Dynamic Analysis and Investigation of the Frequency Response of the Moored Vessel

Shujaathussian.M. Soudagar, Sudhir Kumar Chaturvedi

Abstract: Paper The scope of the paper focuses on the "Investigation or say the study of Frequency Responses of a vessel under open sea conditions." The area of interest is how to change in characteristics properties of the vessel or the design parameter of the berth effects the free motions of the vessel. This paper covers mathematical modelling of the motion equations and study of its application in the development of the Frequency Response Calculation (FRC) section of the software MIKE-21MA. The effects on added mass, Damping, Exciting forces and the responses amplitude operator due to these changes are studied. The effect of this parameter over the free-floating vessel in the case to understand which parameter effects which motion. As the trend of increasing trade between the countries using the water routes rather the inland or airways due of obvious drawbacks in terms of transport the demand of the new building of ports and harbours is now in great demand. It is not just the ports or harbours but at the same time the size of the vessel is also continuously increasing at the same rate. As we move further in the paper, it will be observed how the simple potential coefficient could help us understand the vessel properties.It leads to predefine if the constraints could be increased or decreased at the same time the availability of the suitable berth in terms of draft or environmental conditions to support in vessel motion constraint.

Keyword: Added Mass, Damping, Response Amplitude Operator, Frequency Response, MIKE-21MA.

I. INTRODUCTION

It was up-un-till few years ago Mooring was just practical experience. A vessel was moored to the berth at the harbour *i.e.*, the sheltered parameter which was protected from most of the environmental conditions like the external forces that are arising due to wind, waves and currents.

For a few harbours such as the one with an open link to the sea, would encounter various difficulties with the mooring of the vessel.[1]

The suitable example is Long Beach, Cape Town etc. Which usually shows erratic motions ie, unpredictable motions leading to failure of the lines even in smooth weather. One of the basic reason that could be stated here is due to the:-

a. Resonance phenomena occurring in the harbour.
b. Exciting forces over ship-these forces might seem small but are the cause of large amplitude movements.Reason being the vessel has low frequency, which is nearly very close to the natural frequency of the waves

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Basil Wilson[2] addressed these specific challenges during this attempt to describe the dynamic behaviour of a vessel which is moored and subjected to the waves mathematically. With new developments and advancements in the ocean or navel industries and an increasing demand to accommodate large vessel, which is approved by a very few berths which have water depth sufficient to maintain the draft.

For this case, special mooring arrangement is/are designed in order that the loads implied by the environmental conditions are absorbed by the vessel that is moored at the berth. A mooring system design depends on the following parameters at the berth,

a) Water Depth
b) Weather conditions
c) Ship Size
d) Allowable motion for the moored vessel.

Most of the mooring system used at the harbour is "Spread Mooring System" in which the mooring lines are arranged in the form symmetric system across the longitudinal axis. The drawback of this system is that the vessel does not have the freedom to move along the direction of wave, current or wind in order to make it favourable to its motion.

It is seen that if the motions of the vessel are very small say if they are within the limiting criteria set by the PIANC guidelines. When it's been loaded or unloaded by the land crane, the mooring berth is jetty and is moored using mooring lines and fenders.

As it is also seen that the history of the maritime industry is very long but the development by means of Computational science or Smart development is not very old. Most of the development is done in the past few decades. Hence the design of the terminal of this berth cannot be entirely based on the empiricism. Also, see that the issues faced are far too complicated for numerical calculation. Those it is preferred that the study of the moored vessel over a berth is done using the experimental methods with a scaled down model of the entire berth and the vessel by imitating the actual environmental conditions like that one at "Central Water and Power Research Station, Pune". Though the experimental method of testing the motions and forces over a moored vessel is an effective way of studying the behaviour of the moored system it has following drawbacks.

a. Expensive and Time-consuming: -

The setting up of the model is a very complicated process when we try to imitate the vessel configuration, berth configuration and the environmental condition. As it is essential to maintain the correct elastic properties of the fender or the mooring line properties. Hence for the above-mentioned reason, there are test programs which are usually restricted for the final configuration of

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the berth and mooring design.

b. Limited Insight:-

The insight gained in the trial practical run is very limited due to the complexity of the system. The final outputs play an important role but the physics behind the obtained output is not studied. Like for example,

The low-frequency movement of the vessel that is moored to the structure is observed to be due to the irregular waves as mentioned above. Which is very much a topic of debate amongst the investigators some believe this is due to 2'nd order wave frequency while other communities believe its due to the non-linearity of the elasticity within the mooring lines and the 3'rd community believes its due to the free vibration caused by transitional phenomena.

These providing an edge of computational methods over the experimental test as its far more flexible.

The report basically focuses on the mathematical formulation or study in the prediction of vessel behaviour in open sea conditions and its effects on mooring design set-up which is the next stage in the implementation of FRC in MIKE-21MA. The study will be limited to the 6DoF of the vessel which in-term means a vessel which is moored to a berth by the means of mooring lines and is supported by fender from hitting the berth.

One of the most widely used equation to define the motion of the vessel is by assuming a spring-mass-damper system. As seen below,

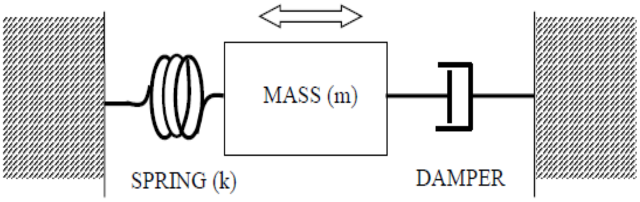

Figure 1, Spring Mass Damper System[28]

The equation representing the above system is,

$$\mathbf{F(t) = (m + a)\ddot{x} + b\dot{x} + c}. \quad (1)$$

Where

a,b and c represent coefficients for the restoring forces due to hydro-dynamic and static conditions. However, the above equation only provides the description of the steady oscillation movement of the vessel in a frequency domain.

Most of the work done in this industry focus on the above equation as the base of their study and is also the base MIKE-21MA-FRC [3].

II. LITERATURE REVIEW

2.1 Mathematical Derivation[4]

In 1989, Lewis stated that the modelling of a vessel motion in 6 DOF is based on the second law of Newton, ie,

$$\sum_{j=1}^{6} M_{ij}\ddot{\eta}_j = F_i(t) \quad (2)$$

Where,

i,j = 1,2,3 Translative motion

j,i = 4,5,6 Rotative motion

M_{ij} :- Mass / Mass Moments

F_{ij} :- Forces / Moments

$\ddot{\eta}_j$:- Translative / Angular acceleration

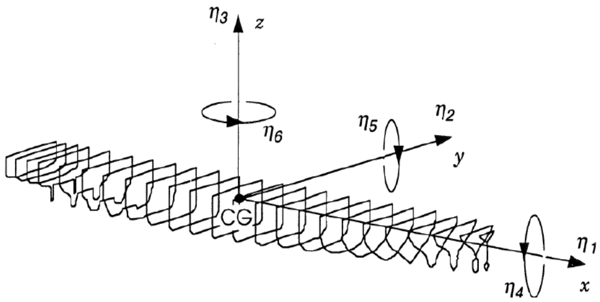

Figure 2, Demonstrating Six Degrees Of Freedom[2]

The LHS side of the equation could be expressed in a term as the sum of gravitational and fluid forces as follows,

$$\sum_{j=1}^{6} \mathbf{M_{ij}\ddot{\eta}_j = F_{Gi} + F_{Hi}} \quad (3)$$

In the above equation, it is noted that the gravitational force that acts on this vessel is due to its weight which is applied at the CoGie, Center of Gravity. Since the gravitational mean force nullifies the buoyant forces, they the two forces are a part of static fluid forces. Fluid force is a sum of hydrodynamic along with the hydrostatic forces which tend to act on the ship,

$$F_{Hi} = F_{HSi} + F_{HDi} \quad (4)$$

Both the forces are derived by integrating the pressure of the fluid over a vessel underwater.

$$F_{Hi} = \iint_S P n_i ds \quad (5)$$

Where,

P:- Fluid Pressure

n_i :- The unit normal over the surface of the hull

In the above equation, the pressure P found by using the Bernoulli equation as shown below,

$$\mathbf{P = -\frac{\rho U_0^2}{2} - \rho\frac{\partial \emptyset}{\partial t} + \frac{\rho}{2}(\Delta\emptyset^2) - \rho g z} \quad (6)$$

The forces expressed in the equation is expressed as follows,

$$F_{HSi} = -\rho g \iint_S P n_i ds$$

The net hydrostatic force in the above equation is a sum of hydro-static and the gravitational force which is best represented in the matrix form w.r.t 6 DOF as,

$$F^{*}_{HSi} = F_{HSi} + F_{Gi} = -\sum_{i=1}^{6} C_{ij}\bar{n}_i e^{i\omega_e t} \quad (7)$$

Where,

C_{ij}:- Spring Coefficient, or say Hydro-static restoring forces

$\bar{n}_i e^{i\omega_e t}$:- Arbitrary motion ie, n_i

$$F_{HDi} = -\rho \iint_S \left(\frac{U_0^2}{2} - \frac{\partial\emptyset}{\partial t} + \frac{1}{2}(\Delta\emptyset^2)\right) n_i ds \quad (8)$$

Where,

U_0:- The Forward speed of a vessel

Ø:- Velocity potential of the flow

In order to get the hydrodynamic force, it is must to define the fluid flow completely. In order to do

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some, the following assumption s are made,
The is assumed to be

1. Incompressible
2. Irrotational
3. Inviscid

$\emptyset=[-U_0x+\emptyset_s(x,y,z)]+[\emptyset_I+\emptyset_D+\sum_{i=1}^{6}\emptyset_R\overline{n_i}]e^{i\omega_e t}$ (9)

Where,

$[-U_0x+\emptyset_s(x,y,z)]$:- Steady term
$[\emptyset_I+\emptyset_D+$ i=16∅Rnieiωet :- Unsteady term
$\emptyset_D$:- Diffraction potential
$\emptyset_I$:- Incident wave potential
$\emptyset_R$:- Radiation Potential

Diffraction potential is defined as the flow in the presence of the vessel or body under rest condition. Incident wave potential is defined as the flow of the regular waves in the absence of the vessel. While radiation potential is defined by the waves generated by the presence of the vessel. Thus it is seen that the unsteady part of the velocity potential is the superposition of $\emptyset_I$ and the solution of $\emptyset_D$ and $\emptyset_R$.

Exciting force is defined as the hydrodynamic forces resulting from the sum of $\emptyset_I$ and $\emptyset_D$. Exciting forces is the term broadly defined as the sum of the diffraction, exciting force along with the Froude-Krylov Force given as,

$F_{EX_i}=\{F_i^{FK}+F_I^D\}e^{i\omega_e t}$ (10)

Where,

F_I^D :- Diffraction excitation force
F_i^{FK} :- Froude-krylov Force
F_{EX_i} :- excitation force

Froude-Krylov excitation force is the result of the integrated pressure over the vessel surface as if the vessel is absent. Hence, making it easy to calculate the F_i^{FK} due to the absence of the hydrodynamic problem. We then calculate F_I^D using the Laplace equation as shown below with the diffraction potential and w.r.t given boundary condition,

$\nabla\emptyset^2=\frac{\delta^2\emptyset}{\delta x^2}+\frac{\delta^2\emptyset}{\delta y^2}+\frac{\delta^2\emptyset}{\delta z^2}=0$ (11)

The radiation forces over a vessel resulting from the radiating wave due to oscillatory motion of the vessel are as expressed below,

$F_{R_i}=\sum_{i=1}^{6}(\omega_e^2A_{ij}-i\omega_eB_{ij})\overline{n_i}\,e^{i\omega_e t}$ (12)

Where,

A_{ij} :- Added Mass Coefficient
B_{ij} :- Damping Coefficient
ω_e :- Encountered Frequency,
$\omega_e=\omega-\frac{\omega^2}{g}U$(13)
Where,
ω:- Incident wave frequency
U:- Vessel forward speed
μ:- The relative heading of the Vessel

The added mass coefficient is defined as the amount of fluid that is accelerated in presence with the vessel. While the damping coefficient is defined as the force component that is proportion to the velocity ie, do the waves generated by the movement of the vessel and this waves disperses the energy from the oscillatory movements.

Following is the summarization of the forces acting upon the submerged vessel which is influenced by the incident waves as,

$F_i=F_{Gi}+F_{Hi}=F_{Gi}+(F_{HSi}+F_{HDi})$
$=(F_{Gi}+F_{HSi})+(F_{EXi}+F_{Ri})$ (14)
$=F^*_{HSi}+F_{EXi}+F_{Ri}$

From the equations above,
The linearized equation of motion that is to be obtained in the equation,

$\sum_{i=1}^{6}\eta_j[-\omega^2(M_{ij}+A_{ij})+i\omega B_{ij}+C_{ij}]=F_i^{FK}+F_I^D$
(15)

Different studies show different approaches in order to solve coefficients and excitation forces but two of the most common approaches used by researchers in the determination are

a) Strip Method:- Implementation of “Lewis forms”
b) Panel Method:- Implementation of “Boundary Element Method” (BEM)

As we obtain the hydro-dynamic coefficient, it creates an ease to solve the linearized equation of motion in the frequency domain as follows,

$\eta_j=\frac{F_{ex}}{-\omega^2(M_{ij}+A_{ij})+i\omega B_{ij}+C_{ij}}$ (16)

2.1.1 Strip Methods[4]

The application of the strip method to a slender body in order to estimate the hydrodynamic forces gives us satisfying results. In this method, the portion of the vessel that is submerged is divided into a finite number of strips. It uses a 2D approach with an assumption that the variation in the flow of the fluid in a C/S plane direction is comparatively greater than the variation that is seen in the longitudinal direction. The 3D coefficient for the global input ie,

1. Added mass
2. Excitation force
3. Damping

can be obtained by integrating the 2D coefficient or each strip along the full length of the vessel. This thus states the basic idea behind the Strip modelling, i.e., reducing the 3D hydrodynamic problem to a series of the 2D problem which reduces the effort in solving.

A complex force coefficient defines the added mass coefficient and the damping coefficient as follows,

$T_{ij}=\omega_e^2A_{ij}-i\omega_eB_{ij}$
$=\rho\iint n_i\left(i\omega_e-U_0\frac{\partial}{\partial x}\right)\emptyset_k ds$ (17)

To solve T_{ij} we must
1’st solve the boundary value problem for $\emptyset_k$, ie, the radiation potential.
2’nd integrate this to the hull surface.
The boundary value leads to 2 different components of $\emptyset_k$ and combination with the vessel approach. Thus allowing the complex force coefficient to be expressed in 2D

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$T_{ij}{}^{0} = -\rho i \omega_e \int_L \int_{C_x} n_i \varnothing_K^0 dldx$ {Where, i,j=1,2,....,4} (18)

Where,

dl :- Shows integral about the section contour C_x

dx:- Shows integral about the ship length L

Now, by approximating further into the boundary conditions and the 2D Laplace eq. it follows that $\varnothing_K^0$ and line integration from the equation could be the solution for a 2D series problem over various c/s about the length of the vessel. The two dimensional sectional coefficient of added mass and the coefficient Of damping could be defined according to the following equations,

$\omega_e a_{ii} - i\omega_e b_{ii} = -\rho i \omega_e \int_{C_x} N_i \Psi_i$ {where, i=1,2...4} (19)

$\omega_e a_{13} - i\omega_e b_{13} = \omega_e a_{31} - i\omega_e b_{31} = -\rho i \omega_e \int_{C_x} N_1 \Psi_3$ (20)

$\omega_e a_{24} - i\omega_e b_{24} = \omega_e a_{42} - i\omega_e b_{42} = -\rho i \omega_e \int_{C_x} N_2 \Psi_4$ (21)

Using the above equation we can represent added mass coefficients and damping coefficient in horizontal mode or in vertical mode as desired but only if the vessel is symmetric about port or starboard. Which is derived from Palmquist and Hua 1995

Based on the strip method if we try to express excitation force shown in the equation, the two-component on the RHS is represented as follows,

$f_j(x) = \rho g \bar{\xi} \int_{C_x} N_j e^{-ikysin\ \mu} e^{kz} dl$ {Where, j=1,2,3,4} (22)

$h_i(x) = \rho \omega_0 \bar{\xi} \int_{C_x} (iN_3 + N_1 \cos\mu + N_2 \sin\mu) e^{-ikysin\ \mu} e^{kz} \Psi_j(y,z) dl$

{Where, j=1,2,3,4} (23)

The corresponding 3D forces may be given by Lewis 1989 is shown as follows,

$\boldsymbol{F_j^I = \int_L e^{-ikycos\mu} f_j(x) dx}$ {Where, j=1,2,3,4} (24)

$F_5^I = \int_L e^{-ikycos\mu}\ f_3(x) dx$ (25)

$\boldsymbol{F_6^I = \int_L e^{-ikycos\mu} f_2(x) dx}$ (26)

$\boldsymbol{F_j^D = \int_L e^{-ikycos\mu} h_j(x) dx}$ (27)

$\boldsymbol{F_5^D = \int_L e^{-ikycos\mu} \left(x + \frac{U_0}{i\omega_e}\right) h_3(x) dx}$ (28)

$\boldsymbol{F_6^D = \int_L e^{-ikycos\mu} \left(x + \frac{U_0}{i\omega_e}\right) h_2(x) dx}$ (29)

His method shows the way of calculating the potential flow about a 2D section with the help of the conformal mapping method. The method can be applied in order to obtain the potential velocity about any arbitrary shaped C/S by plotting more convenient circular section in the new plane.

It is one of the three computational methods for obtaining 2D section hydrodynamic entities of the equations. The three techniques neglect the viscous effect and the basic difference is the approach that each method takes in order to solve the velocity potential around the oscillating cylinder in the following modes,

1. Sway
2. Heave
3. Roll

Multi-pole Method developed by Ursell (1949) is used as a background to satisfy Laplace eq. over the free surface boundary conditions for a circular cylinder. The obtained output could be then used with the conformal mapping in order to yield solution for Lewis form that basically resembles ship sections.

Lewis conformal mapping formula for 2-parameter is as shown below,

$\mathbf{z = M_s(\xi + a_1\xi^{-1} + a_3\xi^{-3})}$ (30)

Where,

a_1 , a_3 :- Lewis Coefficients

M_s :- Scale Factor

$\xi = ie^{\alpha}e^{-i\theta}$:- α:− section edge angle

z = x + iy

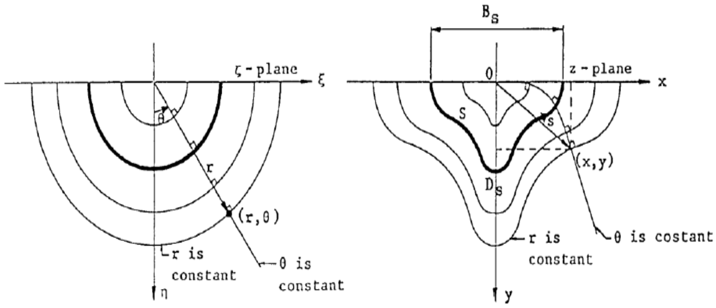

Figure 3, a (left) and b (right), Mapping relation for the moored vessel[2]

For conventional hull-shape as shown in fig. 3 (b), it can be seen that it's possible to derive the coefficients of Lewis in sectional breadth, area & draught are identical between approx, C/S (a) The original geometry of the hull (b) In-depth details are given in "Theoretical Manual of "Seaway", (Journée and Adegeest 2003)

1. Advantage:-

Computational Effort:- Low in order to obtain velocity potential and hydrodynamic quantities.

2. Disadvantage:-

The hydrodynamic characteristics are not obtained for a vessel with near midsection quadratic or vessel with high B/T ratio. Sharp corners and parts that are submerged like bulbs is another complication.

2.1.2 Panel Method[4]

One Drawback of the conformal mapping method is that it does not capture the vessel hull complete characteristics by a continuous function. This gives us a chance to apply the panel method which has an upper-hand to strip method. It is best applicable to analyze large-volume structure over a liner induced wave loads.

It was Hess and Smith in 1964 who developed the panel methods in aviation and that further laid the foundation for its applicability to the flow around the ship. It was found that sources could be scattered over quadrilateral panels ie, a body formed by large no. of small panel elements. Quadrilateral panel has 4 nodes, which basically describe the corners of the given panel by averaging the locations or coordinates of the nodes defining the corner we can define the centre. At the same time, the diagonal vectors joining the opposite nodes defines the cross-product from normal vector as from Bertram 2000, it is seen that the plane of panel is assumed to form the normal and centre.

McTaggart 2002, has very well shown how to solve the velocity potential along with

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the radiation force and the diffraction forces in the frequency domain. The velocity potential of a location in the domain of the fluid is given as,

$$\phi(\vec{x})=\frac{1}{4\pi}\int_{S_b} G(\vec{x},\vec{x_s})\sigma(\vec{x_s})\,dS \qquad (31)$$

Where,

- $\vec{x}$:- Source location over the surface of the vessel hull
- S_b :- Mean surface of the ship that is wet
- $G(\vec{x},\vec{x_s})$:- The function describing the flow over the location due to a source o strength at $\vec{x_s}$
- $\sigma(\vec{x_s})$:- Strength of the source at $\vec{x_s}$

$G(\vec{x},\vec{x_s})$satisfies all the boundary conditions given with the exclusion of normal velocity boundary condition shown on the vessel hull surface as shown below,

$$\frac{\partial\phi(\vec{x})}{\partial n} = v_n(\vec{x}) \text{ ....on ....} S_b \qquad (32)$$

Where,

- $v_n(\vec{x})$:- Normal velocity
- S_b :- Submerged body

With respect to the earlier given boundary condition, the strengths of the source are solved by fulfilling the equation.

$$-\frac{1}{2}\sigma(\vec{x_s})+\frac{1}{4\pi}\int_{S_b}\frac{\partial G(\vec{x},\vec{x_s})}{\partial n}\sigma(\vec{x_s})\,dS=v_n \text{...........on.....} S_b \qquad (33)$$

The hull B.C for the potentials are stated as,

$$\frac{\partial\phi(\vec{x})}{\partial n}=i\omega_e n_k \text{ ....on ....} S_b \qquad (34)$$

$$\frac{\partial\phi(\vec{x})}{\partial n}=\frac{\partial\phi_I(\vec{x})}{\partial n} \text{ ....on ....} S_b \qquad (35)$$

One can discretize eq^n and obtain the sol^n. of source strength along the panel

$$\left\{\frac{\partial\phi}{\partial n}\right\}=[D]\{\sigma\} \qquad (36)$$

Where,

- [D] :- Matrix influencing the velocity potential

$$D_{jk}=-\delta_{jk}\frac{1}{2}+\frac{1}{4\pi}\int_{S_k}\frac{\partial G(\vec{x},\vec{x_s})}{\partial n}\sigma(\vec{x_s}) \qquad (37)$$

Where,

- δ_{jk} - Kroenecker delta function
- S_k - Surface w.r.t panel k and j
- σ - Source strengths

$$\{\emptyset\}=[E]\{\sigma\} \qquad (38)$$

Where,

- [E] :- Velocity Potential

$$E_{jk}=\frac{1}{4\pi}\int_{S_b}\partial G(\vec{x_j},\vec{x_s})\,dS \qquad (39)$$

By obtaining the velocity potential and applying this obtained value along with the Bernoulli equations as mentioned in Eq^n, we can determine the added mass coefficient and the damping coefficient.

It's always seen that a given numerical method is always justified using the practical application in the form of experiments. In this case, there are few complications when we address a practical problem which is caused by the presence of irregular frequencies. While we solve to obtain the strength of the sources the results might get inconsistent due to the irregular frequencies ie, the integral solution to the corresponding irregular frequency is a non-finite solution. In 1990 Faltinsen explained the concept that irregular frequency is the representation of Eigen-frequencies of a fictious fluid flow within the body which has the same open surface conditions on the outer body. The obtained output is not a physical concept instead this impact is seen in the form of inconsistent amplitude peaks.

Limitation:-

Does not predicts the Roll motion of the vessel if the frequency is nearly the same as roll reasonable frequency as damping is predicted w.r.t radiation wave surface. Restricted to bodies with oscillating amplitude to fluid and vessels which small cross-section dimensions.

III. EQUATION OF MOTION

3.1.Motion Study in Frequency Domain

Newton's law of dynamic provides us with the differential form of the equations which describes the movements of the vessel that's floating freely to a simple harmonic wave as a response is as follows,

$$\sum_{j=}^{6}\frac{d}{dt}\left[M_{kj}\frac{dx}{dt}j\right] = X_k \qquad (40)$$

Where,

X_k represents the overall external forces in the given mode, ie, sum of all restoring forces ie, hydrodynamic as well as hydrostatic and exciting forces of wave

M_{kj} represents the moment of inertia matrix, as the origin is placed at CoG of the vessel it is in rest position, which gives us

$$\mathbf{M_{kj}} = \begin{bmatrix} \mathbf{m} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{m} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{m} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{I_k} & \mathbf{0} & -\mathbf{I_{kj}} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{I_k} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & -\mathbf{I_{kj}} & \mathbf{0} & \mathbf{I_k} \end{bmatrix} \qquad (41)$$

Where,

- m:- Mass of vessel
- I_k :- Moment of inertia
- I_{kj} :- Product of inertia

It is wise to neglect the rate of change of mass of vessel while considering the movement which is small for a duration time that is small as a comparison to the period required to load or unload a vessel

Hence the following for the steady oscillation conditions,

$$\sum_{j=1}^{6}\left(\mathbf{M_{kj}}\frac{d^2}{dt^2}+\mathbf{C_{kj}}\right)\boldsymbol{\zeta_j}\, \mathbf{e^{-i\omega t}} = \mathbf{F_k} \qquad (42)$$

Where,

- C_{kj} :- Restoring force coefficient matrix
- F_k :- Hydro-dynamic Force

C_{kj} not just includes the hydro-static restoring forces but also the restoring forces arising due to the mooring system. But the one condition to be included is that this system must be linear load-excursion properties.

If we combine equation, the hydro-dynamic force obtained is as follows,

$$\sum_{j=1}^{6}(-\boldsymbol{\omega}^2\mathbf{M_{kj}} - \mathbf{T_{kj}} + \mathbf{C_{kj}})\boldsymbol{\zeta_j} = (\mathbf{T_{k0}} - \mathbf{T_{0k}})\boldsymbol{\zeta_0} \qquad (43)$$

It has always been a practice to separate T_{kj} for the real and imaginary parts as follows,

$\mathbf{T_{kj} = \omega^2 a_{kj} + i\omega b_{kj}}$ (44)

Where,

a_{kj} :- Added Mass Coefficient (real part)

b_{kj} :- Damping Coefficient (imaginary part)

If we use these quantities in the representation of the movements it gives a real-time eq. of motion as follows,

$\sum_{j=1}^{6}\{-\omega^2(M_{kj}+a_{kj})\sin(\omega t+\varepsilon_j)+\omega b_{kj}\cos(\omega t+$
εj+Ckjsinωt+εj}ζj=xksinωt+δk (45)

Where,

x_k :- Excitation force of the wave

ε_j and δ_k :- Phase angle

The above-obtained equations are merely a set that provides us with the fixing of amplitudes and phases of 6 motions of the vessel under the influence of regular waves over 1 specific frequency rather then real eq[n], of motions.

3.2 Volume[3]

Floating vessel surface is obtained by integrating the vessel hull grid file in 3-direction independently as follows:-

$$\forall = -\iint_{S_b} n_1 x\, dS = -\iint_{S_b} n_2 y\, dS = -\iint_{S_b} n_3 z\, dS$$ (46)

Where,

n_1, n_2, n_3 :- Unit vector perpendicular to body boundary and median of 3 volumes

S_b :- Floating vessel surface

$\forall$:- Volume

3.3 Centre of Buoyancy[3]

Center of Buoyancy is briefly defined as thecentre of gravity for the volume of fluid displaced by the vessel hull.

This plays a very important role in-order to define the stability which is as seen in the figure below.

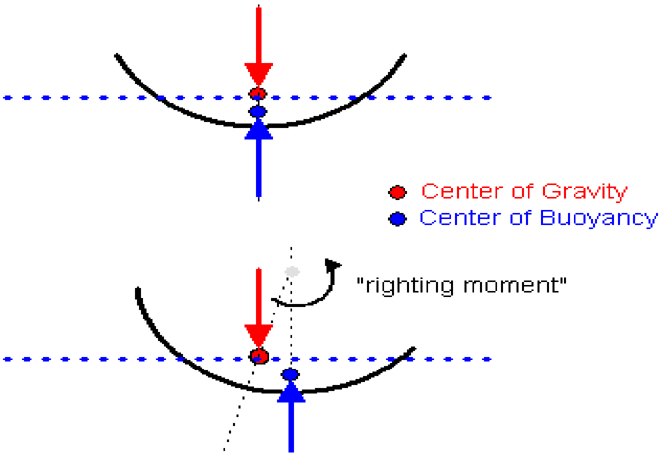

Figure 4, Centre of Buoyancy

Center of Buoyancy is an important phenomenon in order to obtain the components of the hydro-static restoring matrix. They are be obtained in the same way as we solved for surfaces by integrating the mesh.

$$x_b = -\frac{1}{2\forall}\iint_{S_b} n_1 x^2\, dS$$ (47)

$$y_b = -\frac{1}{2\forall}\iint_{S_b} n_2 y^2\, dS$$ (48)

$$z_b = -\frac{1}{2\forall}\iint_{S_b} n_3 z^2\, dS$$ (49)

Where, the CoB (x_b, y_b, z_b) within the co-ordinate system.

Eq. defines the equation of motion outlined in a given section.

Eq. gives us the frequency response functions as,

$$\sum_{k=1}^{6}\{-\omega^2[M_{jk}+A_{jk}(\omega)]+i\omega B_{jk}(\omega)+C_{jk}\}\widetilde{x_k}(\omega) = \widetilde{F_{jD}}(\omega) \quad \{j=1,2,.....,6\}$$ (50)

Where,

$A_{jk}(\omega)$:- Added mass matrices

$B_{jk}(\omega)$:- Damping matrices

C_{jk} :- Restoring coefficient

$\widetilde{F_{jD}}(\omega)$:- Exciting forces

3.4 Radiation Potential[3]

In order to obtain the flow potential radiated wave one needs to solve the integral equations to flow potential. Though most of the elevation in surface and the fluid flow field is obtained using the BW model in MIKE-21MA

This is possible in the frequency domain.

The total wave potential is discretized into,

1. Incident wave mode, j=0
2. Scattered wave mode, j=7
3. Radiated wave mode, j=1,2,......,6 resp.

$$\varphi = \varphi_0 + \varphi_7 + i\omega\sum_{j=1}^{6}\xi_j\varphi_j$$ (51)

Where,

ξ_j :- Ref. 6 DoF response of floating vessel

φ_j :- Wave potential (Wave potential per unit velocity of the floating vessel)

The velocity potential in terms of the incident wave is given by,

$$\varphi_0 = \frac{igA}{\omega}\frac{\cosh[k(z+h)]}{\cosh kh}e^{-i(kx\cos\beta - ky\sin e\beta)}$$ (52)

In the given coordinate system it is to note that Z axis represents the depth or surface of the water.

The conditions over the vessel surface that is floating are shown as,

$$\frac{\partial\varphi_7}{\partial n} = -\frac{\partial\varphi_0}{\partial n}$$ (53)

For initial 8 modes of j is linearizing of the surface B.C is implementation over the surface where the fluid surface z is equivalent to 0.

$$-\frac{\omega^2}{g}\varphi_j + \frac{\partial\varphi_j}{\partial z} = 0$$ (54)

Using B.C. the Laplace for the wave potential this is solved in all eight modes,

1. 1 each for the incident
2. 1 each for scattered
3. 6 each for DoF of radiated waves

$$\Delta^2\varphi_j = 0$$ (55)

3.5 Boundary Element Method[3]

The problems in frequency boundary are governed by the Laplace equation as in equation, which is basically used in solving the radiation potential over the surface of the vessel.

$$\frac{\partial\varphi_j(x_i)}{\partial n} = n(x_i)$$ (56)

In the above eq. the velocity normal is taken in each mode "n".

The integral equation o the BEM are transformed into a linear system of equations,

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$$\frac{\sigma_R(x_i)}{2} + \sum_{k=1}^{N} \sigma_R(x_k) K_{ik} = \frac{\partial \varphi_j(x_i)}{\partial n} \quad (57)$$

The source term obtained from radiation IRF in n x n matrix is used in integral eq. for source distribution.

$$K_{ik} = -\frac{1}{4\pi}\frac{\partial}{\partial N_{x_i}} \iint_S G(x_i; x_k)\, dS(x_k) \quad (58)$$

Where,

$G(x_i; x_k)$:- Green's function
x_i :- Field Point
x_k :- Source Point

One can derive the radiation potential by,

$$\varphi_j(x_i) = -\sum_{k=1}^{N} \sigma_R(x_k) S_{ik} \quad (59)$$

In the above equation.

$$S_{ik} = \frac{1}{4\pi} \iint_S G(x_i; x_k)\, dS(x_k) \quad (60)$$

3.6 Added Mass Coefficient and Damping Coefficient under Frequency Domain[3]

The coefficients matrix can be obtained by defining the radiation potential as follows;

$$A_{ij} - \frac{i}{\omega} B_{ij} = \rho g \iint_{S_b} n_i \varphi_j^R\, dS \quad (61)$$

Where,

φ_j^R :- Radiation potential
A_{ij} :- Added mass
$A_{ij}(\omega) = \mathrm{Re}\left\{\rho \iint_{S_b} n_i \varphi_j^R\, dS\right\}$ (a)
B_{ij} :- Damping
$B_{ij}(\omega) = \mathrm{Im}\left\{\rho \iint_{S_b} n_i \varphi_j^R\, dS\right\}$ (b)

3.7 Inverse Transforms[3]

Once e find the values of $A_{ij}(\omega)$ we can then obtain the added mass coefficient.

$$A_{ij}(\omega) = a_{ij} - \frac{1}{\omega} \int_0^{\infty} K_{ij}(t) \sin\omega t.\, dt \quad (62)$$

As $\omega \to \infty$, the second term vanishes. To obtain damping coefficients, inverse transform of $K_{ij}(t)$ is required as

$$B_{ij}(\omega) = \int_0^{\infty} K_{ij}(t) \cos\omega t.\, dt \quad (63)$$

3.8 Response Amplitude Operators[3]

The RAO is not directly provided. They are obtained by,

$$\sum_{j=1}^{6} \xi_j \left[-\omega^2 [M_{jk} + a_{jk}] + i\omega b_{jk} + c_{jk}\right] = AX_i \quad (64)$$

Where,

ω:- Wave's angular frequency
ξ_j:- Vessel motion
a_{jk}:- Added mass Matrix
b_{jk}:- Damping Matrix
c_{jk}:- Restoring Matrix
X_i:- Wave Excitation per unit wave amplitude
A:- Amplitude of wave

$$Z_j(\omega, \theta) = \frac{\xi_j}{A} \sum_{j=1}^{6} [C_{jk}]^{-1} X_i \quad (65)$$

Where,

$[C_{jk}]^{-1}$ represents the inverse of the matrix within the brackets for eqn. of motion. The RAO is representation for each angular wave frequency and incident wave direction.

$$A = A^{(1)} \cos(\omega t) + A^{(2)} \mathrm{sine}(\omega t) = \Re\left(\tilde{A} e^{-i\omega t}\right) \quad (66)$$

3.9 Wave Drift Forces (2'nd ORDER)[3]

It applies Newman approx. and is derived from the derivation of the source distribution for the diffraction, in the direction of each incident wave.

$$\frac{\sigma_D(x_i)}{2} + \sum_{k=1}^{N} \sigma_D(x_k) K_{ik} = \frac{\partial \varphi_0(x_i)}{\partial n} \quad (67)$$

Where,

σ_D:- Diffraction
β:- Propagation direction

Within the frequency domain, it can be calculated by far-field formulation. Its mean surge and sway forces,

$$F\binom{x}{y}(\beta) = -2\pi\rho \frac{k.(K_{inf}.h)^2}{h[(k.h)^2 - (K_{inf}.h)^2 + K_{inf}.h]} . \int_0^{2\pi} |H(\theta)|^2 . \binom{\cos(\theta)}{\sin(\theta)} d\theta - 2\pi\rho\omega\cos\beta\sin\beta . \mathrm{Im}H\beta \quad (68)$$

Where

β:- Wave propagation direction
ρ:- Water density
k:- Wave number
h:- Water depth
K_{inf}:- Infinite depth number of wave
H:- Kochinfinction ranging 0 to 2π

$$H(\theta) = H_D(\theta).e^{i.\frac{\pi}{2}} + i\omega \sum_{i=1}^{6} Z_j . H_{R_j}(\theta). e^{-i.\frac{\pi}{2}} \quad (c)$$

Where,

H_D :- Diffraction contributor
H_{R_j} :- Radiation contributor
Z_j :- RAO as in eq,22

The mean Yaw movement is given as follows,

$$M_z(\beta) = 2\pi . \frac{\rho\omega}{k} . \mathrm{Re}(H'(\beta)) - \frac{2\pi\rho.(K_{inf}.h)^2}{h[(k.h)^2 - (K_{inf}.h)^2 + K_{inf}.h]} . \mathrm{Im} \int_0^{2\pi} \overline{H(\theta)} H'(\theta)\, d\theta \quad (69)$$

Now for calculating Radiated wave

$$\varphi_j(r, \theta, z) = \frac{\cosh(k(z+h))}{\cosh(kh)} . \sqrt{\frac{k}{2r\pi}}\, e^{i\left(kr - \frac{\pi}{4}\right)} H_R(\theta) \quad (70)$$

While scattered or diffraction mode is given by,

$$\varphi_7(r, \theta, z) = \frac{\cosh(k(z+h))}{\cosh(kh)} . \sqrt{\frac{k}{2r\pi}}\, e^{i\left(kr - \frac{\pi}{4}\right)} H_D(\theta) \quad (71)$$

By applying the Newman's approx. here in far-field sol^n. it is only the diagonal terms in QTF ie, Quadratic Transfer Function which only considers the monochromatic frequency pairs. This, in turn, results in obtaining only the mean drift forces. Thus it is valid only in Deep Water Conditions

3.10 Wave Exciting Forces[3]

It is expressed by the incident wave and provides answer to the radiation problem by applying Haskindrelation. [6

$$F_{jD}(t) = \iint_{S_b} p_I(\vec{x}, t) n_j(\vec{x})\, d\vec{x} + \rho \int_{-\infty}^{\infty} \iint_{S_b} \dot{\varnothing}_{In}(\vec{x}, \tau)\, \varnothing_j(\vec{x}, t - \tau)\, d\vec{x} d\tau \quad (72)$$

Where p_I, represents the 1'st order dynamic pressure of the fluid which is induced over the linear free-surface

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that is satisfied by incident wave potential denoted by $\emptyset_I$

$$\mathbf{p_I} = \frac{\partial \emptyset_I}{\partial t} \quad (73)$$

The waves that are not affected by the presence of the vessel is defined as incident waves.

3.11 Viscous Damping Forces[3]

Defined as the forces carried away by the waves ie, the energy of the vessel taken away by the waves

$$F_{j,visc}(t) = B_j^0 + \sum_{k=1}^{6}[B_{jk}^1\dot{x}_k(t) + B_{jk}^2\dot{x}_k(t)|\dot{x}_k(t)| + B_{jk}^3\dot{x}_k^3(t)] \quad (74)$$

3.12 Hydrostatic And Gravitational Restoring Coefficients[3]

This restoring matrix is not dependent on the frequency of wave denoted by $\boldsymbol{\omega}$ and only depends over the geometry of the vessel. This matrix $\mathbf{C_{j,k}(t)}$in time domain represents the 6 DoF by the following equations

$$\left.\begin{aligned}
C_{3,3}(t) &= \rho g \iint_{S_b} n_3\, dS \\
C_{3,4}(t) = C_{4,3}(t) &= \rho g \iint_{S_b} y n_3\, dS \\
C_{3,5}(t) = C_{5,3}(t) &= -\rho g \iint_{S_b} x n_3\, dS \\
C_{4,4}(t) &= \rho g \iint_{S_b} y^2 n_3\, dS + \rho g \forall z_b - m g z_b \\
C_{4,5}(t) = C_{5,4}(t) &= \rho g \iint_{S_b} x y n_3\, dS \\
C_{4,6}(t) &= \rho g \forall x_b + m g x_g
\end{aligned}\right\} \quad .(75)$$

$$C_{5,5}(t) = \rho g \iint_{S_b} x^2 n_3\, dS + \rho g \forall z_b - m g z_g$$

$$C_{5,6}(t) = \rho g \forall y_b + m g y_g$$

Where,

indices b:-	Center of Buoyancy
indices g:-	Center of Gravity
∀:-	Volume
ρ:-	Density of water
S:-	Floating vessel surface
g:-	Acceleration due to Gravitation
n_j:-	The normal vector of mode j

3.13 Inertial Coefficients[3]

It is a matrix which is set under an assumption that the vessel which is stable and floating under no external constrainss. The mass of the vessel is given as follows,

$$m = \rho\forall$$

$$x_b = x_g\ , y_b = y_g$$

$$\mathbf{M} = \begin{bmatrix} m & 0 & 0 & 0 & mz_g & -my_g \\ 0 & m & 0 & -mz_g & 0 & mx_g \\ 0 & 0 & m & my_g & -mx_g & 0 \\ 0 & -mz_g & my_g & I_{11} & I_{12} & I_{13} \\ mz_g & 0 & -mx_g & I_{21} & I_{22} & I_{23} \\ -my_g & mx_g & 0 & I_{31} & I_{32} & I_{33} \end{bmatrix} \quad (76)$$

It is seen that the vertical CoG highly depends on the weight distribution over the vessel ie, loading and unloading condition.

The moment of inertia is given by,

$$\mathbf{I_{ij}} = \rho\forall r_{ij}|r_{ij}| \quad (77)$$

Its an 3 x 3 array.

3.14. External Force [3]

The overall external force is given by,

$$\mathbf{F_{j,nl}(t)} = \mathbf{F_{j,moor}(t)} + \mathbf{F_{j,visc}(t)} + \mathbf{F_{j,w}(t)} + \mathbf{F_{j,c}(t)} + \mathbf{F_{j,drift}(t)} \quad (78)$$

Where,

$F_{j,moor}$ (t) :-	Mooring forces
$F_{j,visc}$ (t):-	Viscous damping forces
$F_{j,w}$ (t):-	Wind forces
$F_{j,c}$ (t) :-	Current forces
$F_{j,drift}$ (t):-	Drift forces

IV. METHODOLOGY

The methodology defines the process and the steps used in order to reach the conclusion. For this paper, we have used the data provided in MIKE-21 MA. The standard vessel dimensions are initially used as the input parameter along with the following conditions,

Number of frequency to solve as 256 with minimum frequency of 0.01227Hz and a maximum frequency of 3.14163Hz along with the total number of the direction of 19 numbers with minimum angle of 0° and maximum angle of 360°. The 2^{nd} order wave drift forces are not included in the current study which basically solves using Newman's approximation[5].

As seen in the following figure 5 shows the process followed in order to write this research paper. The research follows or says studies the vessel by varying the following characteristics. The following are the six case study,

Case 1:- Standard dimension
Case 2:- Variation in dimension ±15%
Case 3:- Variation in Center of Gravity
Case 4:- Variation Radii of Gyration
Case 5:- Variation in Water Depth
Case 6:- Variation in Draft Condition

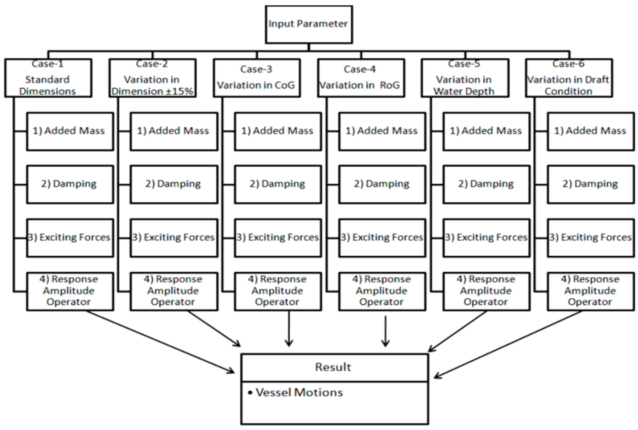

Figure 5.Flow chart for the FRC calculation

The obtained outputs are in the form added mass, radiation damping, Excitation forces, response amplitude operator which are four basic parameters that help one in understanding the vessel stability and constraints needed in order to maintain its functioning and berth.

a) Added mass is defined as the inertia passed by the vessel to the surrounding fluid in the form of acceleration.
b) Damping is defined by the energy carried away from the vessel that in turn trying to bring the vessel to the rest condition.

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c) Exciting forces over ship-these forces might seem small but are the cause of large amplitude movements. Reason being the vessel has a low frequency which is nearly very close to the natural frequency of the waves, It is the term broadly defined as the sum of the diffraction.

The numerical derivations and its formulation are seen in the section above.

V. CASES FOR BULK CARRIER

5.1. Added Mass

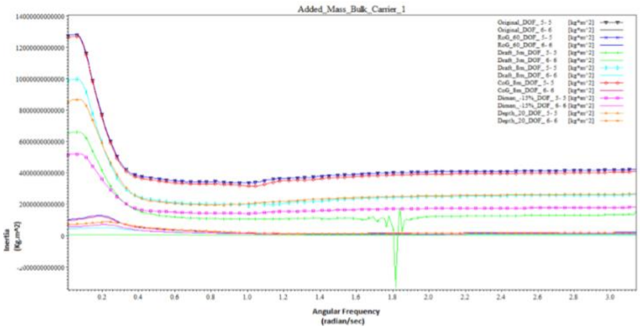

Figure 6, Added Mass for Bulk Carrier

Added mass can be simply defined as the inertia forces exerted over a system due to the motion of the vessel in the surrounding fluid. Also stated as the acceleration obtained by the surrounding water due to the movement of the vessel. The issue of added mass is caused due to the fact that the vessel and the fluid cannot share the same space[6].
It was seen that during the study of seakeeping performance of a vessel it is important to understand and determine the acceleration that is obtained due to the added mass. In the above graph, it is seen that the added mass for a vessel can be approximately one fourth or one-third of the mass of the vessel.
It is necessary to study this property in order to check the subsea risk assessment during the pitching effect.
From the graph it is seen that the added mass is dependent on the following factor:-

a) Displacement
b) Fluid Density
c) Hull Geometry

a) Displacement:-
As studied earlier that the added mass is the phenomena of the wave property but is seen from the graph that it also depends on the configuration of the vessel. As the vessel size increases the added mass also increases.
This can be seen in the graph that as the keel clearance is more the added mass effect increase but after some limits depending on the vessel properties if the keel clearance is less the vessel tends to be more stable but if this more there is sudden fluctuations seen causing the instability of the vessel for a frequency of 1.8 rad/sec (or Hz)

b) Fluid Density:-
Everybody in assumed to have some velocity and/or acceleration ifit is placed in water. Reason being the density of the fluid and the vessel. The difference in densities helps the vessel to keep floating at the same time wave, current or/and wind tends to push the vessel in a specific direction. Now if the vessel tends to maintain its inertial velocity and/or acceleration it tends to transfer this velocity to the surrounding fluid causing the added mass to increase.

c) Hull Geometry:-
It is seen from the graphs that as we vary the geometrical parameters of the vessel hull the added mass vary proportionally ie, if we reduce the beam of the vessel it automatically reduces the added mass.
While at the same time if we increase the draft the added mass increases making the vessel more stable but subjects it to more of the surge motions.

5.2. Damping

Damping for a vessel is defined as the amount of energy that is dissipated through the wave that is generated by the vessel motion ie. Out-going waves.

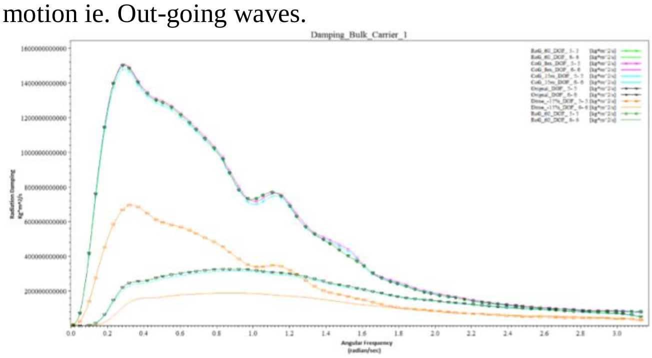

Figure 7, Damping for Bulk Carrier

From the above fig. it is seen that the damping is greatly influenced by

a) Vessel size
b) Keel clearance

As we can see in most cases the graph is kind of overlapping but as the dimension is reduced the amount of forces dissipated is seen to reduce considerably. At the same time if we reduce the keel then there is a rise in the peak between the 1 to 1.2Hz, which goes on increasing with decreasing keel.
This, however, means there will be instability during the process especially in

a) Surge amplitude.
b) pretension

Thus, a vessel with a higher dimension in a water condition off small depth has a 2'nd order effect.

5.3. Response Amplitude Operator

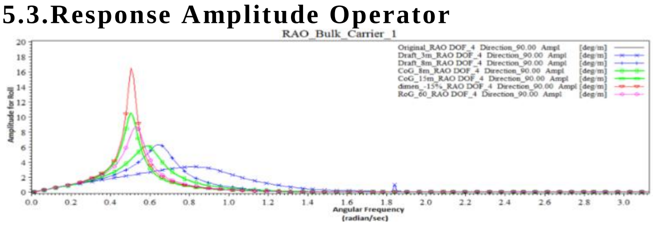

Figure 8, Response Amplitude Operator for Bulk Carrier

This parameter is one of the most important property to study the stability of the vessel in terms of roll motions.
It is defined as a collection of engineering data that helps Naval architect to understand the likewise behaviour of the vessel when it's operating under the sea conditions.
As seen in the graph it is one o the most sensitive property and is affected by the change of any of the property not just in vessel dimensions but also the berthing conditions.
As seen in the graph the most significant parameter that

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affects the vessel stability here are:-

a) Dimension
b) Draft conditions
c) Radii of Gyration [RoG]
d) Center of Gravity [CoG]

a) Dimension

It is seen that as the vessel size is reduced the ability to of the vessel in terms to lose the stability by rolling motion is also reduced that means the significant wave height that is need cause this instability to need to be very high.

b) Draft Conditions

As we know the draft is the height of the vessel that is under the water. It is seen that if the draft of the vessel is more maintaining the minimum keel-clearance has an RAO similar to that of change in CoG by +2m. in magnitude both have the same effect but the frequency of wave changes

However the value of RAO reduces as the draft decreases as the surface below the water-level are less the vessel is subjected to basically 2 different forces,

1. The wave that tries to push the vessel away from the mooring set
2. Wind forces on the exposed vessel are is like to opposite

Those seen that even small wave height can cause significant instability in the vessel also seen that there is a large duration to which the vessel is subjected to significant wave height.

c) Radii of Gyration

Effect of radii of gyration is actually seen to be varying based the category of the vessel ie if we changer RoG of a Container vessel it is subjected to change in RAO to a very high extent. The following can be used as the reason as the number of container or positioning container changes the Radii of gyration tends to shift.

But in case of stable vessels like the gas carriers or bulk carries it is nearly the same as that of the original dimension of the vessel.

d) Center of Gravity

It is seen that the CoG does not have much of change if we vary the CoG by ±2m from the basic CoG

VI. CONCLUSION

Sensitivity Test Analysis

By following the sensitivity test and analyzing the results, following where the conclusion derived,

a. Radii of Gyration

The graphical analysis sensitive analyzing it is found that radii of gyration basically effects specifically just one motion, and that was the Roll motion. The calibrated study for

1) Longitudinal Axis:- R_{xx}
2) Transversal Axis:- R_{yy}
3) Vertical Axis:- R_{zz}

Each influencing roll, pitch, yaw movement of the vessel respectively. As seen the variation in Rxx does not show a significant effect as the mass distribution of the vessel was seen to be symmetrical. Hence during RAO analysis, it is best to study the vessel motion by varying the parameter in $R_{yy}$and R_{zz} It should be kept in mind that R_{yy}=R_{zz}, and provides the best possible results.

b. Co-ordinate for Center of Gravity

Changing the position of the centre of gravity is seen to affect the motion of the vessel in more the one way. During the process, it was seen that the best possible way to adjust the location of the CoG as the avg. value of the mean square root of the errors of six degree of motion. It was seen that the effect of longitudinal and transversal position of the CoG does not have a big variation or effect on the motions. However, a variation of centre of gravity in the vertical position. This value of CoG varies as the process of loading or unloading operation.

c. Draft and Water Depth

Draft and Water Depth are one of the important factors in the study of Added mass and Damping. Since the difference between the two parameters gives under keel clearance. This is seen that the Pitch and yaw are influenced by the two motions. As the draft increases with enough keel clearance, the vessel seems to have very steady motions. But, if the draft is fewer instability increases and can e saw in damping graph in the forms of bumps.

d. Viscous Damping

It was found that the potential damping is greater then the viscous damping. Which eventually meant that viscous damping does not significantly effect with response spectrum.

VII. RECOMMENDATIONS

a. Selection of Parameters

The potential damping, wave drift forces and added mass are calculated using the diffraction technique and can be used to investigate,

1) Awkward draught
2) Sway speed
3) Changing draft of the vessel.

b. Real Measurements

One important thing that needs to be kept in mindthe prior application of these results is to know the real-time parameter and the factors that may affect the measurement of this real-time data like the noises or vibrations that effects actual wave or tidal data collection.

c. Wave Direction

It is suggested to analyze the responses of the vessel to a large number of waves in different directions. As each wave spectra possess different energy which comes in a different direction. Hence, it is best to calculate the waves acting on the vessel to vary in steps of 5 rather than 15. This helps us to increase accuracy during the process of data analysis. It is seen that in most cases RAO or exciting forces are highly influenced by the amplitude of a wave that is incident at 90°. However one may check a wide range for better accuracy.

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