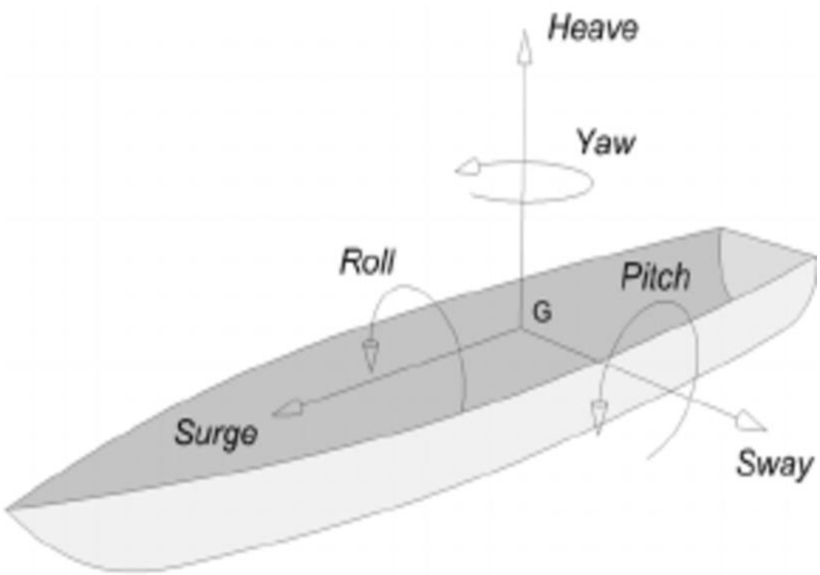

Figure 1: Showing the Six Degrees of Motion [7]

The strong, watertight construction and durability attribute of floating structures, structurally enabling it to survive rough water was never really an issue to the old boat builders, as yatches were basically used for leisure or a few sea activities, hence the seaworthiness was not of important factor to be looked at during design and operational stages. Easy motions coupled with freedom from jerky and excessive rolling motion-Sea kindliness; that quality of a floating vessel, which could 'friendly" withstand the violent wave forces and render them kindly to both the vessel and its crew members and operations. Other qualities such as the vessels habitability- and space for living quarters for crew members- were not given serious concerns over the centuries[1]. Vessels were built based on adapted designs and sometimes with mythical beliefs and these factors were never given concerns till there were issues on sea transportations ranging from capsizing collision grounding to other safety related incidents such as fire.

Some inventors and scholars issued some write ups. Notably was the St Denis and Pierson papers in 1953.This paper tries to address the issue with seakeeping and proposed that the seaworthiness of any good floating vessel can be evaluated based on the vessels responses, the realistic seaway, the purpose of the floating structure and strength of the vessel sea-kindliness[1]. Since the prediction of ship motion and its behavioral abilities at sea has posed serious problems, it was only important that it got more attentions. Various approaches were adopted ranging from the strip theories, which divide the ships' profile views into two dimensional body plans and determining its hydrodynamic properties such as the added masses and damping for the modes of freedoms. One of the popular Strip theory papers that was invented and still made relevance to the marine ship building industry today was that proposed by Salvesen and Tucks[8]These popular strip methods were also combined with Conformal mapping techniques which was first adopted from the popular Lewis 2-parameter conformal mapping techniques used for estimating ship vibration problems.

Other methods for computing the added mass and damping were also proposed amongst which are the Frank Pulsating source theories method, which uses the high and rigorous green theorem[2]. All of these techniques were cumbersome to carry out by computations by hand and as even, they tend to give close approximations with the experimental values such as those conducted by Ogilvie[8].

II. MATERIALS AND METHODS

The equation of motion of a ship is modelled in analogy with a mass-spring mechanical vibrating system where the vessel is compared to the solid mass and the fluid in contact with the moving vessel, as the spring and the oscillatory motions are same in six degrees.
Considering the solid motion of the vessel, modeled from Newton's second law of motion, mathematically as;

$$M\ddot{\eta} = \sum F_{ext} \quad (1)$$

Where;
M = the total solid mass matrix of the vessel, in *Kg*

$\ddot{\eta}$ = the acceleration in *rad/s²* and

F_{ext} = is the total excitation force, in *Newton*

Writing the above equation (1) and considering the added mass and damping hydrodynamic forces and restoring for coefficients in six degrees, we have

$$\sum_j^5 3\left[\left(M_{ij} + A_{ij}\right)\ddot{\eta}_j + B_{ij}\dot{\eta}_j + C_{ij}\eta_j\right] = \sum F_i \quad (2)$$

Where

$\sum M_{ij}$ = the general 6 by 6 mass matrix of the vessel in i, j mode

A_{ij} = the global added mass matrix in i, j modein *Kg*

B_{ij} = the global hydrodynamic damping matrix in i, j modein *Kg*/s and

C_{ij} = are the global restoring coefficients in i, j mode in $t^2/$ *Kg.*

Two approaches can be applied with regards to solving the equations of motion.One may use either the frequency domain method or the time domain method[2]. In the frequency domain, the ship's motions are treated as low amplitude sinusoidal motions. The calculation is fast since the computation is done in one-step for a particular frequency response. It can produce usable results. However, the method should not be used if the Froude number is too high and the vessel of interest is not sufficiently slender (i.e. the ratio between the breadth and draft is larger than 6).

On the other hand, the time domain method is popular when very large ships are considered. The disadvantage is that the method itself is complex and more computationally intensive. It requires many thousands of small incremental time steps in computations.
The coupled equation of heave and pitch response are given as[8]
Heave:

$$(M + A_{33})\ddot{\eta}_3 + B_{33}\dot{\eta}_3 + C_{33}\eta_3 + A_{33}\ddot{\eta}_5 + B_{35}\dot{\eta}_5 + C_{35}\eta_5 = F^{3excitation} \quad (3)$$

Pitch

$$(I_{55} + A_{55})\ddot{\eta}_5 + B_{55}\dot{\eta}_5 + C_{55}\eta_5 + A_{53}\ddot{\eta}_3 + B_{53}\dot{\eta}_3 + C_{53}\eta_3 = F^{5excitation} \quad (4)$$

Where

$$I_{55} = Mr_{55}$$

r_{55} = the radius of gyration of the vessel for pitch.
The hydrodynamic potentials in the mode of heave and pitch are gotten from the Lewis conformal mapping approach with N=10[2].The excitations for each mode in pitch and heave is a combined sectional strip excitation of the Froude-krylov forces,restoring moments and forces and the diffractionforces[12],[13],[14].

2.2 The Simulation Model

Equations (3) and (4) are all second order differential equations (ODE) and can all be solved numerically with different numerical methods. To solve the above ordinary differential equations, it is a common practice to first reduce them to first order differential equations. Hence, we have six first order differential equations instead of three. Amongst the different ODE techniques used, the most efficient of them all used in solving these time step kind of problems are the Runge-Kutta fourth order algorithm[9]. This is done first by reducing them to first order differential equations and then solving them numerically. Reducing equations (3)and ,(4) to solve for the coupled heave and pitch for each time step can be written as

$$\frac{d\eta_3}{dt} = z(t)(5)$$

$$\frac{d\eta_5}{dt} = y(t) \tag{6}$$

And the heave motion for each time step is given as

$$\eta_{3(i+1)} = \frac{1}{6}(u_1 + 2u_2 + 2u_3 + u_4) \tag{7}$$

And pitch

$$\eta_{5(i+1)} = \frac{1}{6}(m_1 + 2m_2 + 2m_3 + m_4) \tag{8}$$

Where the variables $u_{1,}u_{2,}u_{3,}u_4 m_{1,}m_{2,}m_{3\,,}m_{4,}$ are components of the above equations in terms of the pitch and heave added masses, and their coupling hydrodynamic potentials ,their retardation functions and the excitation forces at each time step.

2.3 Software Architecture and Implementation

The Model View Control approach in this work tries to duplicate or model real world problems with an equivalent analogy of the computer object and as such provides the concept of "classes", the blueprint from which these objects are built. Therefore, a single software designed in object-oriented approach must have at least a class. For serious applications, the number of classes range from a few hundred and above. Furthermore, these classes are grouped and that breeds other software design pattern such as Model View Controller class or commonly known as MVC, Model, View Presenter (MVP) amongst others[10]. Since the class is the base for every development, it is only logical that for proper design architecture, such a pattern is followed and in this project, the Model View Control (MVC) was adopted.

In this MVC approach, the various parts of this program is divided into the model, view and control classes for a lot of reasons ranging from code reusability and maintenance and easy debugging and modern conventional design approach amongst others. It will be quite worthy while to mention and briefly explain some of the classes and component that make up each of the MVC components we have adopted for this program. Another important tool that could help organize each class component is the Unified Modeling Language (UML)[11],[12].This gives a tabular representation of the components that make up the real object of these classes, which are the attributes and themethods. The attributes comes first and its generally represented by the programming data type(Boolean, double, float, long, short, byte, Arraylist<>,array) followed by the variable name of the attribute of the object whose class is considered. The methods comes next which are generally represented by the qualifier (public, private) and the return type(double, string, float, arraylist <>,void) and the name of the method. Methods with a "+" are public method while those without a + are private method. Figures 2 and 3depicts some of the UML diagram of the model class.

Sectional Heave Computation Model
double[] mapCoef double breadth double density double angFreq

```
+Heave Computation Model void init()
+double get Wave Number()
+Array List<Double>get Theta()
+Array List<Double>get YValList()
+Array List<Double>getXValList()
+Array List<Double>getPsiBOC()
+double[][] getPsi2M()
+Array List<Double> getPsi2MAtPI()
+double[][] getF2M()
+double[][] getMatrixBForP2M()
+Array List<Double> getP2M()
+double getA()
+Array List<Double> getIs1()
+Array List<Double> getIs2()
+Array List<Double>getPsiS()
+double[][] getMatrixBForQ2M()
+Array List<Double> getQ2M()
+double getB()
+Array List<Double>getW()
+double[][] getPhi2M()
+Array List<Double> getIPhis1()
+Array List<Double> getIPhis2()
+Array List<Double>getPhiS()
+Array List<Double>getM()
+Array List<Double>getPhiC()
+Array List<Double>getN()
+double get MO()
+double get NO()
+double get Heave Added Mass()
```

Figure 2; UML diagram for Sectional Heave Added Mass. Java

Mapping Coefficient Model
Double[] stationOffset Double[] yval Double[] xval
+ Double Sectional Area() +Double[] get Guess() +Arraylist<double>get() +Double[][] For MatrixB() +Double[][] For MatrixA() +Double[][] solved Matrix() +Double Stop Condition LHS() +Double Stop Condition RHS()

Figure3: UML diagram for Mapping Coefficient Model. Java

2.4 Program Description

The motion prediction tool was developed using JAVA programming language. A summarized flow chart of the computation is shown in figure 2.3

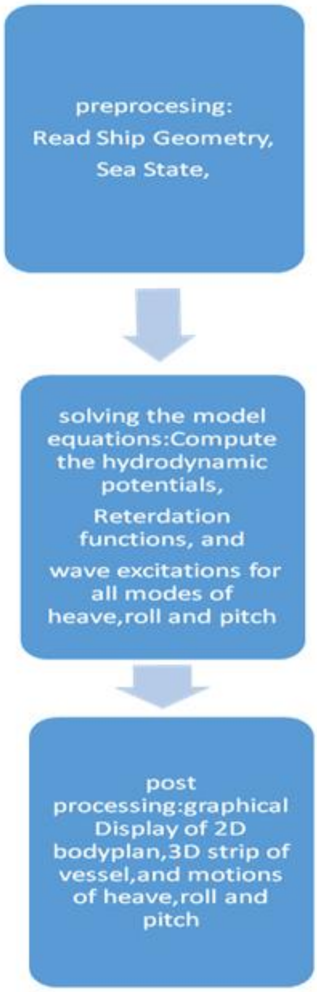

Figure 4: A Simplified Flow Chart for the Seakeeping Tool

The simplified graphical user interface of the main page of the application is shown in the figure 2.4 below

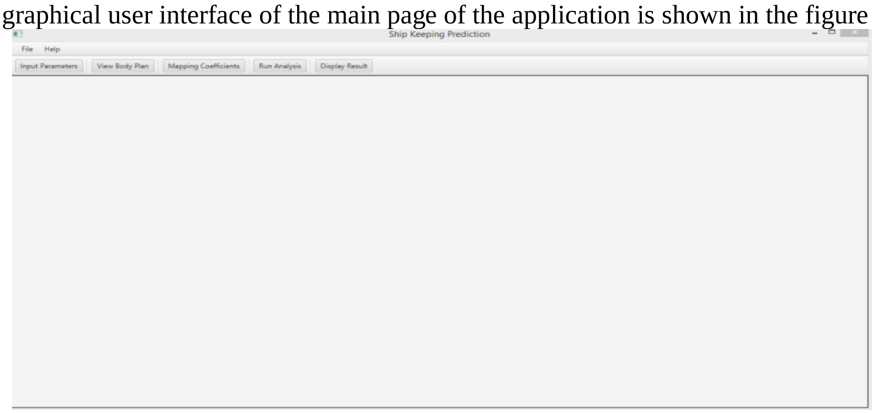

Figure 5: First GUI Seakeeping Tool

III. RESULTS AND DISCUSSIONS

This program is tested against the known S175 container vessel with monochromic wave loads conditions. It will attempt to validate the response motions of the popular ITTC container S175. In line with standard practices, the body plan is first described as shown in the figure 3.1 and the vessels particulars inputed into the program. Some of the principal vessel particulars are shown in table 3.1

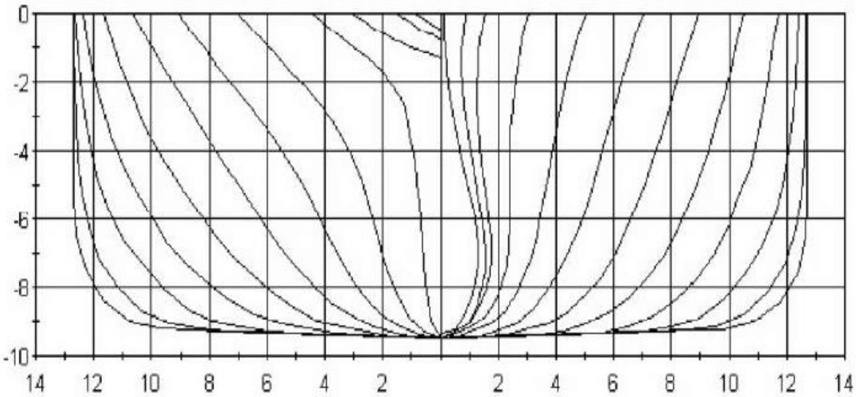

Figure 6: Bodyplan of the Container Ship S175 [6].

Table 1: The Main Particulars of the S175 Container Vessel [6]

Vessel Particulars	Model values	Units
LBP	175	M
Draught	9.5	M
Moulded beam	25.4	M
Waterplane Area	3147	m^2
Volume displacement	24140	m^3
LCG	2.34	M
VCG	9.52	M
Radius of gyration of roll	8.3	M
Radius of gyration of pitch	42.8	M
Block coefficient	0.57	

Table 2: Monochromic Wave Model

Wave Model Particulars	Values	Units
Wave period	30	Sec
Acceleration due to gravity	9.81	ms^{-1}
Wave amplitude	1	M
Sea density	1025	kg/m^3
Water depth	100	M

The wave particulars given above corresponds to the of wave in transitional water. The wave kinematics corresponding to this wave is given in appendix A. The simulation was carried out for 30 seconds and with varying times of 0.5s, for the S175 container vessel. The shape of the response of the pitch and heave motions tends to replicate that shown in Thein's, work. Although the values were not realistically close as some non-dimensional constants have been applied which gives a wide disparity in the outcome especially for the heave and pitch motion probably largely due to their coupled nature as resulted from the model.

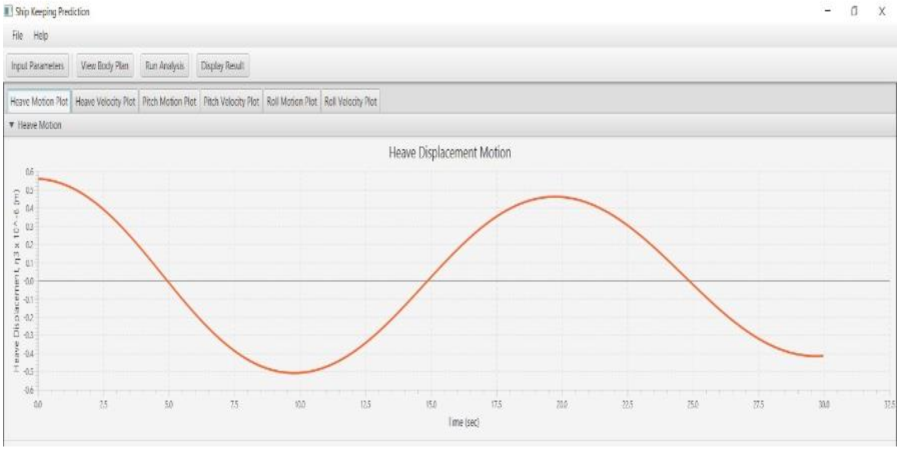

Figure 7: Heave Displacement Responses for S175 Vessel for 30 Second and with 0.05 sec Times Step

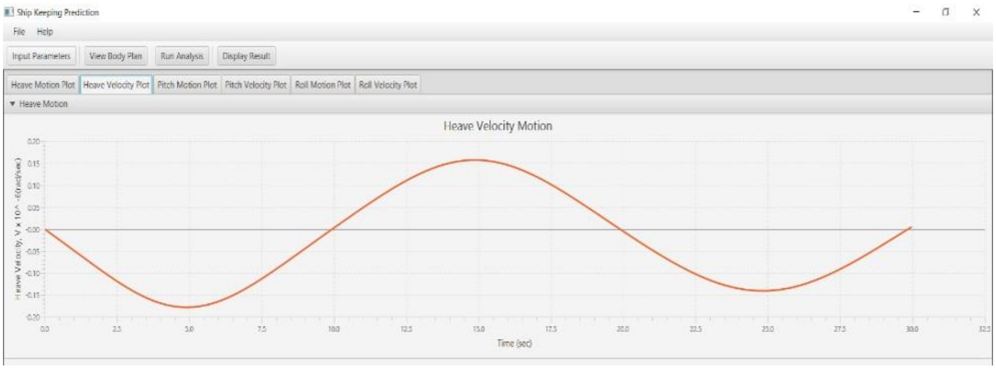

Figure 8: Heave Velocity Responses for S175 Vessel for 30 Second and with 0.05sec Times Step

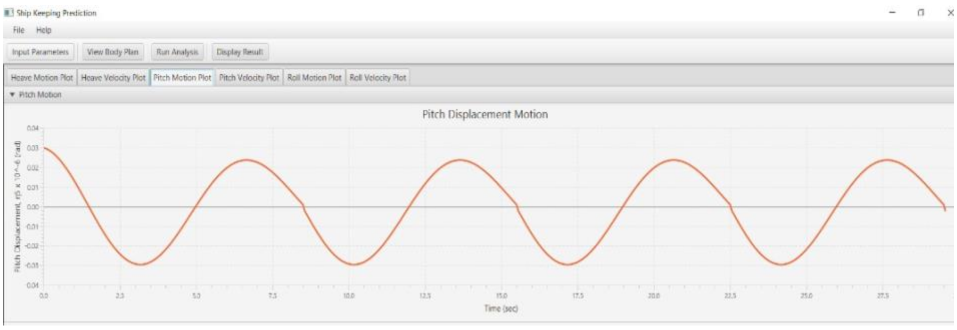

Figure 9: Pitch Displacement Responses for S175 Vessel for 30 Second and with 0.05sec Times Step

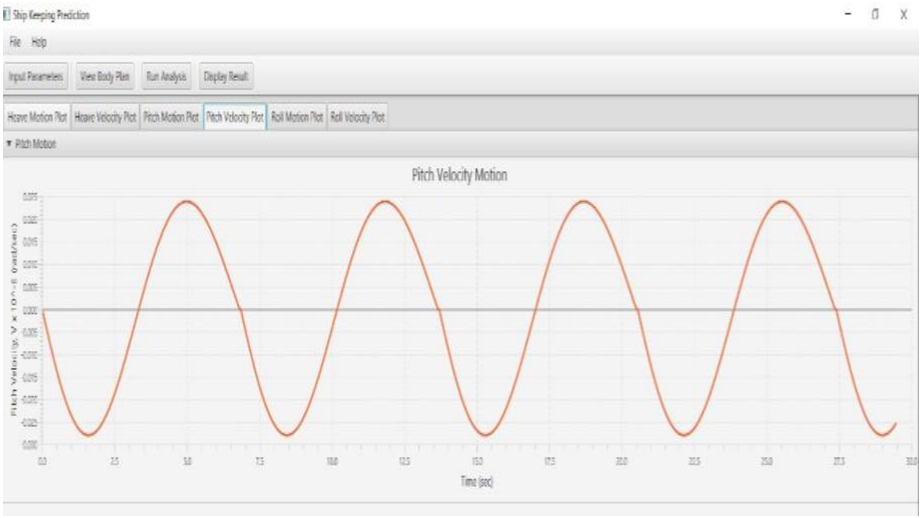

Figure10: Pitch Velocity Response for S175 Vessel for 30 Second and with 0.05sec Times Step

The program was tested for a time of 30seconds with two varying time step and a frequency of 5rad/s with a frequency step of 0.05 radian for the time domain computation of the retardation function for all modes at time step of 0.5sec with a total time simulation of 30 second, and a ships speed of 5knots which translate to 2.57m/s and 45 degree sea heading (0.8 radian), it took the program about 45minutes to compute. This is probably so as the program attempts to capture the non-linear Froude krylov force in real time. It was also discovered that the real time computation took that long owing to the attempt by the program to capture the instantaneous real time diffraction forces along the kinematic properties of the fluid in striking the vessel hull. The results seem way bigger than the normal due to the fact that it has not been normalized by standards and experimental results. The simulation for the 0.25sec time step and a total time of 30 seconds took about an hour and 15 minutes. Results tend to be much smoother with a smaller times step of 0.1 especially for roll motion with a consequential longer computation time seems a lot. In all, the program attempts to predict the typical response of floating vessel as the response builds gradually, it tend to show a similar oscillatory shape to the wave model used for this studies. It was observed that the results maybe much improved with a smaller times step and the inclusion of more strips but at the expense of longer computational time.

The program was used in attempting to validate its pitch and heave against Chalmers Big Time ,CBT and VERES and the results are show below

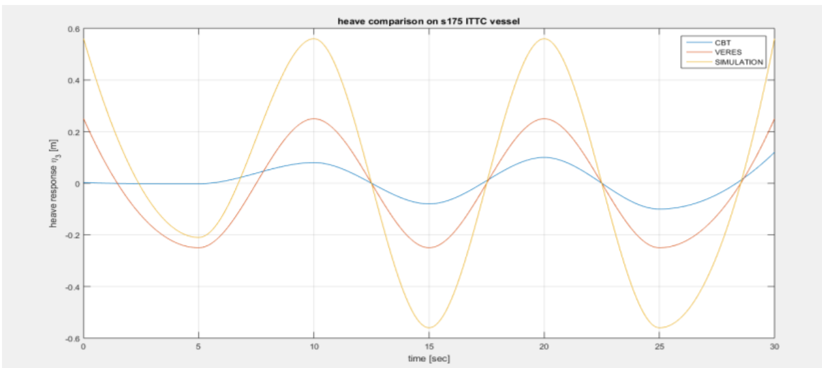

Figure 11: Comparison of the S-175 Container Vessels Heave Responses with the CBT, VERES and the Developed Tool

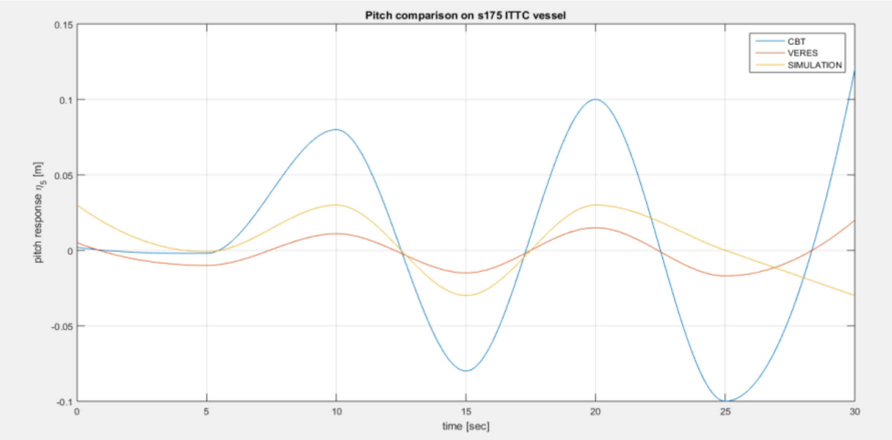

Figure12: Comparison of the S-175 Container Vessels Pitch Responses with the CBT, VERES and the Developed Tool

The response tends to follow same trend as the CBT and VERES at the intermediate time range. The values of the heave response tend to be a bit higher than the ones given by CBT and VERES by an average 0.07m. This difference may arise as a result different damping values and the non-capturing of non-linear froude-krylov forces which could be attributed the different models used. The pitch responses comparison tends to give a much better trend of prediction especially with the VERES tool. The speed comparison in these tools cannot be compared as at the time of this report as there was no available data sources for this comparison.

IV. CONCLUSION

This seakeeping prediction tool was an attempt at developing ship motion tool to study preliminarily motioned floating vessel in time domain. It considered the computation of the two dimensional added mass and damping for the modes of motions in heave, pitch and their coupling effects and the hydrodynamic properties of roll as well. These hydrodynamic properties were computed in frequency domain and for the time domain computations, they were converted to time domain quantities using the retardation function. An Attempt was made in computing non-linear Froude-krylov forces along with the diffraction forces and the hydrostatic pressure forces which all form the combined excitation forces for each degree of freedom all considered along with the conversion from one coordinate system to the other. Those modelled coupled equations were solved simultaneously by applying the Runge-kutta numerical method of fourth order. The algorithms were written and the source code developed in JAVA language along with other graphing API and libraries.

However, this prediction tool has some discrepancies and can only be used for studies and no practical works. It was developed basically for vessels whose offsets are well defined as it cannot intuitively make up for those offsets missing. Also other floating structures were not considered like floating rigs and as such cannot even be used to study the response of such structures along static vessels as well. It also adopted the linear strip theory approach which stipulates that the ratio of the length to the breadth should not be more than 6, therefore vessels who don't fulfill these stipulations cannot have preliminary studies carried out with this tool. Although the time domain computations is highly time consuming even with smart computers it is very possible with the modern smart devices coming up that such prediction tool can be built probably on android or IOS operating systems, which are proving to be a lot smarter these days.

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NOMENCLATURE

Symbol	**Definition**	**Unit**
$A_{i,j}$	The global added mass in the i,j mode	kg
$M_{i,j}$	The mass of the given i,j mode of the motion	kg
M	The total mass matrix of the vessel	kg
$C_{i,j}$	Global restoring coefficients of the i,j mode of response	t^2/kg
$\ddot{\eta}$	The acceleration of the respective mode of motion 0	rad/s^2
$B_{i,j}$	The global damping of the i,j mode of the response	kg/s
$\eta_{i,j}$	The motion in the i, j mode	m
F_{ext}	Total excitation in the respective mode	N

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