Analysis of Causeway Ferry Dynamics for Safe Operation of Improved Navy Lighterage System

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ABSTRACT

The causeway ferry is a modular arrangement of multiple powered and unpowered barges, which is used for transportation of vehicles and heavy cargo from open ocean to undeveloped shores. The non-linear connections between the modules and the combined motion of the system are of interest for safe operation. A numerical simulation of the causeway ferry with four barges using AQWA is made to understand the motion behavior and estimate the loads on the connectors. Effect of shallow water, shielding effect due to multi-body, and second order drift forces are presented here.

KEYWORDS

Multi-body; Nonlinear connection; Shallow Water; Causeway Ferry, AQWA

INTRODUCTION

The Causeway Ferry is a system of powered and unpowered barges connected together using nonlinear mechanical joints. This is an integral part of the Improved Navy Lighterage System which travels in open water carrying cargo from a Roll-on Roll-off Discharge Facility (RRDF) to undeveloped ports or a Floating Causeway (FC). To obtain the safe operation window at various sea states of this multi-body system, it is required to understand its behavior in a realistic random seaway. The hydrodynamic analysis must consider shallow water effects (Huijsmans and Dallinga (1983)) since the vessel operate between deep sea through the surf zone onto the beach. The close proximity of the modules induces significant multi-body hydrodynamic interaction effects. The standard probabilistic frequency domain analysis methods are based upon the linearity of the incident wave excitation and the vessel response transfer functions. The nonlinear connection joining the modules makes the dynamic response of the system highly nonlinear. A time domain analysis approach including nonlinearity of the mechanical module to module connectors, multi-body and shallow water effects is thus taken to accurately model the system.

A four module platform which includes one power module, two unpowered intermediate module and one beach module with a bow ramp and a forward dynamic positioning thruster is studied. A numerical model of the multi-body barge system is created in ANSYS AQWA (ANSYS (2012)); the wave diffraction and radiation forces are calculated in frequency domain and then transformed into time domain impulse response functions. The mechanical joints are modeled with a combination of non-linear mooring lines and fenders with stiffness coefficients obtained from full scale prototype. The loads on vessels and connections are obtained for irregular sea condition including second order drift forces (Pinkster (1979)) and effects of all connections are then calculated in time domain. Various physical parameters such as effect of water depth, second order drift forces and multi-body hydrodynamics have been studied for capturing the significant forces accurately. Important numerical parameters such as proper time step to capture the impulse force when two modules collide with each other and the frequency range for retardation function are also studied.

The highly stochastic nature of the loadings on the mooring lines and fenders requires careful post processing of the results and expressing them using statistical analysis methods. An attempt is made to quantitatively represent the random loadings in an understandable form. Wang and Moan (2004) suggests using Generalized Pareto Diagram (GPD) method being superior in expressing extreme loads on structures where behavior of the tail in distribution function requires careful consideration. Comparison of shallow water and including multi-body effects and significance of second order drift forces are also discussed.

IMPROVED NAVY LIGHTERAGE SYSTEM (INLS)

The INLS is made up of barges also known as modules. Seven different module types are used to make up the assemblies.

The Improved Navy Lighterage System (INLS) comprises of three sub systems:

1. Roll-on/Roll-off Discharge Facility (RRDF)
2. Causeway Ferry (CF)
3. Floating Causeway (FC)

Roll-on/Roll-off Discharge Facility (RRDF)

The RRDF is a nine module platform including a docking module connected using flexible and side connections. This floating system is used to interface between LMSR using side or stern ramps to various lighterage watercrafts such as the Causeway Ferry (CF) or Landing Craft utility (LCU) vessels. Warping tugs are used to push the RRDF modules into place and moving the completed discharge facility into position. This provides a 240x72 foot floating transfer dock on which vehicles can be rolled down from a ship, then onto a lighterage craft.

Causeway Ferry (CF)

The Causeway Ferry is a three or four module platform (see Figure 1) comprising of a powered module, two intermediate modules and a beach module connected using flexors and shear connectors. The power module has a water jet propulsion system which gives it a maximum speed of 10 knots. Intermediate modules are unpowered barges to carry cargo. The beach module also doesn't have a stern thruster but has a bow ramp and a forward dynamic positioning thruster which helps keeping the causeway ferry in required position.

Floating Causeway (FC)

The Floating Causeway (FC) resembles a jetty made by connecting multiple unpowered barges. The purpose is to allow watercraft such as Causeway Ferry (CF) or Land Craft Utility (LCU) to discharge cargo where water depth is reasonable. Up to 19 modules may be connected using flexible, side and anchored connections to create an 1100ft long jetty. Following unpowered modules are used in this system:

1. Intermediate Modules (IM)
2. Docking Modules (DM)
3. Ramp Modules (RM)

PROBLEM DESCRIPTION

The Causeway Ferry (CF) assembly travels in open water carrying vehicles and cargo from RRDF to the FC in near calm water condition (sea state 3). Operating at higher sea states poses danger of connection failure due to higher multi-body interaction effects and second order drift forces and correspondingly higher loading on flexor and shear connectors. An accurate numerical model of the CF would help understand various operating scenarios and enable Navy to safely perform full scale tests.

Figure 1: Causeway Ferry (CF)

The numerical model needs to simulate the multi-body Causeway Ferry assembly in open ocean with realistic wave conditions. The effect of water depth (infinite depth vs. finite water depth) is another important factor which may change the vessel response transfer function, and also the wave frequency according to the dispersion relation.

$$\sigma^2 = gk \tanh kh \tag{1}$$

where σ is the wave frequency, k is wave number, g is gravitational acceleration and h is the water depth.

The close proximity of the modules causes hydrodynamic interaction effects such as multiple scattering effects and shielding effects. The numerical model must incorporate such interactions between bodies to accurately simulate vessel motions.

The modules are connected to each other using flexors and shear connectors. These connections allow the modules to pitch freely and separate from each other within a limit (dead band).

Shear Connector

Each module has two shear connectors at the bow and stern. Shear connectors are an open hinge system comprised of a steel bar which is pushed into a half pipe. The shear connector ensures no relative heave, however the half pipe length and diameter is slightly higher than the steel bar which makes the connection a sloppy fit to allow open ocean connection and results in a dead band. The effective behavior of this joint can be expressed in terms of stiffness coefficients in sway, heave, pitch and roll motion. Note that the surge and yaw motions are not restricted by shear connectors.

Sway Stiffness (K_{22})

The half pipe is wider than the bar length which produces a gap of 0.0508m (2 inch) on either side. This allows the vessel to sway freely until the bar impacts the edge of the half pipe when it encounters a very high stiffness.

Heave Stiffness (K_{33})

The diameter of the half pipe is larger than the diameter of the bar. This leaves about 0.0127m (0.5 inch) space above and below the bar which allows small relative heave motion. Once the bar comes in contact with the half pipe, it experiences a very high stiffness.

Roll Stiffness (K_{44})

Even though the diameter of the half pipe is larger than the diameter of the bar, it leaves a very small amount of space for relative roll motion. The bar almost immediately comes into contact of the half pipe in relative roll and then experiences a very high stiffness.

Pitch Stiffness (K_{55})

The bar and the half pipe create a horizontal hinge allowing the modules to freely pitch relative to each other up to a certain angle (approximately 15 degrees after which module surfaces comes in contact). The pitch stiffness may be considered zero for this analysis.

Flexor

Flexors are used to provide tensile stiffness to prevent the modules from moving away from each other. Two flexors, one at the port and one at the starboard side are connected to adjacent modules. A pneumatic ram is used to push the flexor into adjacent module receiver and “Guillotine” plates are manually engaged in that adjacent module to hold the flexor. The pneumatic ram is then retracted to securely pull modules together ensuring the shear connector bar touches the half pipe creating horizontal hinge. The flexor keeps the shear connector bar and the half pipe engaged and provides non-linear longitudinal tensile stiffness.

The effective behavior of the flexors may be expressed in terms of surge and yaw stiffness.

Surge Stiffness (K_{11})

Considering $x = 0$ is mild contact of the shear connector bar with the half pipe. When the shear connectors are engaged, any relative surge in negative x direction will result in compression to provide a very high stiffness. The modules are allowed to separate up to certain limit called the dead band which is about 0.0254m (1 inch) and then the flexors engage to provide a non-linear stiffness and prevent further separation of the modules.

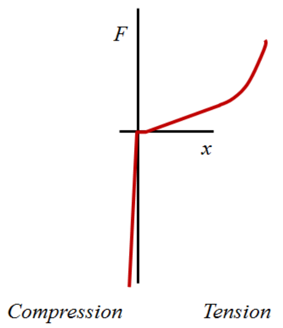

Figure 2: Surge Stiffness

Yaw Stiffness

The flexors allow a certain amount of relative yaw motion. The yaw motion is restricted by one flexor and one shear connector. Since the flexor has a dead band in surge, thus there is a dead band in the yaw stiffness as well.

MODELING DETAILS

The numerical modeling is done using the hydrodynamic analysis tool ANSYS AQWA Workbench Version 14.0.0. The vessel geometry are created using Rhinoceros Version 4.0. A four barge system consisting of a Power Module, two Intermediate modules and a Beach Module is considered for the analysis.

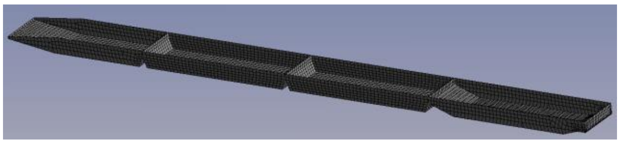

Figure 3: Module mesh details

The principle dimension and the position of each barge are shown in Table 1. The barges are assumed to be even keel and the bow and stern of two consecutive vessels are separated from each other by 0.13m. The mid-ship of the PM is set at the global origin and then IM305, IM302 and BM are placed along the positive x-axis direction consecutively.

Table 1: Vessel dimensions and location in Global Co-ordinate System

	PM	IM305	IM302	BM
L (m)	26.1070	23.6980	23.6980	22.3860
B (m)	7.3200	7.3200	7.3200	7.3200
D (m)	2.4380	2.4400	2.4400	2.4400
T_s (m)	0.8000	0.8000	0.8000	0.8000
T_B(m)	0.8000	0.8000	0.8000	0.8000
x_{CG}(m)	-0.0792	0.0004	0.0004	-2.1535
z_{CG} (m)	1.5570	1.4580	1.4580	1.5270
Trim (deg)	0.0000	0.0000	0.0000	0.0000
X_{ORIGIN}(m)	0.0000	25.0279	48.8513	72.0187
Radius of Gyration				
k_{xx} (m)	2.4888	2.4888	2.4888	2.4888

	PM	IM305	IM302	BM
k_{yy} (m)	6.5268	5.9245	5.9245	5.5965
k_{zz} (m)	6.7878	6.1615	6.1615	5.8204

Mooring lines and Flexor Connection Details

A four point mooring system is used to hold the system in place. These mooring lines are artificial moorings used to keep the numerical model from drifting too far from the simulation starting position due to second order drift forces. The anchors are set above sea level and the mooring lines are linear. The Flexors are modeled using non-linear mooring lines with appropriate length and stiffness values obtained from full scale prototype data.

Shear Connector Details

The shear connectors are a combination of a hollow pipe and a solid rod each attached to bow and stern of two consecutive vessels. When in contact, they create a hinge joint which allows free relative pitching motion of two barges but restricts relative heave, sway, and roll motion. The shear connector does not restrict surge motion when vessels are moving away from each other but this motion will be restricted by the Flexors. When the vessels surge in opposite direction, the shear connector provides very high compression stiffness in surge direction.

To model the shear connector joint in AQWA, multiple fenders with different direction of action are used. The prototype has two shear connectors per module, but for simplicity in modeling only one shear connector in modeled in AQWA.

Environment Details

It is necessary to model a realistic ocean condition to predict the loads on the vessels and connections accurately. Ochi (1978) describes different wave spectrum to be used for ocean structure design. A Pierson Moskowitz wave spectrum is chosen with wave height and period equivalent to sea state 3 (Hs=1.524m, Tz=3.7s). Also, it is important to generate the irregular waves with random phase difference in such a way that two simulations can be compared to each other for which they must have encountered same wave excitation forces at any given time instant. A seed value of 1000 is set to generate the random phase in each AQWA simulation to obtain comparable results.

STATISTICAL ANALYSIS - GENERALIZED PARETO DISTRIBUTION FITTING

When a probability distribution is fit to certain data, the high density regions usually have a good agreement between the data and the distribution. But the fit of the distribution in the tail is usually not accurate as there are not enough data points in the tail region. However in many applications, fitting the data in the tail region is the main concern. For example in this project we are interested in the extreme value distribution of the flexor tensions between the bodies.

The Generalized Pareto Distribution (GPD) is a distribution developed to specifically model the tail regions. The GPD models the tail of the data as a conditional distribution given a threshold value. Thus only the data points which are beyond the threshold value are of interest.

Theory of Generalized Pareto Distribution

The Generalized Pareto Distribution is a two parameter (k and σ) distribution where, k is the shape parameter and σ is the scale parameter. Figure 4 shows the probability density of the GPD for positive, zero and negative values of the shape parameter. It is a generalization of both exponential distribution (k=0) and Pareto distribution (k>0). The GPD includes these two distributions in a larger family so that a continuous range of shapes is possible.

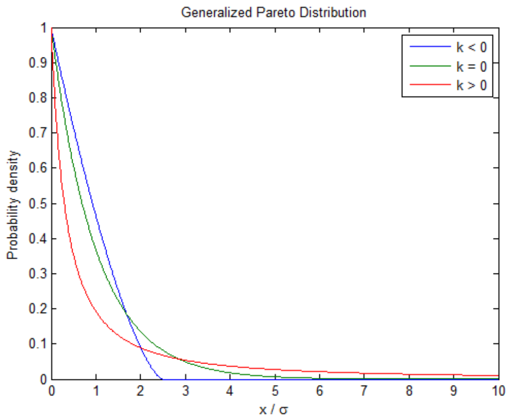

Figure 4: Variation of GPD density with shape parameter k

When the shape parameter is negative, the distribution has zero probability above an upper limit of $(-1/k)$. For non-negative values of k, GPD has no upper limit.

The GPD gives the conditional probability of the exceedances of a process X over a specified threshold value u. The conditional distribution is shown in Eq.(2).

$$\Pr(X > x \mid X > u) = \left[1 - k\left(\frac{x-u}{\sigma}\right)\right]^{-\frac{1}{k}} \quad (2)$$

Return Levels

In most cases, the fitting of a distribution is represented by its cumulative distribution function. But sometimes, it is more useful to plot the distribution in terms of quantiles or return time between occurrences. In this project, we are specifically interested in the return times of a particular extreme tension. The return time of a particular tension value is defined as the expected time between occurrences of tension time series exceeding this particular tension value.

The unconditional distribution of the process is given by Eq.(3).

$$\Pr(X > x) = \Pr(X > x \mid X > u) \cdot \Pr(X > u)$$
$$= \zeta_u \left[1 - k\left(\frac{x-u}{\sigma}\right)\right]^{-\frac{1}{k}} \quad (3)$$

Where $\zeta_u = \Pr(X > u)$ is calculated empirically from the data. Thus a value x_m that is exceeded on an average once every m observation would be given by

$$\Pr(X > x_m) = \frac{1}{m} = \zeta_u \left[1 - k\left(\frac{x_m - u}{\sigma}\right)\right]^{-\frac{1}{k}} \quad (4)$$

$$x_m = u + \frac{\sigma}{k}\left[(m\zeta_u)^k - 1\right] \qquad \text{for } k > 0$$
$$x_m = u + \sigma \log(m\zeta_u) \qquad \text{for } k = 0 \quad (5)$$

For presentation in this case, it is convenient to express the return plots in terms of return times in hours. If there are n_y observations in an hour, then N-hour return period corresponds to $m = N \times n_y$ observation return. Thus the N-hour return level is defined by

$$x_N = u + \sigma \log(N n_y \zeta_u) \quad (6)$$

Figure 5 shows the plot return times versus the return tension values in a flexor (in Newtons). The time is plotted in the logarithmic scale. The blue line represents the best fit model of GPD for the given data. The red and green lines provide the 95% confidence interval over the parameters of the distribution. The red dots represent the top 100 data points in the given time series data of tension. The return periods of the data are calculated from the empirical distribution function obtained only from the data. It can be seen from Figure 5 that the best fit model is quite in agreement with the extremes of the data. Most of this theory has been described in the book by Coles (2001). The theory has been repeated here for completeness.

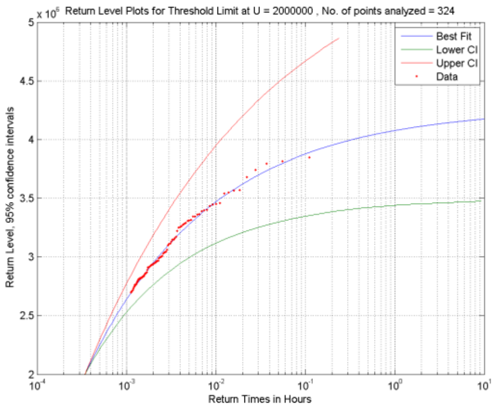

Figure 5: Return Level Plots for the Tension in a Flexor

RESULTS AND DISCUSSION

The vessel motion and loads on the connections were compared for various cases. The results are as follows:

Water depth effects on vessel motion

Tension on the port side flexor between intermediate module and beach module is shown in Figure 6. The comparison of shallow water and deep water are presented in Figure 7. Shallow water case shows higher tension in flexors and higher forces in the fenders.

Effect of including multi-body interaction

The comparison of including multi-body interaction in the simulation is presented in Figure 8. Including multi-body effects in the simulation reduces the flexor tensions and fender forces due to shielding effects.

Selecting simulation type (NAUT/DRIFT)

There are two types of time domain simulation available called DRIFT and NAUT. The hydrodynamic calculations are generally subdivided into parts and they are either evaluated using linear theory or nonlinear theory. Both time domain simulation techniques available provide selective nonlinear solutions. The capability of NAUT and DRIFT are listed in Table 2.

Three cases have been analyzed to find out most conservative way to estimate loads on the connections viz. DRIFT with NODR card, DRIFT with Slow Drift and NAUT. Among these three cases, DRIFT with Slow Drift gave highest loads on the connections. The comparison plot of NAUT vs. DRIFT with Slow Drift is shown in Figure 9.

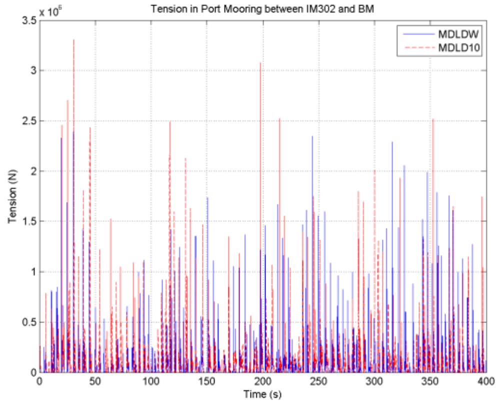

Figure 6: Flexor forces in deep and shallow water

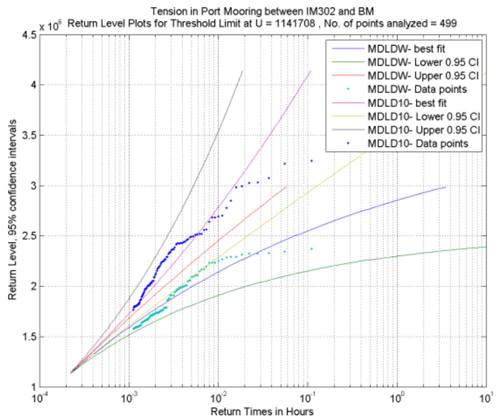

Figure 7: Water depth effects

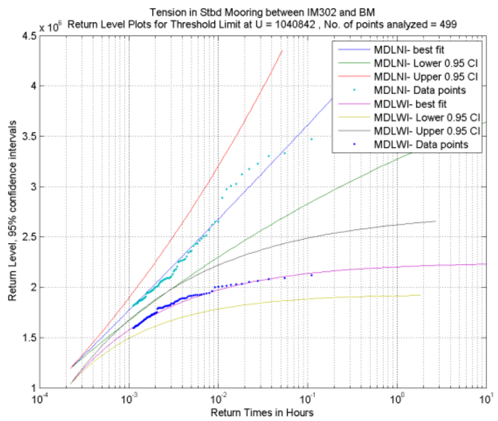

Figure 8: Multi-body effects

Table 2: AQWA NAUT and DRIFT Capabilities

	Hydrostatics	Diff/Radiation	Froude-Krylov	Drift Force	Drag
DRIFT	Linear	Linear	Linear	2nd Order	Non-linear
NAUT	Non-linear	Linear	Non-linear	Not Calculated	Non-linear

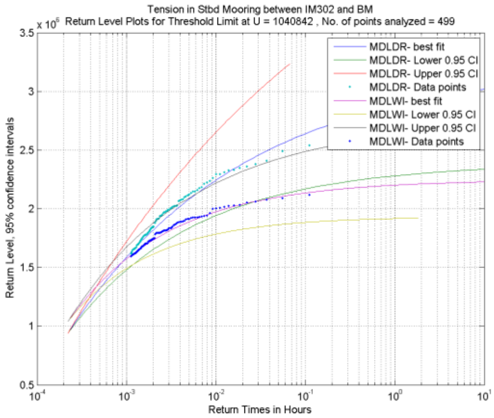

Figure 9: AQWA Drift with Slow Drift vs. AQWA NAUT

CONCLUSIONS

The Causeway Ferry has been modeled successfully using the numerical modeling tool AQWA. The nonlinear flexor and shear connectors are modeled using mooring and fender elements and found to show expected behavior in a realistic random sea. The limitation of simulating more than 3 bodies with full QTF matrix was encountered. Hence, various combinations of the DRIFT and NAUT are compared to achieve the most conservative load estimation approach. The impulsive loading on the flexors were analyzed using Generalized Pareto Diagram and a brief introduction to the method is also presented here.

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