COMPARATIVE ANALYSIS OF MOORING SYSTEMS OF FLOATING CYLINDRICAL STRUCTURE IN TIME DOMAIN

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ABSTRACT

Mooring design has an essential influence on stability, seakeeping and fatigue loads on offshore structures. It has thus become state of the art to include detailed mooring analysis and optimisation as a crucial part of the design process of moored systems. In this context it is common to carry out large-scale time domain simulations for a number of well-defined loadcases, which are usually defined by classification societies such as e.g. DNV-GL. The analysis study will perform the comparison of different types of mooring for an exemplary partially submerged cylindrical floating structure.

The goal of analysis is to compare resulting loads in time domain using a fully coupled dynamic analysis of the mooring and floater. The analysis is using and extending approaches recently developed at the chair of ocean engineering (OCN-SIM Flex Software, www.ocnacademy.org). In order to facilitate a comparison, an extended hydrodynamic loads equation of the floating structure is implemented and verified with mathematical model in OCN-SIM Flex using the Airy wave theory with single unidirectional, harmonic excitation. Dynamic tensioning or slackening by winches shall not be considered. Moreover, the dynamic behaviour of the structure can be characterized based on the results of the time-domain simulations. Thus, for instance transfer functions can be determined by performing a frequency analysis of the simulated time-domain response to harmonic wave excitation.

TABLE OF CONTENTS

1. INTRODUCTION

1.1. Background

Nowadays, a floating body structure with mooring system configuration is being extensively used as an offshore facility not only in the oil/gas and renewable energy industry, moreover, moorings of buoys are used in almost every area of offshore engineering. This system has been deployed widely around the world as a unique design facility which is regarded as a promising concept for an flexibility and economic oil/gas and energy production. Floating offshore structure, like any other, require stability to be operational especially under extreme environmental conditions. Mooring systems are therefore required to provide such stability againts structure dynamics, while ensuring allowable excursion. With so much depending on the mooring systems of these floating structures, it is worthwhile to understand the performance of each of system components and the global reponse of the mooring system.

The nonlinear-coupled dynamic analysis of the floating systems is becoming more and more important in order to evaluate the dynamic interaction among the floater and moorings. Concious of the fact that such structures will be taken to ensure that their design are appreciably reliable. One way to verify the analysis performed in the prototype design process is by model testing. A model of design floater is built and subjected to the same environmental loads in the wave basin as those used in the prototype design with the deployed mooring system for stationkeeping. During testing, the response and behaviour of the floater and mooring line system to various forcing due to wind, wave and current are measured and compared to those obtained in the design of the prototype floater. For as long as the testing procedure is conceptually and practically correct, the result obtained independently represent the performence to be expected of the prototype floater under the given loading conditions, if it is installed in the field. Conducting model tests requires wave basins, which are typically much smaller than the prototype system, depending on the chosen model scale, basin dimension may not be sufficiently large to accomodate the directly scaled mooring system. Consequently, the size of the floater and the accompanying mooring system are reduced such that they adequately fit into the test facility, and the test engineer has a primary task to replicate the static and dynamic behaviour of the prototype system on the model to be tested in the wave basin. Essentially, the effects of the mooring system in the wave basin on the model floater must be equal to those which the prototype mooring system has on the full scale floater.

This introduce the need of such a program tools for evaluation of the equivalent mooring system in order to represent it's behaviour in the full depth system. Lately, several software programs are established and developed in order to perform the nonlinear-coupled dynamic analysis of floating system, such Orcaflex, Mimosa, ect. The use of those program tools mostly was costly and not reachable by such student/reasercher. Therefore, OCN Simflex was developed open-source, another motivation is to satisfy scientific needs, i.e. be able to view and change the code depend on the needs. The program tools project is under development process at the chair of ocean engineering University of Rostock . At the mean time, the formulations that implemented in the program are still focus mostly in mooring line, while for the hydrodynamic calculation of the floating body still has to be implemented. This introduces the need for the implementation of the floating structure hydrodynamic force equations to the program tool, in order to process the evaluation by the comparison analysis of the mooring systems and body structure responses. In a later section of this report, a proper distinction of the scope of work is drawn for clarity.

1.2. Objective of Research

The Mooring systems are major tools for maintaining the dynamic responses of floating body . The challenge of understanding the behaviour of a floating structure under environmental loads and influence of a mooring system is quite hard, and the design of mooring system with high integrity requires the ability to isolate the various dynamic effects induced by different loads acting. The dynamic response of a floater combined with mooring system would most often over-shadow its static response. For this reason, it is considered good practice to study the mooring line behaviour and the static/dynamic response of floater under its influence independently in design, to allow a clear attribution of observed results to the correct floater responses.

In this study, the author presents a comparative study of mooring systems analysis and develop a hydrodynamic loads algorithm by means of a coupled time domain analysis and check the plausibility by means of simple hard-coded examples in Matlab program. The algorithm is included a numerically discrete implementation of drag term of morison equation. Furthermore, The hydrodynamic loads algorithm will be used for the implementation to the mooring analysis program tool (OCN Simflex, *www.ocnacademy.org*), since at the mean time, the software program is in development process and still need the implementation of floaters hydrodynamic loads part. In order to execute the comparative analysis of mooring systems, a response behaviour of both the mooring system and the floater with considering non linear coupled dynamic analysis are presented. The comparative analysis of response behaviour result are calculated fully in time domain by simulating several case of mooring system configurations.

1.3. Scope of Research

The purpose of the research is to study the effect of mooring on a body structure such a buoy. The analysis present a comparison analysis result of several mooring systems configurations considering the non linear coupled analysis. Generally, the study will cover the following activities below :

1. Establish, verify and test mathematically the hydrodynamic force algorithm for a slender floater using Matlab Program.
2. Preparation of Floating cylinder structure main dimension, Mooring Configuration and wave loadcases.
3. Evaluate the loadcases in time domain analysis and compare the result concerning the response behaviour of mooring line and the floater.

Chapter 2 presents the theoretical background that will be helpful to give the prespective for the analysis. The basic knowledge and key definitions that relate to the analysis will be present here.

Chapter 3 presents the overall description of the software programs that is used in the analysis, the analysis use two program, OCN Simflex and Matlab.

Chapter 4 presents the implementation of hydrodynamic force algorithm steps for a floater, which is modelled as a slender cylindrical structure using Matlab program.

Chapter 5 presents the main dimension preparation of the cylindrical floating structure and mooring system configurations, the loadcases scenario, and finally the evaluation procedure in time domain.

Chapter 6 presents the comparative result of the loadcases evaluation in time domain analysis concerning the loads, seakeeping, mooring/floaters response behaviour and stability with single harmonic excitation using OCN Simflex program. Furthermore, comparing the result of each configurations of mooring system.

Chapter 7 provides the conclusions and the recommended further studies from this study.

2. THEORETICAL BACKGROUND

This chapter will review the basic knowledge to give a perspective for the analysis. Furthermore the key definitions that are related to the analysis will also be explained here. The explanations are separated in several part regarding the subsequents of the calculation procedure as follows :

1. Coordinate System and Equilibrium
2. Regular Wave - Linear Airy Wave
3. External Loads
4. Coupled Dynamic Analysis
5. Motion and Response Analysis (in time domain)

The Hydrodynamic Loads, in Point 2 is described generally in this chapter, while for the detail explanation is provided in chapter 4.

2.1. Coordinate System and Equilibrium

2.1.1. Coordinate System

There will be two systems of orthogonal that used, in order to express and resolve the various vectors of the model. The global system serves as an absolute, earth-fixed reference of the cylinder body position and orientation. The local system serves the body bound reference of cylinder body position and orientation. Cylinder body is assumed as unconstrained due to force-based coupling of rigid bodies to the mooring in OCN-Simflex. The Cylinder body is defined in the global coordinate system correspond to 6 degree of freedom which expressed as coordinate direction. The 6 coordinates consist of 3 coordinates of body translation at (x, y, and z) axes and 3 coordinates of body orientation that rotate about the axes. Furthermore, the first angular displacement of body orientation α about x axis is the pitch, the second angular displacement of body orientation β about y axis is the roll and the third angular displacement of body orientation γ about z axis is the yaw. The global and local coordinate system are shown as follows :

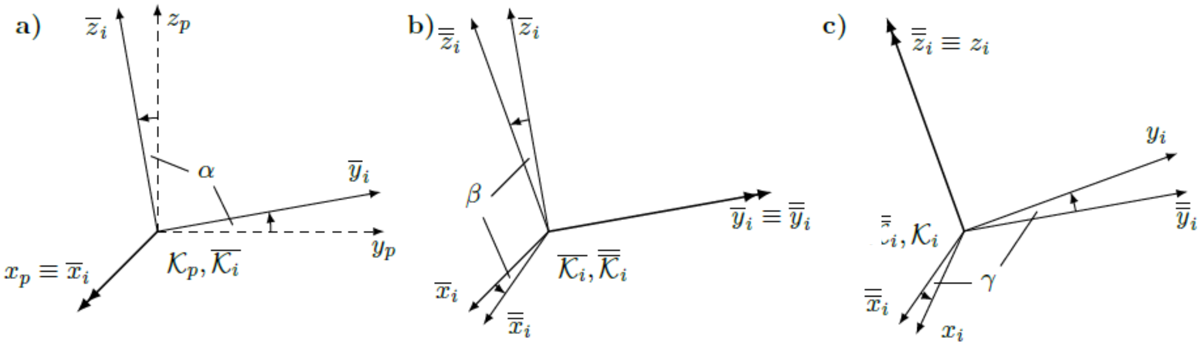


Figure 1 Coordinate systems

Reference : OCN Simflex User Manual (2017)

The coordinate system that described here is based on the coordinate system of OCN Simflex program. The program use the XYZ-Euler angles to specify rotations. The rotation of rigid body coordinate system K_i relative to the global earth coordinate system K_p is decribed by three axes rotations about x, y and z axis. The XYZ-Euler angle rotation of rigid body are internally converted to 4 Euler-parameters. The basic theory concerning this can be clearly found in *Ahmed A.Shabana (2005).* All the system equation are defined in 3D coordinate system, Furthermore, the upper subscript G, in each symbol considered as the value that obtained with respect to global coordinate system, while the B, in each symbol is considered as the value that obtained with respect to local coordinate system.

2.1.2. Stability and Equilibrium

The response of the floater can be divided into hydrostatic analysis and hydrodynamic analysis The hydrostatic analysis will be governed by the structure weight and buoyancy force balance, this is important for the success of subsequent hydrodynamic analysis. On the other hand, the hydrodynamic analysis will be the key factor to analyze the performence of the cylindrical floater from its motion. Under normal circumtances, the hydrostatic analysis can be the starting point to analyze the stability of the floater. However, OCN Simflex uses an arbitrary configuration as a starting point for time domain analyses.

Stability analysis describes the position of the floater in static equilibrium where the forces of gravity and buoyancy are equal and acting in opposite directions in line with one another. *Ship Hydrostatic (2002)* has mentioned that stability is the ability of a body, in this setting a ship or floating vessel, to resist the overturning forces and return to its original position after the disturbing forces are removed, It requires initial stability. Initial stability is achieved from a small perturbation from its original position. There will be initial stability when there is an uprighting moment larger than zero. Hence, the floater will be back to its initial position when the inclining moment is taken away.

Based on Newton's law*, Journee,J.M.J (2001),* explain that a floating structureis said to be in a state of equilibrium or balance when the resultat of all the forces acting on it is zero and the resulting moment of these forces is also zero. If a structure is floating freely in rest in fluid, the following equilibrium or balance condition are fulfilled :

- Horizontal equilibrium, the sum of the horizontal forces equal to zero, may influenced by other external force such moorings
- Vertical equilibrium, the sum of the vertical forces equal to zero, using Archimides principle which hold for the vertical equilibrium between buoyancy and gravity forces as follows :

$$\rho g \nabla = gm \tag{2.4}$$

Then derive to the change of draft ΔT which caused by additional mass, p :

$$\Delta T = \frac{p}{\rho . A_{WL}} \tag{2.5}$$

ΔT = change of draft due to additional mass

p = additional mass

ρ = water density

A_{WL} = water plane area

g = gravity acceleration

∇ = Volume of the submerged body

m = mass/weight of body

- Rotational equilibrium, the sum of the moments about G – or any other point equals to zero, with rotational equilibrium equation as present below (when an external heeling moment acts on the structure) :

$$M_H = \rho g \nabla . y = gm. y \qquad (2.6)$$

Where y is lever arm.

2.2. Regular Wave – Linear Airy Wave

The study will analyze the wave loads by using regular waves form, in order to calculate the loads on cylindrical floater. The classical linear wave theory developed by Airy and Laplace will be used. Chakrabarti,S.[2005] has described that regular waves have the characteritics of periodic process which the surface elevation has the shape of harmonic function. Hence, the theory will describe the properties of one cycle in regular waves and these properties are invariant from cycle to cycle. Below figure show a harmonic wave seen from two different perspectives, the wave profile that shown as a function of distance x at a fixed instant in time, and as function of time record of water level observed at one location.

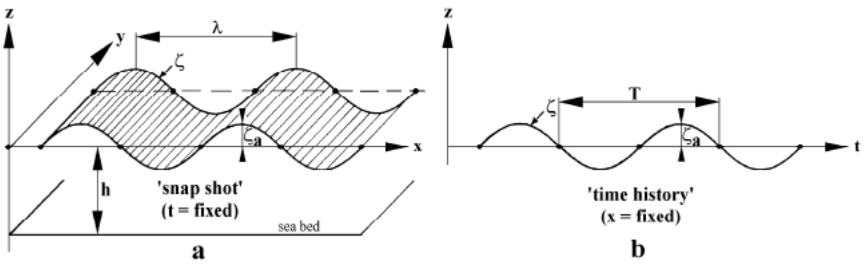


Figure 2 Harmonic wave definition.

Reference:Journee and Massie (2001)

The x axis is positive in the direction of wave propagation, the still water level is the average water level when there is not wave is present. The z axis is directed upward with positive value, most of relevant values of z are negative which are below the water level. The water depth, h with positive value is distance between the seabed and still water level (z = -d). The horizontal distance (measured in direction of wave propagation) between any two successive wave crest along x axis in space domain is the wave length, λ. The distance between any two successive wave crest along time domain is the wave period, T.

The potential theory is used to solve the flow problem in regular waves. In order to use this linear wave theory, it will be necessary to assume that the water surface slope is very small, this means that the wave steepness is so small. Hence, the terms in the equations of the waves with a magnitude in the order of the steepness-squared can be ignored. Using the linear theory holds here that harmonic displacements, velocities and accelerations of the water particles and also the harmonic pressures will have a linear relation with respect to the wave surface elevation.

A velocity potential φ can be used to describe the velocity field at time t. The velocity of water particles (u,v,w) in three translational direction follow from the definition of velocity potential φ :

$$u = \frac{\partial \varphi}{\partial x},\ v = \frac{\partial \varphi}{\partial y},\ w = \frac{\partial \varphi}{\partial y}$$

$$\vec{U} = (u, v, w) = \left(\frac{\partial \varphi}{\partial x}.\frac{\partial \varphi}{\partial y}.\frac{\partial \varphi}{\partial z}\right) \qquad (2.7)$$

$$\nabla_{\varphi} = \vec{U} = \frac{\partial \varphi}{\partial x}\ .\ \vec{\imath},\frac{\partial \varphi}{\partial y}\ .\ \vec{\jmath},\frac{\partial \varphi}{\partial z}\ .\ \vec{k}$$

Where,

u, v, w = velocities of water particle at x, y and z axis direction

$\frac{\partial \varphi}{\partial x}.\frac{\partial \varphi}{\partial y}.\frac{\partial \varphi}{\partial z}$ = partial derivatives of the velocities at x, y and z axis direction

∇_{φ} = gradient of scalar function / velocity potential

The profile of simple wave with small steepness style has the shape of sine or cosine and the motion of water particle in a wave depend on water depth and wave phase.

$$\varphi(x, z, t) = P(z)\ .\sin(kx - wt) \qquad (2.8)$$

Which p(z) is (as yet) an unknown function of z. The velocity potential φ(x,z,t) of the harmonic waves has to fulfill requrements as follows :

1. Continuity condition or Laplace equation

   There are two important assumptions in order to arrive to Laplace equation, First assumptions is continuity equation for homogeneous and incompressible flow :

$$\nabla x\vec{U} = \frac{\partial \mathrm{u}}{\partial x} + \frac{\partial \mathrm{v}}{\partial y} + \frac{\partial \mathrm{w}}{\partial z} = 0 \qquad (2.9)$$

Where,

$\nabla = \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}$ = nabla operator

$\vec{U}$ = velocity vector

Second asssumption is Non rotational/invicid flow. Concequently, the motion is irrotational if the rotation vector or vorticity, ω_v is zero, i.e.

$$\omega_v = \nabla x\vec{U} = \begin{vmatrix} \vec{\imath} & \vec{\jmath} & \vec{k} \\ \frac{\partial \varphi}{\partial x} & \frac{\partial \varphi}{\partial y} & \frac{\partial \varphi}{\partial z} \\ u & v & w \end{vmatrix} = \vec{\imath}\left(\frac{\partial \mathrm{w}}{\partial y} - \frac{\partial \mathrm{v}}{\partial z}\right) - \vec{\jmath}\left(\frac{\partial \mathrm{w}}{\partial x} - \frac{\partial \mathrm{u}}{\partial z}\right) + \vec{k}\left(\frac{\partial \mathrm{v}}{\partial x} - \frac{\partial \mathrm{u}}{\partial y}\right) = \vec{0}$$

(2.10)

By using two assumption above, we will find the Laplace equation:

$$\nabla^2 \varphi = \frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = 0 \qquad (2.11)$$

Subtituting equation 2.8 into 2.11 we get P(z) and wave potential :

$$\frac{d^2 \mathrm{P(z)}}{\partial z^2} - k^2 P(z) = 0 \quad \rightarrow \quad P(z) = C_1 e^{+kz} + C_2 e^{-kz} \qquad (2.12)$$

$$\varphi(x,z,t) = (C_1 e^{+kz} + C_2 e^{-kz}) \,.\sin(kx - wt) \qquad (2.13)$$

Where C1 and C2 as yet undetermined constants. The complete mathematical problem in order to find a velocity potential of Non rotational and incompressible fluid motion consist of the solution of the Laplace equation with respect to relevant boundary condition in the fluid. The boundary conditions will be found from physical considerations.

2. Boundary Conditions
   a. Bottom Condition

      No water can flow through the bottom, a flat bottom will be considered here.

$$w|_{z=-d} = 0 \quad \rightarrow \quad \left.\frac{\partial \varphi}{\partial z}\right|_{z=-d} = 0 \qquad (2.14)$$

      Where d is the water depth. Subtituting boundary condition into equation 2.13 we get P(z) and wave potential :

$$C_1 = \frac{C}{2} e^{+kd}, C_2 = \frac{C}{2} e^{-kd} \rightarrow P(z) = \frac{C}{2}\left(e^{+k(d+z)} + e^{-k(d+z)}\right) = C \cosh k(d+z) \qquad (2.15)$$

$$\varphi(x,z,t) = C \cosh k(d+z) \,.\sin(kx - wt) \qquad (2.16)$$

      Where C as yet undetermined constant.

b. Surface condition

The distinction between the different type of fluid motion result come from the condition of the boundaries which is imposed on the fluid domain. Two types of surface boundary conditions will be considered :

- Free Surface Dynamic Boundary Condition

This criterion is corresponding with the forces on the boundary. At the free surface, boundary condition is simply that, the water pressure is equal to constant atmospheric pressure, p0 on the free surface.

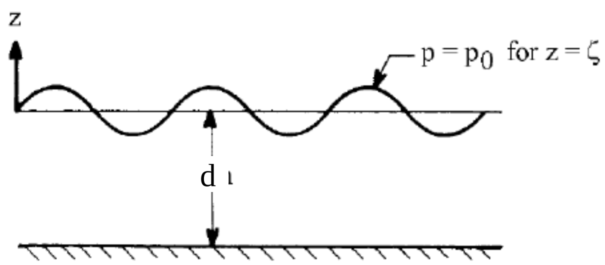


Figure 3 Atmospheric pressure at the free surface

Reference:Journee and Massie (2001)

The Bernoulli equation for an unstationary irrotational flow :

$$\frac{P}{\rho} + g \cdot z + \frac{\partial \varphi}{\partial z} + \frac{1}{2}(u^2 + w^2) = Ct \qquad (2.17)$$

At surface P = P_0 and $z = \xi(x,t)$:

$$g \cdot \xi + \left.\frac{\partial \varphi}{\partial t}\right|_{z=\xi} + \frac{1}{2}(u^2 + w^2)|_{z=\xi} = 0 \qquad (2.18)$$

Since we still use assumption that the water slope is very small which means that the convective velocity term also become small, linearizing can be applied. Hence, $\frac{1}{2}(u^2 + w^2)|_{z=\xi} = 0$ can be neglected. And we apply the boundary z = ξ $\rightarrow z = 0$ and yields :

$$\left.\frac{\partial \varphi}{\partial t}\right|_{z=\xi} = \left.\frac{\partial \varphi}{\partial t}\right|_{z=0} \qquad (2.19)$$

Hence, the equation 2.21 at the surface can be written as follows :

$$g \cdot \xi + \left.\frac{\partial \varphi}{\partial t}\right|_{z=0} = 0 \rightarrow \xi = -\frac{1}{g} \cdot \left.\frac{\partial \varphi}{\partial t}\right|_{z=0} \qquad (2.20)$$

Subtituting equation 2.16 into 2.20 we get wave profile and wave potential:

$$\xi = \xi_a \,.\cos(kx - \omega t) \quad with \quad \xi_a = \frac{\omega C}{g}\,.\cosh kh \quad (2.21)$$

$$\varphi = \frac{\xi_a g}{\omega}\,.\frac{\cosh k(d+z)}{\cosh kd}\,.\sin(kx - \omega t) \quad (2.22)$$

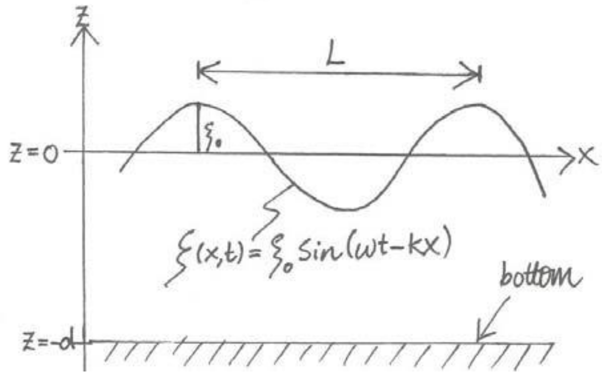


Figure 4 Sinusoidal wave profile

Reference : Gudmestad(2010)

- Free Surface Kinematic Boundary Condition

A water particle at free surface will always remain at surface. Let's consider the velocity in the vertical direction as :

$$w = \frac{\partial \varphi}{\partial z} = \left.\frac{Dz}{Dt}\right|_{z=\xi(x,t)} = \left.\left(\frac{\partial z}{\partial t} + u\,.\frac{\partial z}{\partial x}\right)\right|_{z=\xi(x,t)} = \left(\frac{\partial \xi}{\partial t} + u\,.\frac{\partial \xi}{\partial x}\right) \quad (2.23)$$

Since we use the water surface slope is very small which means that the wave steepness is also small, hence, a linearizing can be applied and leads :

$$\underbrace{\left.\frac{\partial \varphi}{\partial z}\right|_{z=\xi(x,t))}}_{\text{Velocity at wave surface}} = \underbrace{\left.\frac{\partial \varphi}{\partial z}\right|_{z=0}}_{\text{Velocity at still surface}} = \frac{\partial \xi}{\partial t} \quad (2.24)$$

Here, the non-linear cross term $u\frac{\partial \xi}{\partial t}$ term becomes smaller (second order) and can be disregarded. And the velocity at wave surface is set equal to the velocity at still surface. A differentiation of the free surface boundary condition equation 2.20 with respect to t yields :

$$\frac{\partial^2 \varphi}{\partial t^2} + g\frac{\partial \xi}{\partial t} = 0 \rightarrow \frac{\partial \xi}{\partial t} + \frac{1}{g}\,.\frac{\partial^2 \varphi}{\partial t^2} = 0 \quad for\ z = 0 \quad (2.25)$$

Combining equation 2.27 and 2.28 delivers the free surface kinematic boundary condition called Cauchy-Poisson condition:

$$\frac{\partial z}{\partial t}+\frac{1}{g}\cdot\frac{\partial^2 \varphi}{\partial t^2}=0 \quad for\; z=0 \qquad (2.26)$$

In order to obtain the final linear flow velocity, we need to establish the relationship between ω and k (or equivalently T and λ) referred to above. A subtitution of wave potential equation 2.22 into 2.26 gives dispersion relation for arbitrary water depth d.

$$\omega^2 = k\, g\,.\tanh kh \qquad (2.27)$$

Hence, by combining velocity potential equation 2.22 and dispersion relation equation 2.27, we obtain kinematic of water particle flow velocity in x (u) and z (w) directions as water particle kinematics:

$$u=\xi_a\,.\,\omega\,.\frac{\cosh k(d+z)}{\sinh kd}\,.\cos(kx-\omega t) \qquad (2.28)$$

$$w=\xi_a\,.\,\omega\,.\frac{\sinh k(d+z)}{\sinh kd}\,.\sin(kx-\omega t)$$

While, the acceleration are definned as derivation of flow velocity and written as follows :

$$\dot{u}=\xi_a.\,\omega^2.\frac{\cosh k(d+z)}{\sinh kd}.\sin(kx-\omega t) \qquad (2.29)$$

$$\dot{w}=-\xi_a.\,\omega^2.\frac{\sinh k(d+z)}{\sinh kd}.\cos(kx-\omega t)$$

2.3. External Loads

A floating structure will experience different kind of external loads (e.g. from wind and wave). In order to obtain the motion of the structure, it is necessary to obtain the integration of all loads components, which are generally considering several forces as follows :

- Static force (Stiffness, Buoyancy, and gravity forces)
- Hydrodynamic Force (Froude-Krylov, Hydrodynamic mass, Drag, Diffraction and Radiation Forces)
- Environment force (wave/drift force, wind and curent force)
- Other (Mooring force, ect)

All the forces that mentioned above will be take into account depend on the non dimensional parameters, which are called Keulegan Carpenter (KC) number, which is assumed equivalent to H/D and diffraction parameter, $\pi D/L$. Both non dimensional parameters make distinction regarding small or large structures. Here, H is wave height, D is diameter of cylinder body and L is wave length.

S. Chakrabarti (2005), explain that the vertical axis H/D is equivalent to the Keulegan Carpenter number. For example, at the mean water level, $KC = \frac{u_0 T}{D} = \frac{gT^2 H}{2LD}$, which in deep water $L = \frac{gT^2}{2\pi}$ becomes approximately $KC = \pi\, H/D$. According to this chart then, when H/D is less than 2 (i.e. KC less than 6, regions I and II), potential theory will be used. On the other hand, for H/D greater than about 2 (regions II, V and VI), morison equation should be used.

The Limits of application for small vs. large structure diagram are shown as follows :

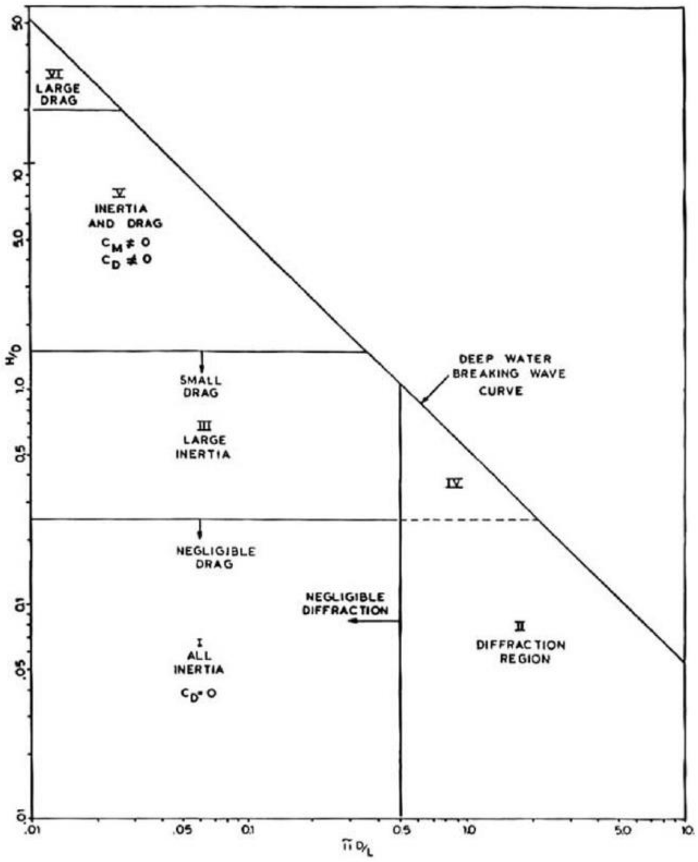


Figure 5 Limits of application for small vs. Large structure

Morison equation is used to compute forces on small structures, the forces depend on inertia and drag force. While for large structures, potential flow theory is used, the forces depend on diffraction and radiation force, the diffraction part determines exciting forces on structure due to wave in its equilibrium and radiation part determine the added mass and damping coefficients of moving structure in water. The analysis is using a slender cylinder floating structure is designed to satisfy the requirement limit of region VI, regarding the Limits of application for small vs. large structure diagram. Thus, the drag force is considered as the main force which influence the floating structure motion responses.The non dimensional diffraction parameter, $\pi D/L$ will be design less than 0.5 with H/D parameter more than 2. Since the body structure considered as small structure, the wave flow separates from the surface of the structure and incident flow is not pertubed much and the diffraction force are dominating. Hence, based on the list of external force above, the diffraction/radiation forces are negligible and the hydrodynamic force will consider only drag force due to vicous damping, friction force will be neglected since the analysis concern to floating body motions not for body structure resistance analysis. For other external load, such mooring force is considered also since the body structure will have interaction with a mooring system configuration. In this analysis the static force will be combination of buoyancy and gravity force only without stiffness. As summation, in this analysis. All force components are neglected,except the drag force, buoyancy and gravity force.

2.3.1. Hydrodynamic Morison Force

As already mentioned previously that the body structure in the analysis is assumed as slender (hydrodynamically transparent) structure, since diffraction and reflection phenomena are negligible. Hence, The hydrodynamic equation is determined by using morison equation method. In order to calculate hydrodynamic forces, it is necessary to integrate pressure field over the wetted surface. The main force components are :

- Froude Krylov load, follows from the pressure field of the undisturbed wave (froude-krylov term)
- Load due to added mass, follows from the pressure field of relative acceleration of fluid and structure (hydrodynamic mass term)
- Load due to viscosity, follows from the pressure field of relative velocity of fluid and structure (non linear drag term)

Morison et al proposed as approach in which the horizontal and vertical force on a section of body structure is express as sum of an inertia force and non linear drag force. For a fixed cylinder structure in the wave flow, the linear inertia force resulting from froude krylov and hydrodynamic mass force, while non linear drag is caused by viscous effect and the associated downstream wake. The viscous force includes form and friction drag, and it is proportional to the drag coefficient, C_d, as well as to the square of the instationary flow velocity, where the notation $|u|u$ ensures that drag force and velocity always always act in the same direction. Both of forces yield a hydrodynamic forces in a flow direction as follows :

$$dF = \underbrace{\rho . Cm . d\forall . \frac{\partial u}{\partial t}}_{\text{Froude Krylov and Hydrodynamic Mass Force}} + \underbrace{\frac{1}{2} . \rho . C_d . dA . |u| . u}_{\text{Viscous Force}} \tag{2.33}$$

For a moving structure in the wave flow, the froude krylov force remains unchaged, while the hydrodynamic mass force and the viscous force depend on the relative acceleration and velocity of wave flow and structure. Those forces yield a horizontal and vertical forces with general equation which expressed as follows :

$$dF_x = \underbrace{\rho . d\forall . \frac{\partial u}{\partial t}}_{\text{Froude Krylov Force}} - \rho . C_a . d\forall . \underbrace{\left(\frac{\partial u}{\partial t} - \dot{u}_c\right)}_{\text{Hydrodynamic Mass Force}} + \underbrace{\frac{1}{2} . \rho . C_d . dA . |u - v| . (u - v)}_{\text{Viscous Force}} \tag{2.34}$$

Where :

Cm = (1+Ca) = inertia coefficient with C_a as added mass coefficient

Cd = Drag coefficient

dz = separated verical distanc in z axis

d∀ = Volume of submerged cylinder $\left(\pi D^2/_4 \times dz\right)$

dA = The cross sectional which perpendicular to flow direction $(Dxdz)$

r = half of diameter

D = Diameter of cylinder

u = Wave flow velocity

v = Body structure velocity

$\frac{\partial u}{\partial t}$= Wave flow acceleration

$\dot{u}_c$= Body structure acceleration

For the detail explanation of morison equation can be found in *Gunther Clauss, Eike Lehmann and Carsten Östergaard (1992)*. As the water particle acceleration and velocity are phase-shifted by 90°, the same applies to the associated inertia and drag force. The hydrodynamic force total, yield forces act in relative flow direction and torques from body orientation that rotate about the axes. For the detailed equation will be described in chapter 4.

2.3.2. Hydrostatic Force

The hydrodtatic force in this analysis will consider buoyancy and gravity force. A body submerged in a fluid will experiences an upward buoyant force, the force is an upward force exerted by a fluid opposes the weight of an immersed floating body structure. The equation of buoyancy force is described as follows :

$$F_{\mathrm{b}} = \rho g \nabla \qquad (2.35)$$

Where,

F_{b} = buoyancy force

∇ = volume of the submerged part of the object

g = acceleration of gravity

ρ = water density

While, in the gravity force, gravity is a natural phenomenon by which all things with mass are brought toward one another. On earth, gravity gives weight to physical objects. The equation form is present as follows :

$$F_{G} = gm \qquad (2.36)$$

Where,

F_{G} = buoyancy force

g = acceleration of gravity

m = mass of the total body

2.3.3. Mooring Force

It is essential that floating structures have precise motions and position systems. For several floating structure design, the mooring system is important to hold the structure against winds, waves and currents . *Chakrabarti, S. (2005)* has mentioned that mooring system design is a trade-off between making the system compliant enough to avoid excessive forces on the floater and making it stiff enough to avoid difficulties due to excessive offsets. This is very difficult in shallow water. *Chakrabarti, S. (2005)* also suggests to develop increasingly integrated moorings/riser system design methods to optimize the system components to ensure lifetime system integrity.

Furthermore, *Faltinsen (1990)* has mentioned that the tension forces in the lines depend on their weight and elastic properties and are also depending on the manner in which moorings are laid. The moorings have an effective stiffness composed of an elastic and a geometric stiffness which combined with the motion of the unit will introduce forces on lines. However, in this analysis, the mooring line consider as inelastic line.

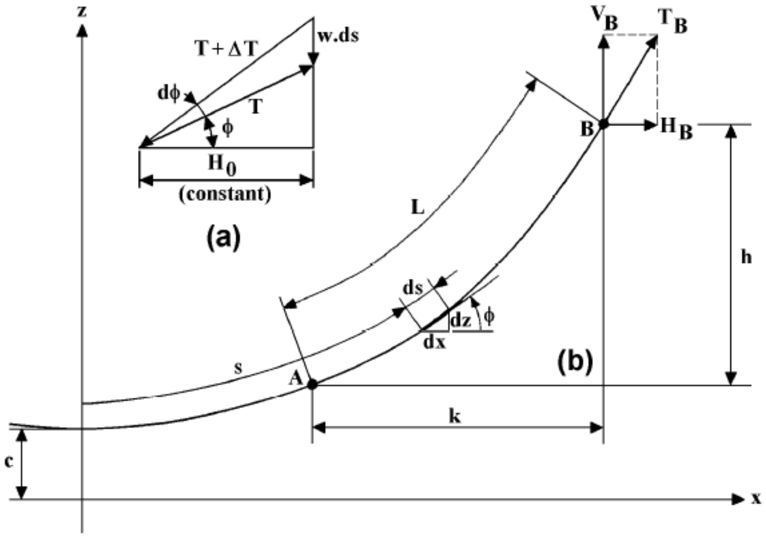


Figure 6 Cable curve symbols

Reference : Reference:Journee and Massie (2001)

An inelastic line is figured with length L, which attached at anchor point A, and at a suspension point B. The anchor point (x_A, z_A) and the suspension point (x_B, z_B) are defined in 2D coordinate system above, with k as the horizontal distance between anchor and suspension point, while h is the vertical distance between anchor and suspenson point. Derived from the lecture of *Prof. Mathias Paschen, Sea Load and Offshore Structure*, a visualisation of static analysis of a cable line are presented as follows :

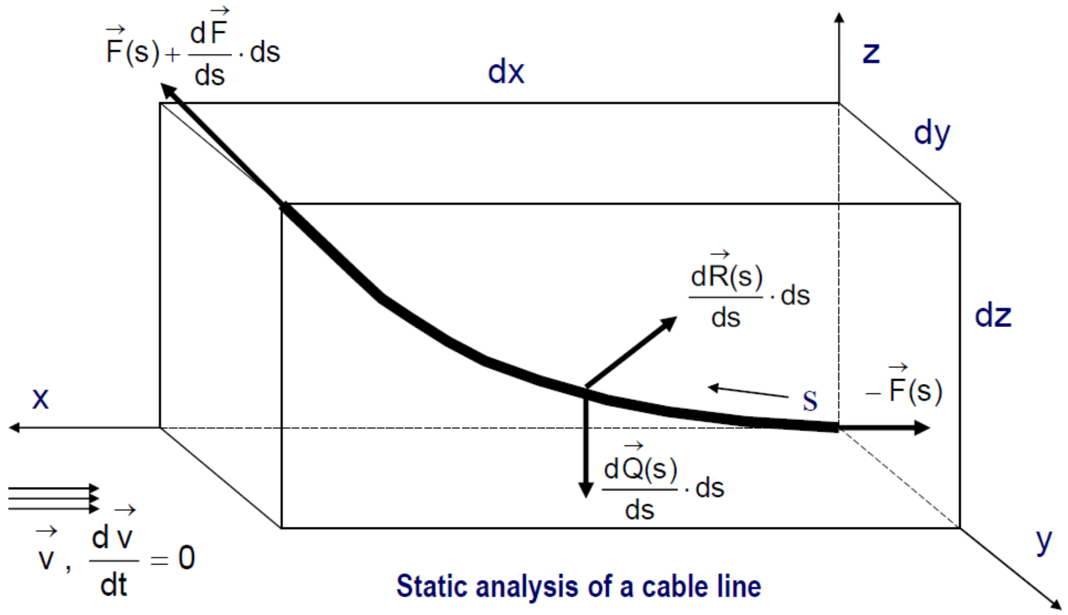


Figure 7 Static Analysis of a cable line

Reference : Prof.Paschen, Mathias. Lecture of Sea Loads on Offshore Structure

Here, F is The tension, Q is the weight of cable line, R is the hydrodynamic load, v is velocity of current and s is coordinate. The main point of the mooring line analysis is the tension function F and the vector coordinate, s. The expression below mention that the second term present the increasing tension.

$$F(s) + \frac{dF}{ds}.ds \tag{2.37}$$

When using morison equation, the drag term will have more influence. In order to find the second term of the above expression, the equation can be derived from :

$$\left(\frac{dF}{ds} + \frac{dR}{ds} + \frac{dQ}{ds}\right).ds = 0 \tag{2.38}$$

Where

$$\frac{dQ}{ds} = \begin{pmatrix} 0 \\ 0 \\ -q \end{pmatrix} \tag{2.39}$$

$$\frac{dR}{ds} = \frac{1}{2}.\rho.v^2.d.c_i \tag{2.40}$$

$$F = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = F.\frac{d}{ds}.\begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{2.41}$$

q here is the weight of mooring sistem in water per meter. Then, the equilibrium force can expressed as follows :

$$\begin{aligned} \frac{dF}{ds}\cdot\frac{dx}{ds} + F\cdot\frac{d^2x}{ds^2} + \frac{dR_x}{ds} &= 0 \\ \frac{dF}{ds}\cdot\frac{dy}{ds} + F\cdot\frac{d^2y}{ds^2} + \frac{dR_y}{ds} &= 0 \\ \frac{dF}{ds}\cdot\frac{dz}{ds} + F\cdot\frac{d^2z}{ds^2} + \frac{dR_z}{ds} - q &= 0 \end{aligned} \tag{2.42}$$

As mention previously, one of the important factor should be known, if we know the coordinate vector, s, we may use additional fomula of geometrical condition :

$$\left(\frac{dx}{ds}\right)^2 + \left(\frac{dy}{ds}\right)^2 + \left(\frac{dz}{ds}\right)^2 = 1 \tag{2.43}$$

Then, in other way we can use :

$$\frac{dx}{ds}\cdot\frac{d^2x}{ds^2} + \frac{dy}{ds}\cdot\frac{d^2y}{ds^2} + \frac{dz}{ds}\cdot\frac{d^2z}{ds^2} = 0 \tag{2.44}$$

The equation (2.44) have a meaning and can be derived as follows :

$$\frac{dF}{ds}.\frac{dx}{ds} + F.\frac{dx^2}{ds^2} + r_x\left|\frac{dx}{ds}\right.$$

$$\frac{dF}{ds}.\frac{dy}{ds}+F.\frac{dy^2}{ds^2}+r_y\left|\frac{dx}{ds}\right.$$
$$\frac{dF}{ds}.\frac{dz}{ds}+F.\frac{dz^2}{ds^2}+r_z\left|\frac{dz}{ds}\right. \qquad (2.45)$$

Then, in order to obtain the mooring line tension $\frac{dF}{ds}$, we sum up the three equation above and derive to expression :

$$\frac{dF}{ds}=-\left[\frac{dR_x}{ds}\cdot\frac{dx}{ds}+\frac{dR_y}{ds}\cdot\frac{dy}{ds}+\left(\frac{dR_z}{ds}-q\right)\cdot\frac{dz}{ds}\right]$$
$$\frac{d^2y}{ds^2} = -\frac{1}{F}\cdot\left(\frac{dF}{ds}\cdot\frac{dy}{ds}+\frac{dR_y}{ds}\right)$$
$$\frac{d^2z}{ds^2} = -\frac{1}{F}\cdot\left(\frac{dF}{ds}\cdot\frac{dz}{ds}+\frac{dR_z}{ds}-q\right) \qquad (2.46)$$

Faltinsen (1990) mention that, in spread mooring configurations, the total mooring forces of surge, heave and pitch $(F_1^M, F_3^M\ and\ F_5^M)$ in equilibrium position and can be written as follows :

$$F_1^M=\sum_{i=1}^{n}H_{Bi} \qquad (2.47)$$
$$F_3^M=\sum_{i=1}^{n}V_{Bi}$$
$$F_5^M=\sum_{i=1}^{n}H_{Bi}\left[x_{Bi}sin\theta_{Bi}-z_{Bi}cos\theta_{Bi}\right]$$

Where θ is considered as pitch angle. All these force will be computed as input value in motion and response analysis.

2.4. Coupled Dynamic Analysis

As a floating cylindrical structure, will be deployed together with slender members (moorings) responding to wave loading in complex ways. In the traditional way, the hydrodynamic interaction among the floater and moorings cannot be evaluated since the floater and moorings are treated separately. Moreover, this traditional method, also known as the decoupled analysis, the hydrodynamic behavior of the system is only based on hydrodynamic behavior of the floating structure and ignores all or part of the interaction effects (mass, damping, stiffness, current loads) between the floater and moorings. In order to capture the interaction between the floater and moorings, one extensive method has been introduced and developed in the last decade. This method, also known as the nonlinear-coupled dynamic analysis, ensures higher dynamic interaction among the components responding to environmental loading due to environmental load especially waves since the main coupling effects will be included automatically in the analysis. Hence, the accurate prediction of the response for the overall system as well as the individual response of floater and moorings can be obtained.

An integrated floating structure consist of a mooing system and moored floating structure (Floating slender cylinder). Coupled dynamic analysis considers the interaction between these two components in calculating the motions and forces of floating structure.

In this analysis, the equations of motion refer to newton's law and the coupling force between mooring and floater can be expressed as :

$$\begin{bmatrix} F_m^G(\dot{X},X,t) + F_M^G + F_B^G - F_G^G \\ \tau_m^G(\dot{X},X,t) + \tau_M^G + \tau_B^G - \tau_G^G \end{bmatrix} = m^G(X).\ \begin{bmatrix} a^G \\ \alpha^G \end{bmatrix} \qquad (2.48)$$

Where,

F_m^G *and* τ_m^G= Morison hydrodynamic force in global coordinate system

F_M^G *and* τ_M^G= Mooring force in global coordinate system

F_B^G *and* τ_B^G= Buoyancy force in global earth coordinate system

F_G^G *and* τ_G^G= Gravity force in global earth coordinate system

a^G *and* α^G= Acceleration in global earth coordinate system

m^B= Mass and inertia matrice in global earth coordinate system

Finally, in order to solve the 6DOF motion equation in the time domain, the external/internal forces and the coupled mooring forces are evaluated at each time step at instantaneous body position and up to the free surface, and then the equation envolves to the next time step using a step-by-step numerical integration scheme.

2.5. Motion and Response Analysis in Time Domain

Finally, the 3 forces and 3 torques due to 6 degree of freedom from internal, external and coupled mooring forces are resulted from OCN Sim Flex program due to the morison hydrodynamic equations implementation. In order to evaluate the morison hydrodynamic equations implementation in the program, it is necessary to obtain the final result of body motion response and mooring line tension, then make such a comparative study of those results.

The solution of dynamic equation can be found by frequency domain or by time domain analysis. Frequency domain analysis will be applicable for the environmental load that gives satisfactorily results by linearization theory, while time domain analysis will be performed as direct numerical integration of the equation of motions which involves non linear functions to predict the maximum response and capture higher order load effect.

Time domain analysis requires a proper simulation length to have a steady result. Furthermore, the time domain analysis procedure consist of a numerical solution of rigid body equation of motion for the floater subject to external/internal actions which may originate in the fluid motion due to waves, floater motion, and positioning system. However, in this analysis, a normal time domain simulation is computed by numerical integration of the equations of motions.

The loadcases analysis will be evaluated using dynamic analysis in some stages regarding the mooring configurations. The dynamic analysis of the system will be performed to asses the global dynamic response.

An acceptable model designed will be combined with 2 condition of mooring configurations. The effect of changing the mooring configuration for each condition induced by 4 regular wave loadceses are compared. This stage analysis will using time domain analysis using OCN Simflex program. The analysis comprises :

- Displacement versus time as motion response
- Maximum Line tension

As mention in previously, the resulting forces and torques in equation (4.18) and (4.19) are in global system coordinate. In order to solve the acceleration which will be an input value in new displacement time step calculation, it is necessary to transform the resulting forces and torques, from global, $F^G \; and \; \tau^G$, into local body coordinate system, $F^B \; and \; \tau^B$. The transformation calculation are present as follows:

$$F^B(t) = T.F^G \qquad and \qquad \tau^B(t) = T.\tau^G \tag{5.1}$$

Where T is transformaton matrix, equation 4.3. For a floating structures, it is considered that total mass as well as its distribution over the body is considered to be constant with time, which the range of time is large relative to period of motions, this means that small effect can be ignored. The inertia tensor, I^B also are transformed to local body coordinate system, the inverse of inertia tensor is present as follows :

$$(I^B)^{-1} = T.I^G.T^T \tag{5.2}$$

Then, the total inverse mass and inertia matrice will be taking into account both result of above transformation equation as present as follows :

$$\left(\overrightarrow{m^B}\right)^{-1} = \begin{pmatrix} M^{-1} & 0 & 0 & 0 & 0 & 0 \\ 0 & M^{-1} & 0 & 0 & 0 & 0 \\ 0 & 0 & M^{-1} & 0 & 0 & 0 \\ 0 & 0 & 0 & I_{xx}^{-1} & I_{xy}^{-1} & I_{xz}^{-1} \\ 0 & 0 & 0 & I_{yx}^{-1} & I_{yy}^{-1} & I_{yz}^{-1} \\ 0 & 0 & 0 & I_{zx}^{-1} & I_{zy}^{-1} & I_{zz}^{-1} \end{pmatrix} \tag{5.3}$$

Here, we consider moment inertia of cylinder as follows :

$$I_{zz}^B = \frac{M^B.r^2}{2}$$

$$I_{xx}^B = I_{yy}^B = \frac{M^B.r}{2}(3r^2 + h^2) \tag{5.4}$$

Where, M^B as mass in local body coordinate system, h as height and r as radius of solid cylinder, and it is noted that in many application $I_{xz}^B = I_{zx}^B$ is not known or small, hence their term are neglected.

In order to find acceleration for motion equation of a rigid body in local body coordinate system, the equation follow Newton'second law. The vector equation for acceleration is given as follows:

$$\begin{bmatrix} a^B \\ \alpha^B \end{bmatrix} = (m^B)^{-1}. \begin{bmatrix} F^B(t) \\ \tau^B(t) \end{bmatrix} \tag{5.5}$$

Where,

F^B= resulting external force acting in the center of gravity

τ^B = resulting external torque acting about the center of gravity

m^B = mass and moment inertia of rigid body at centre gravity

α^B = angular acceleration of the center of gravity

a^B = acceleration of the center of gravity

T= rotational transformation matrice

t = time

The direct numerical integration of the equation of motion will be applied in the time domain analyses. The numerical integration is carried out using Verlet Integration. The verlet algorithm is a method for numerical solution of Newton's equation of motion. By taking acceleration value from equation (5.5) with a known value of rigid body original position (4.1) and motion velocity, the rigid body displacement new position by using general equation of verlet algorithm is present as follows :

$$r_{(t+\Delta t)} = r_t + \begin{bmatrix} v_t \\ \omega_t \end{bmatrix} \Delta t + \frac{1}{2} \begin{bmatrix} a_t \\ \alpha_t \end{bmatrix} \Delta t^2 \qquad (5.6)$$

Where,

$r_{(t+\Delta t)}$ = position at the end of time step for each 6 DOF

r_t = position at the beginning of time step for each 6 DOF

$\begin{bmatrix} v_t \\ \omega_t \end{bmatrix}$ = motion velocity and angular velocity for each 6 DOF

$\begin{bmatrix} a_t \\ \alpha_t \end{bmatrix}$ = motion acceleration and angular acceleration for each 6 DOF

t = current time

Δt = time step size

The time domain step is done by using OCN-Simflex program. The rigid body displacement at end of time step versus time and the maximum tensions versus time are present as final result of this time domain analysis in order to determine the Response motion of the slender body.

3. ANALYSIS PROGRAMS

The explanation about the OCN Simflex below are adopted from OCN Simflex User Manual. This program is used to calculate such an approximate dynamic simulation of a flexible object such mooring, buoy, net, fishing gear, ect. The analysis in this program based on time domain, with analysis general procedure as present as follows :

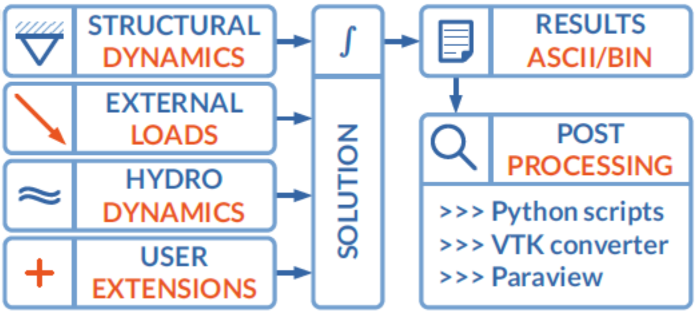


Figure 8 OCN Sim Flex system architecture

As input parameters, the structural dynamics require information of coordinate systems, rope, rigid body, ect, for the external load such fluid require information of field type, velocities, ect, for hydrodynamic require information of rigid bodies/ropes hydrodynamic coefficient. The results are presented in Python script, VTK converter and then obtaining the result by using paraview. Moreover, the user can modify or develop the input parameter by using such a comment languange.

Regarding the type of solvers, OCN-Sim Flex provide 4 type of method integration scheme methods as follows :

1. Langrangian dynamics – explicit Euler method
2. Langrangian dynamics – velocity Verlet integration
3. Reconstructed reaction forces formulation type I
4. Reconstructed reaction forces formulation type II

In this analysis, method that will be used is method number 4.

3.1. Langrangian Dynamics Methods

Regarding the Langrangian dynamics – non recursive formulation, equations of motion derived using Langrangian dynamics and a set of n_q minimal coordinates :

$$q = \begin{bmatrix} q_1 \\ \vdots \\ q_{n_q} \end{bmatrix} \tag{3.1}$$

Which q here is a given rigid body velocity at degrees of freedom. The contraints given in explicit form as :

$$r = \begin{bmatrix} r_1 \\ \vdots \\ r_{n_N} \end{bmatrix} = r\,(q,t) \tag{3.2}$$

The position vector only depends on the generalized coordinates q and not on time.

$$r = r\,(q) \tag{3.3}$$

The coordinate system and position description are presented as figure below:

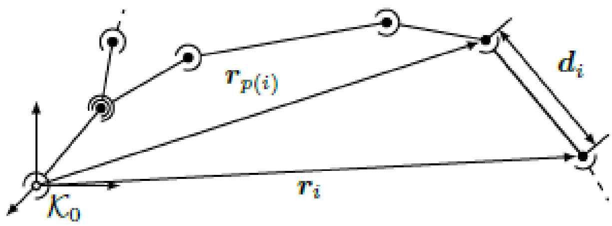


Figure 9 Position r_i and element length d_i of node and position r_i of predecessor p(i) of node i

Refrence : OCN Simflex User Manual

Based on OCN Simflex user manual, the rotation system is expressed by 3 euler angles for XYZ axes. Rotation about Z-axis is not considered, and relative joint angle about X and Y axis is considered as α_i *and* β_i of body i. P_i is the set of reference system as first node $i, P_i = \{P_i, i\}$ is the set of function the function that extend the first reference node by node i itself. The diplacement vector of node i considered as d_i^i, with respect to its joint in the local coordinate system $K_i, q_i = [\,\alpha_i\ \beta_i\,]^T$ the vector containing the relative joint XY-euler angles

α_i as well as β_i and T^{0k} the transformation matrix from K_i to the reference system K_i.

For the transformation rotation , The position r_i^0 of node i is evaluated in the global earth coordinate system, K_0 is the sum of all displacement vectors of it's previous references nodes P_i.

In order to calculate velocity projection, jacobian matrice $J_{ij}, j \in \overline{P_i}$ as well as the associated joint velocities $q_{ij}, j \in \overline{P_i}$ can be combined with joint velocities q onto the Cartesian velocities of node i as follows :

$$\begin{aligned} {}^0\boldsymbol{v}_i &= \begin{bmatrix} \boldsymbol{J}_{i1} & \cdots & \boldsymbol{J}_{i,n_N} \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{q}}_1 \\ \vdots \\ \dot{\boldsymbol{q}}_{n_N} \end{bmatrix} \\ {}^0\boldsymbol{v}_i &= \qquad \boldsymbol{J}_i \qquad \dot{\boldsymbol{q}} \end{aligned} \tag{3.4}$$

with masspoint's Jacobian matrix with respect to joint $J_{ij}, j \in \overline{P_i}$:

$$\boldsymbol{J}_{ij} = {}^{0,p(j)}\boldsymbol{T} \begin{bmatrix} {}^j\boldsymbol{S}_\alpha {}^j\boldsymbol{d}_{i,p(j)} & {}^j\boldsymbol{S}_\beta {}^j\boldsymbol{d}_{i,p(j)} \end{bmatrix}, \quad j \in \overline{\mathbb{P}}_i . \tag{3.5}$$

With S as derivatves expression, While for $J_{ij}, j \notin \overline{P_i}$, the velocity projection vector is :

$$\begin{aligned} \begin{bmatrix} {}^0\boldsymbol{v}_1 \\ \vdots \\ {}^0\boldsymbol{v}_{n_N} \end{bmatrix} &= \begin{bmatrix} \boldsymbol{J}_1 \\ \vdots \\ \boldsymbol{J}_{n_N} \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{q}}_1 \\ \vdots \\ \dot{\boldsymbol{q}}_{n_N} \end{bmatrix} \\ {}^0\boldsymbol{v} &= \quad \boldsymbol{J} \qquad \dot{\boldsymbol{q}} \end{aligned} \tag{3.6}$$

Here all submatrices J_{ij} become $0_{(3,2)}$ if $, j \notin \overline{P_i}$ and the masspoint's Jacobian matrix needs to be extended to :

$$\boldsymbol{J}_{ij} = \begin{cases} {}^{0,p(j)}\boldsymbol{T} \begin{bmatrix} {}^j\boldsymbol{S}_\alpha {}^j\boldsymbol{d}_{i,p(j)} & {}^j\boldsymbol{S}_\beta {}^j\boldsymbol{d}_{i,p(j)} \end{bmatrix} \\ \boldsymbol{0}_{(3,2)} \end{cases} \tag{3.7}$$

By physical interpretation, an expression equation can be arranged as :

$${}^0\boldsymbol{v}_{ij} = {}^0\tilde{\omega}_{j,p(j)} \; {}^0\boldsymbol{d}_{i,p(j)} \tag{3.8}$$

Concequently, it can be found from this relationship, that the veloccity component v_{ij} of node i due to the angular velocities of joint $j \in \overline{P_i}$ can be interpreted as the cross product of angular velocity of node j with respect to it's presecessor p(j) and distance form joint j to node i. This fact is ilustrated in figure below :

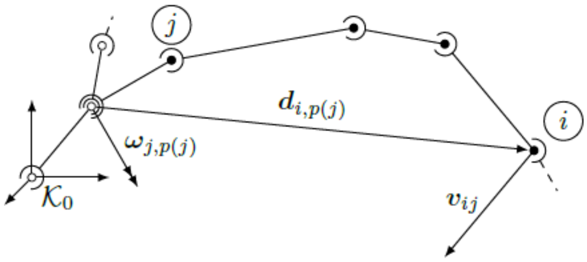


Figure 10 Velocity component v_{ij}

Refrence : OCN Simflex User Manual

Accelerations, can be found by differentiating equation 3.7 with respect to time and leads the system's vector of accelerations :

$$^{0}\boldsymbol{a} = \frac{\mathrm{d}\,^{0}\boldsymbol{v}}{\mathrm{d}\,t} = \boldsymbol{J}\ddot{\boldsymbol{q}} + \dot{\boldsymbol{J}}\dot{\boldsymbol{q}} \qquad (3.9)$$

The derivation of Jacobian with respect to time leads to quadratic terms in the joint velocities $\dot{q}$ in the last term in the above equation. By ignoring high frequent vibrations induced e.g by vortexes, the time derivatives of the joint angles are typically very small, i.e. $\dot{q} \ll 1$. Consequently the resulting quadratic velocity terms can be neglected resuting in :

$$^{0}\boldsymbol{a} = \boldsymbol{J}\ddot{\boldsymbol{q}} + \cancelto{\boldsymbol{0}_{(3)}}{\dot{\boldsymbol{J}}\dot{\boldsymbol{q}}} = \boldsymbol{J}\ddot{\boldsymbol{q}} \qquad (3.10)$$

For equation of motion, applying the principle of virtual power, the equationsof motion of all nodes can be derived as :

$$\underbrace{\begin{bmatrix} m_1\boldsymbol{I}_{(3,3)} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & m_{n_N}\boldsymbol{I}_{(3,3)} \end{bmatrix}}_{\boldsymbol{M}} \underbrace{\begin{bmatrix} \boldsymbol{a}_1 \\ \vdots \\ \boldsymbol{a}_{n_N} \end{bmatrix}}_{\boldsymbol{a}} = \underbrace{\begin{bmatrix} \boldsymbol{f}_1^{e} \\ \vdots \\ \boldsymbol{f}_{n_N}^{e} \end{bmatrix}}_{\boldsymbol{f}^{e}} + \underbrace{\begin{bmatrix} \boldsymbol{f}_1^{r} \\ \vdots \\ \boldsymbol{f}_{n_N}^{r} \end{bmatrix}}_{\boldsymbol{f}^{r}\,.} \qquad (3.11)$$

The upper left index indicating the coordinate system is omitted. The subtitution of cartesian acceleration leads to :

$$\begin{aligned} \boldsymbol{J}^{\mathrm{T}}\boldsymbol{M}\boldsymbol{J}\ddot{\boldsymbol{q}} &= \boldsymbol{J}^{\mathrm{T}}\boldsymbol{f}^{\mathrm{e}} + \cancelto{\boldsymbol{0}}{\boldsymbol{J}^{\mathrm{T}}\boldsymbol{f}^{\mathrm{r}}} \\ \boldsymbol{M}^{\mathrm{q}}\boldsymbol{a} &= \boldsymbol{f}^{\mathrm{q,e}} \end{aligned} \qquad (3.12)$$

Because the reaction fforces are perpendicular to the constraint manifold, which is defined by the columns of the Jacobian matrix, the system's generalised mass matrix :

$$\boldsymbol{M}^{\mathrm{q}} = \boldsymbol{J}^{\mathrm{T}}\boldsymbol{M}\boldsymbol{J} \qquad (3.13)$$

The vector of generalised external forces become:

$$f^{q,e} = J^T f^e \tag{3.14}$$

Equation above can be assumed as projections of the respective inertia and external forces to the constraint manifold.

3.2. Reconstructed Reaction Forces Formulation Methods

This method using Langrangian classical method – Langrangian dynamic, which based on explicit constraint equations and minimal coordinates or implicit constraint equations and redundant coordinates. Depending on choice of formulation exact solution of constraints (explicit equations) or violatoin of cinstraints due to numerical integration of constraints (implicit constraints).

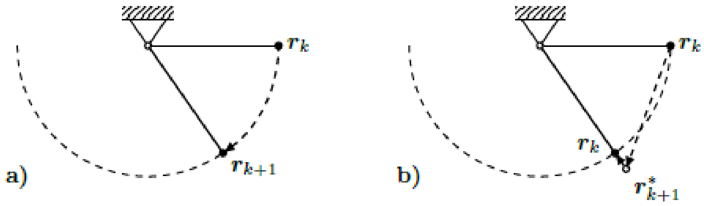


Figure 11 Example pendulum. a) Exact solution of explicit contraints equations b) Violation of constraints due to numerical integration of implicit constraint equations. Violation corrected by projection.
Rerence : OCN Simflex User Manual

The integration using projection based on solvers with two steps First is Predictor step, which neglect reaction forces, accelerations solely due to external forces, the acceleration, velocities and positions dissatisfy constraints, project positions to cconstraint manifold. The Second is Corrector step, which reconstruct averaged reaction forces based on projected position, apply trapezoidal rule based on external forces at end of timestep and averaged reaction forces, with project position to constarint manifold :

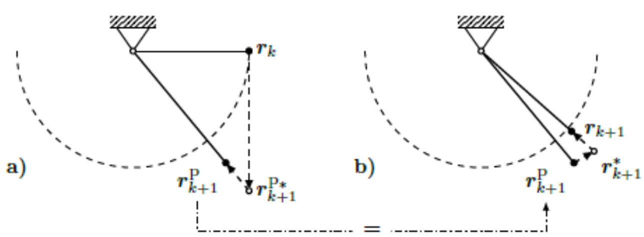


Figure 12 Example pendulum. a) Predictor step, b) Corrector step.

Refrence : OCN Simflex User Manual

The equation of motion based on Langrangian dynamic and dependant cooordinate (primary constraints given in implicit form) as :

$$\bar{g}(\boldsymbol{r},t)=\begin{bmatrix}\bar{g}_1(\boldsymbol{r},t)\\ \vdots \\ \bar{g}_{n_C}(\boldsymbol{r},t)\end{bmatrix}=\mathbf{0} \qquad (3.15)$$

Where the position vector only depends on the generalized coordinates q, the constrant vector is expressed as :

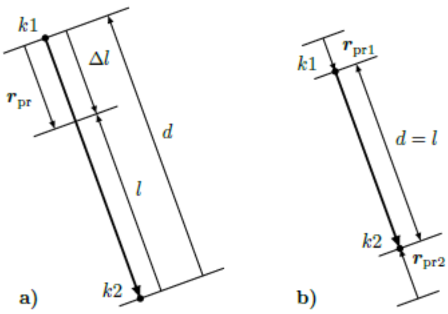
$$\bar{g}(\boldsymbol{r})=\mathbf{0} \qquad (3.16)$$

Rotation projection which is using XYZ euler joint angles is the same as Langrangian dynamic method at previous chapter.

The projected positions r should fullfil the constraint condition above because for projection position, The relaxation algorithm, the position r^* violating the constraint equations back towards the constraint manifold, the operator r is expressed as :

$$\boldsymbol{r}=\mathrm{relax}(\boldsymbol{r}^*) \qquad (3.17)$$

The projection of th epositions can be expressed :



(3.18)

Figure 13 Projection of the positions. a) Constraint prior to projection, b) Constraint after projection

Reference : OCN Simflex User Manual

The projection vector $r_{pr,iC}$ is distributed to the two nodes by spiltting it into two vectors of opposite direction. So that the node with the higher mass is shifted less due to it's higher inertia. The two vectors, by which the nodes are to by shifted, are then obtained as :

$$\boldsymbol{r}_{\mathrm{pr1},i_C}=\boldsymbol{u}_{\mathrm{g},i_C}\frac{m_{2,i_C}}{m_{1,i_C}+m_{2,i_C}}\Delta l_{i_C} \quad \text{and} \quad \boldsymbol{r}_{\mathrm{pr2},i_C}=-\boldsymbol{u}_{\mathrm{g},i_C}\frac{m_{1,i_C}}{m_{1,i_C}+m_{2,i_C}}\Delta l_{i_C} \qquad (3.19)$$

As shorthand, the projection algorithm is implemented as an iteration over all constraints and repeated n_{Iter} times :

$$\boldsymbol{r}^{i+1}_{k_{1/2}(i_C)} = \boldsymbol{r}^{i}_{k_{1/2}(i_C)} + \alpha\ \boldsymbol{r}_{\mathrm{pr}1/2,i_C} \tag{3.20}$$

Here, α is intriduced s weight factor in order to stabilise the solution, typically set to 0.5. Wihin one iteration step, the position $\boldsymbol{r}^{i}_{k_{1/2}[i_C]}$ might occur in several concurring constraints. In this case, the position already changed by the preceding projection of another constraints is used as a basis for the projection of the current constraint. By combining the relaxation algorithm and updated velocity which will be described below, the reconstructed type I and II are established as follows :

$$\hat{\boldsymbol{v}}_{k+1} = (\hat{\boldsymbol{r}}_{k+1} - \hat{\boldsymbol{r}}_k) / \Delta t\,. \tag{3.21}$$

For Type I (velocity-verlet), velocity verlet integration with subsequent relaxations and reaction force reconstruction :

$$\begin{aligned}
{}^{\mathrm{P}}\hat{\boldsymbol{r}}^{*}_{k+1} &= \frac{1}{2}\hat{\boldsymbol{M}}^{-1}\left(\hat{\boldsymbol{f}}^{\mathrm{e}}_k + \cancel{\hat{\boldsymbol{f}}^{\mathrm{r}}_k}\right)\Delta t^2 + \dot{\hat{\boldsymbol{r}}}_k\Delta t + \hat{\boldsymbol{r}}_k \\
\frac{\hat{\boldsymbol{f}}^{\mathrm{r}}_k + {}^{\mathrm{P}}\hat{\boldsymbol{f}}^{\mathrm{r}}_{k+1}}{2} &\approx \frac{2\hat{\boldsymbol{M}}\left({}^{\mathrm{P}}\hat{\boldsymbol{r}}_{k+1} - \dot{\hat{\boldsymbol{r}}}_k\Delta t - \hat{\boldsymbol{r}}_k\right)}{\Delta t^2} - \hat{\boldsymbol{f}}^{\mathrm{e}}_k \\
\hat{\boldsymbol{r}}^{*}_{k+1} &= \frac{1}{2}\hat{\boldsymbol{M}}^{-1}\left(\frac{\hat{\boldsymbol{f}}^{\mathrm{e}}_k + {}^{\mathrm{P}}\hat{\boldsymbol{f}}^{\mathrm{e}}_{k+1}}{2} + \frac{\hat{\boldsymbol{f}}^{\mathrm{r}}_k + {}^{\mathrm{P}}\hat{\boldsymbol{f}}^{\mathrm{r}}_{k+1}}{2}\right)\Delta t^2 + \dot{\hat{\boldsymbol{r}}}_k\Delta t + \hat{\boldsymbol{r}}_k \\
&= \frac{1}{4}\hat{\boldsymbol{M}}^{-1}\left({}^{\mathrm{P}}\hat{\boldsymbol{f}}^{\mathrm{e}}_{k+1} - \hat{\boldsymbol{f}}^{\mathrm{e}}_k\right)\Delta t^2 + {}^{\mathrm{P}}\hat{\boldsymbol{r}}_{k+1}
\end{aligned} \tag{3.22}$$

For Type II (velocity-verlet), velocity verlet integration with subsequent relaxations and reaction force reconstruction. Stabilisation of predictor step by partial inclusion of previous reaction forces :

$$\begin{aligned}
{}^{\mathrm{P}}\hat{\boldsymbol{r}}^{*}_{k+1} &= \frac{1}{2}\hat{\boldsymbol{M}}^{-1}\left(\hat{\boldsymbol{f}}^{\mathrm{e}}_k + \alpha_{\mathrm{reac}}\frac{\hat{\boldsymbol{f}}^{\mathrm{r}}_{k-1} + \hat{\boldsymbol{f}}^{\mathrm{r}}_k}{2}\right)\Delta t^2 + \dot{\hat{\boldsymbol{r}}}_k\Delta t + \hat{\boldsymbol{r}}_k \\
\frac{\hat{\boldsymbol{f}}^{\mathrm{r}}_k + \hat{\boldsymbol{f}}^{\mathrm{r}}_{k+1}}{2} &\approx \frac{2\hat{\boldsymbol{M}}\left(\hat{\boldsymbol{r}}_{k+1} - \dot{\hat{\boldsymbol{r}}}_k\Delta t - \hat{\boldsymbol{r}}_k\right)}{\Delta t^2} - \frac{\hat{\boldsymbol{f}}^{\mathrm{e}}_k + {}^{\mathrm{P}}\hat{\boldsymbol{f}}^{\mathrm{e}}_k}{2} \\
\hat{\boldsymbol{r}}^{*}_{k+1} &= \frac{1}{4}\hat{\boldsymbol{M}}^{-1}\left({}^{\mathrm{P}}\hat{\boldsymbol{f}}^{\mathrm{e}}_{k+1} - \hat{\boldsymbol{f}}^{\mathrm{e}}_k\right)\Delta t^2 + {}^{\mathrm{P}}\hat{\boldsymbol{r}}_{k+1}
\end{aligned} \tag{3.23}$$

Based on equation 3.10, that the sum of reaction forces acting on node i equals the difference of inertial forces, and by splitting the summed up reaction force, a bar reaction force acting along bar element f_i^{b} and the bar reaction force resulting from the sucessor bar element s(i) leads :

$$f_i^{\mathrm{b}} = f_{s(i)}^{\mathrm{b}} + M_i a_i - f_i^{\mathrm{e}} \tag{3.24}$$

Note, that the bar reaction force resulting from successor node cntributes with a negative sign due to Newton's third law. Accordingly, compared to it's succcesor element s(i), the additional forces acting on node i :

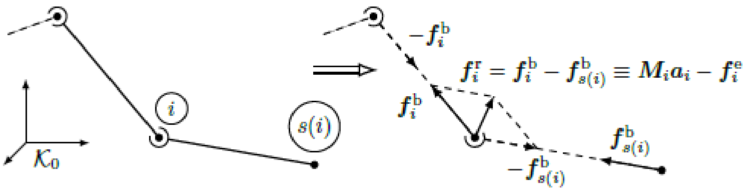


Figure 14 Joint and reaction forces

Reference : OCN Simflex User Manual

4. HYDRODYNAMIC FORCES ON FLOATING CYLINDRICAL STRUCTURE AND MOORING LINE

4.1. Implementation of Alghotythm in Matlab

The dynamic movement of fluids can be expressed in mathematical formulas by using MATLAB software as one of Mathematical Modelling Languange application. The primary purpose is to develop an algorithm for the numeric integration of hydrodynamic loads on slender cylindrical objects by using morison equation. The hydrodynamic load of the objects here consist of the floater and the mooring line. Subsequently, the plausibility of the developed algorithm has to be checked.

There are several steps of equation implementations in order to arrive to the hydrodynamic force result. The hydrodynamic force alghorythms are presented in for 2 object, the cylindrical floating structure and the mooring line. The hydrodynamic force alghorythm of cylindrical structure is defined as follows :

1. Cylinder position and velocity vector at coordinate system using transformation matrix calculation
2. Wave elevation calculation
3. Airy wave velocitiy at every marker point on the cylinder at x and z axes
4. Relative Velocity between cylinder structure and wave
5. Transformation of relative velocity and filtering result with respect to wave elevation
6. Drag Coefficient
7. Hydrodynamic Morison forces equation, with respect to drag force due to viscosity only

While, the hydrodynamic force alghorythm of mooring line is defined as follows:

1. Mooring line position, velocity and acceleration vector at coordinate system
2. Wave elevation calculation

3. Airy wave velocitiy and acceleration at every marker point on the mooring line at x and z axes
4. Relative Velocity and acceleration between mooring line and wave
5. Transformation of relative velocity and acceleration and filtering result with respect to wave elevation
6. Added mass and Drag Coefficient
7. Hydrodynamic Morison forces equation, with respect to froude krylov, hydrodybanic mass and drag force

The detail Matlab codes of Morison hydrodynamic algorithm and the plausible sample result are present in appendix B and C.

4.1.1. Object Position and Velocity at Coordinate system

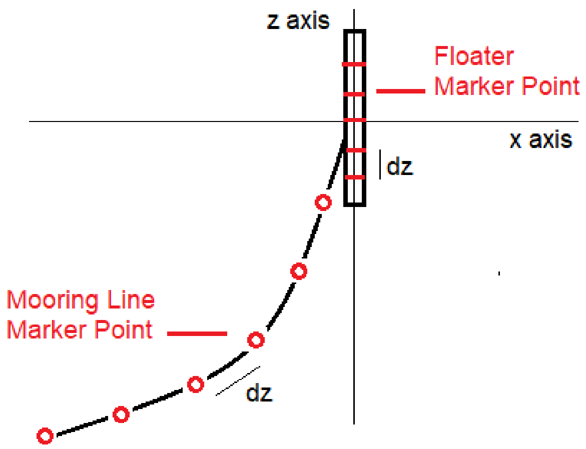


Figure 15 Cylinder models coordinate system marker point

In order to derive morison hydrodinamic equation, a floating cylinder body and a mooring line is design as present in the figure above. Suppose a vertical cylinder is subject to a incoming wave with a horizontal velocity changing both in time and vertically in the z-direction. The approach in practice is to evaluate by using Morison's formula, the force acting on a small section of cylinder should be computed at each depth and integrated to the total force. Thus, the cylinder should be separated in to several ammount of slices which mention as markers point. For the next equation, it is necessary to transform the marker point position and velocity. The position and velocity transformation from local body coordinate to global earth coordinate in matlab are defined as follows :

$$r^G = r^G_{ref} + (T.r^B) \quad (4.1)$$

$$v^G = v^G_{ref} + (\omega.T.r^B) \quad (4.2)$$

where,

r^G = positions of markers at global earth coordinate system

r^B = positions of markers at local body coordinate system

v^G = velocity of markers at local body coordinate system

r^G_{ref} = Position of body Reference at global earth coordinate system

v^G_{ref} = Velocity of body Reference at global earth coordinate system

T = Transformation Matrix between the local body fixed coordinate system and the global earth fixed coordinate system expressed as :

$$\mathbf{T} = \begin{bmatrix} \cos\alpha_3\cos\alpha_2 & \sin\alpha_3\cos\alpha_1 + \cos\alpha_3\sin\alpha_2\sin\alpha_1 & \sin\alpha_3\sin\alpha_1 - \cos\alpha_3\sin\alpha_2\cos\alpha_1 \\ -\sin\alpha_3\cos\alpha_2 & \cos\alpha_3\cos\alpha_1 - \sin\alpha_3\sin\alpha_2\sin\alpha_1 & \cos\alpha_3\sin\alpha_1 + \sin\alpha_3\sin\alpha_2\cos\alpha_1 \\ \sin\alpha_2 & -\cos\alpha_2\sin\alpha_1 & \cos\alpha_2\cos\alpha_1 \end{bmatrix} \quad (4.3)$$

T is an orthogonal matrix with the property that $T^T = T^{-1}$, with $(\alpha_1, \alpha_2, \alpha_3)$ as euler angle.

For the mooring line hydrodynamic position, velocity and acceleration, are assumed as a moving marker point at each segment except for the anchor point which is assumed as fixed point. Therefore, the velocity and acceleration at this point is assumed equal to zero.

4.1.2. Wave Elevation

The implementation in matlab for wave elevation of a long-crested regular wave, propagating along the positive x axis, in time variant is written as follows :

$$\zeta(t) = \zeta_a \cos(k\ x - \omega\ t) \quad (4.4)$$

Where,

ξ_a = wave amplitude

k = wave number

$\omega = \frac{2\pi}{T}$

t = time variant

The form of water surface equation above is simulated that the wave moves in the positive x-direction. The wave elevation is defined for each marker point at x and z axes due to time variant. In the implementation for the cylinrical floater, all the result value such relative velocity, hydrodynamic morison equation at each marker point along x and z axes will be filtered and only considered the result for the marker point below the wave elevation (the submerged part). While the hydrodynamic load result for mooring line is taken for all marker point since all part of mooring line is designed always below the wave elevation.

4.1.3. Airy Wave Velocity and Acceleration

The velocity and acceleration as one of components for hydrodynamic equation are calculated in linear wave theory, further, the theory also known as Airy wave theory (first order potential theory). Since the vertical cylinder will be modelled as a floating body, the velocity and acceleration will be considered coming from 2 axis vertical and horizontal. The equation of velocity of airy wave theory acting from x and z direction are shown as follows :

$$u^G_{wave} = \xi_a \omega \frac{\cosh k(z+d)}{\sinh kd} \cos(kx - \omega t) \qquad (4.6)$$

$$w^G_{wave} = \xi_a \omega \frac{\sinh k(z+d)}{\sinh kd} \sin(kx - \omega t)$$

while for the acceleration of airy wave, are shown as follows :

$$\dot{u}^G_{wave} = \xi_a \omega^2 \frac{\cosh k(z+d)}{\sinh kd} \sin(kx - \omega t) \qquad (4.7)$$

$$\dot{w}^G_{wave} = -\xi_a \omega^2 \frac{\sinh k(z+d)}{\sinh kd} \cos(kx - \omega t)$$

Where :

u^G_{wave} *and* w^G_{wave} = wave velocity in horizontal and vertical direction in Global coord. system

$\dot{u}_{wave}^{G}\ and\ \dot{w}_{wave}^{G}$ = wave acceleration in horizontal and vertical direction in Global coord. syst.

ξ_a = wave amplitude

$\omega = \frac{2\pi}{T}$

T = period

k = wave number

d = sea depth

t = variant value of time set

x = variant value of domain position of cylinder in x axis (divided to n marker point in x axes)

z = vertical length of each stripes cylindrical at submerged body (divided to n marker point in z axes)

The velocity and acceleration of the wave are calculated by taking into account the phase angle of the wave as well as the respective diving depth of the cylindrical floater and mooring line section.

Overall the input value for the velocity of airy wave theory are range value of domain space (x), time (t) and (z), and the other independent input value are wave amplitude (ξ_a), depth (d), period (T) and wave length (λ) since omega (ω) and wave number (k) can be obtained as follows :

$$\omega = \frac{2\pi}{T} \tag{4.8}$$

$$k = \frac{2\pi}{\lambda} \tag{4.9}$$

Furthermore, the wave velocity is used for relative velocity calculation between the velocity of wave and velocity of cylinder structure for morison equation of the floater, which is considered as moving floating structure. While, for the wave acceleration is used directly for morison equation of mooring line which is considered as fixed structure.

4.1.4. Relative Velocity

The implementation of wave flow velocity both in horizontal and vertical axes in morison hydrodynamic force equation for cylindrical floater use relative velocity between the body structure and wave flow as shown as follows :

$$(u_{rel}^{G} = u_{wave} - u_{body}) \ and \ (w_{rel}^{G} = w_{wave} - w_{body}) \quad (4.10)$$

$$(\dot{u}_{rel}^{G} = \dot{u}_{wave} - \dot{u}_{body}) \ and \ (\dot{w}_{rel}^{G} = \dot{w}_{wave} - \dot{w}_{body})$$

Where,

u_{rel}^{G}= relative velocity in horizontal direction

u_{wave}= wave flow velocity in horizontal direction

u_{body}= new projection of body structure velocity in horizontal direction

w_{rel}^{G}= relative velocity in vertical direction

w_{wave}= wave flow velocity in vertical direction

w_{body}= new projection of body structure velocity in vertical direction

4.1.5. Transformation of relative velocity, acceleration and filtering result with respect to wave elevation

The resulting relative velocity and wave flow acceleration are in global earth coordinate system. Since the velocity and acceleration in the morison hydrodinamic force equation should be implemented in local body coordinate system, therefore, those result should be transform from global earth coordinate to local body coordinate which is implemented in matlab as follows:

$$u_{rel}^{B} = (\omega_v . T^T . r^G) + u_{rel}^{G} \qquad and \qquad w_{rel}^{B} = (\omega_v . T^T . r^G) + w_{rel}^{G} \quad (4.11)$$

Where,

u_{rel}^{B} = Horizontal relative velocity in local coordinate system

w_{rel}^{B} = Vertical relative velocity in local coordinate system

u_{rel}^{G} = Horizontal relative velocity in local coordinate system

w_{rel}^{G} = Vertical relative velocity in local coordinate system

ω_v = Angular velocity of floating body

T^T = Transpose of transformation matrix

r^G = position vector in global coordinat system

With ω_v in this equation as angular velocity. After obtaining the resulting velocity transformation in local body coordinate system, it is necessary also to filter the result which acting with respect to submerged cylinder part only, hence, the result will be filtered with respect to submerged part below wave elevation only. It mean the result of velocity and acceleration which respect to the cylinder body marker points above wave elevation will be neglected. For further detail about the code, can be seen in the appendix D.

4.1.6. Added Mass and Drag Coefficient

The added mass and drag coefficient are taken as one value by using example suggestion of drag and inertia coefficient values given by *Clauss (1992)* as shown as follows :

Table 1 Sample coefficient value by Clauss (1992)

	$Rn < 10^5$		$Rn > 10^5$	
KC	C_D	C_M	C_D	C_M
< 10	1.2	2.0	0.6	2.0
$\geqslant 10$	1.2	1.5	0.6	1.5

4.1.7. Morison Equation

The hydrodynamic equation is determined by using morison equation method, since the cylindrical body floater and mooring line are considered as a slender transparent body, also the body structure and wave load are designed to satisfy the limit diagram of chakrabarti at region VI (refer to figure 5). The morison equation of moving floater body is determined for each slice of cylinder floating body as describe previously for each marker points. A morison equation is defined from *Gunther Clauss, Eike Lehmann and Carsten Östergaard (1992)*. Since the floater wave load are designed for region VI of chakrabarti diagram, the morison equation only consider the Non linear drag force term as shown as follow :

$$dF = \frac{1}{2}.\rho.C_d.dA.|u - v|.(u - v) \qquad (2.34)$$

While for the morison equation of mooring line is determined for moving body also, however the morison equation consider the froude krylov, hydrodynamic mass force and drag force due to vicosity as shown as follows :

$$dF_x = \rho . d\forall . \frac{\partial u}{\partial t} - \rho . C_a . d\forall . \left(\frac{\partial u}{\partial t} - \dot{u_c}\right) + \frac{1}{2} . \rho . C_d . dA . |u - v| . (u - v) \qquad (2.33)$$

Cm = (1+Ca) = inertia coefficient with C_a as added mass coefficient

Cd = Drag coefficient

dz = separated vertical distance in z axis

$d\forall$ = Volume of submerged cylinder

dA = The cross sectional which perpendicular to flow direction

r = half of diameter

D = Diameter of cylinder

u = Wave flow velocity

v = Body structure velocity

$\frac{\partial u}{\partial t}$= Wave flow acceleration

$\dot{u}_c$= Body structure acceleration

The added mass and drag coefficient will consider one coefficient for any stripes/marker point using approach sample from *Claus (1992).*

4.2. Plaussible Results

A plaussible results of Morison Force equation are obtained to be checked for both objects, cylinder structure boody and mooring line. The input value of objects design geometry and wave loadcase are designed as similar as possible for both object for the comparison study result, the input are presented as follows :

Loadcases	Value
Depth-d (m)	16.0
Wave Height-H (m)	5.4
Amplitude-A (m)	**2.7**
Period-T (s)	**5.0**
Frequency-f (Hz)	0.2
Horizontal Wave Velocity-v (m/s)	1.0

Omega-ω	**1.3**
Wave Numb. (rad/m)	0.3
Wave Length-L (m)	30.0
H/D **(>=20)**	**20.0**
$\pi D/L$ **(<=0.03)**	**0.02**
Structure Velocity-x (m/s)	1.0
Structure Acceleration-x (m/s^2)	1.0
nMarkers	11.0
Cylinder Floating Structure	
Diameter of Cylinder (m)	2.7
Length of Cylinder (m)	12.0
Mooring Line	
Diameter of Line (m)	2.7
Length of Line (m)	12.0

The horizontal morison force equation of cylinder floating structure are presented as 2 result, first is as force which applied at each slice/segment of the structure (defined as nMarkers) at each time step, and second is as total force which applied at the whole structure at each time step. The first and second results are presented as follows :

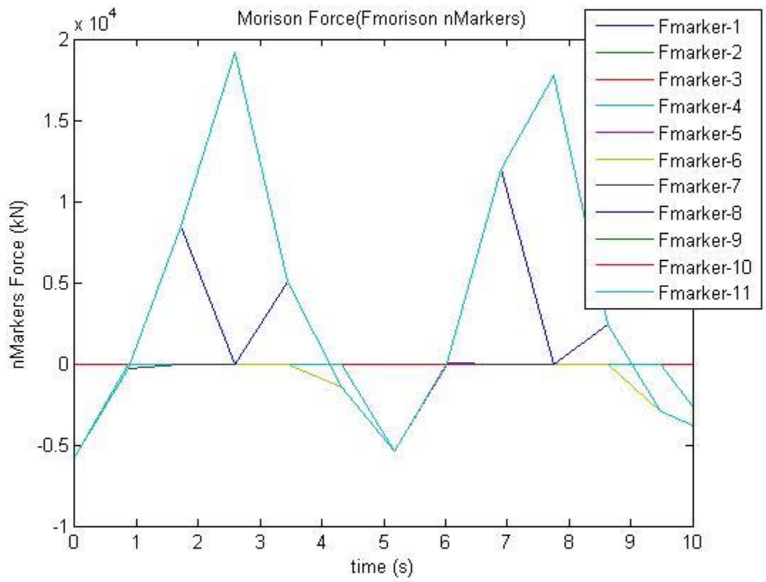


Figure 16 The Applied Morison Force at each segment of floating structure

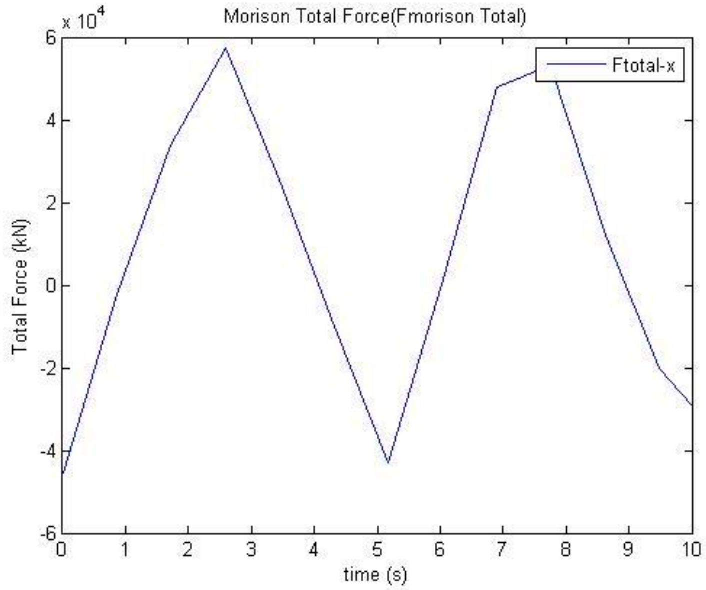


Figure 17 The Applied Morison Force as total force of the structure

Since the morison equation that applied at cyinder floating structure is designed to satisfy the region VI of chakrabarti diagram, thus, the morison force equation only contain the drag force term. From the result above it is observed that the maximum morison force is 2 x 10^4 kN which applied at marker point 11, which located at the bottom part of cylinder. While the maximum morison force that applied as total force is 6 x 10^4 Kn.

The horizontal morison force equation of mooring line are presented as 2 result as previous object, first is as force which applied at each slice/segment of the line (defined as nMarkers) at each time step, and second is as total force which applied at the whole structure at each time step. The first and second results are presented as follows :

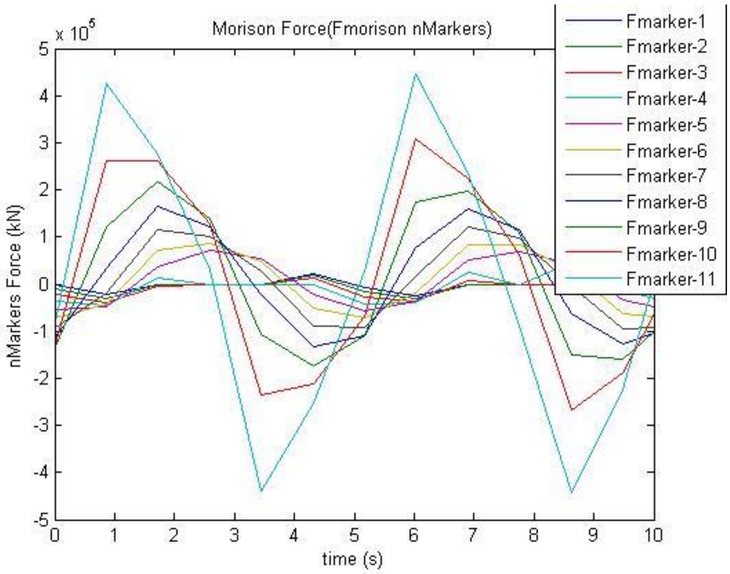


Figure 18 The Applied Morison Force at each segment of mooring line

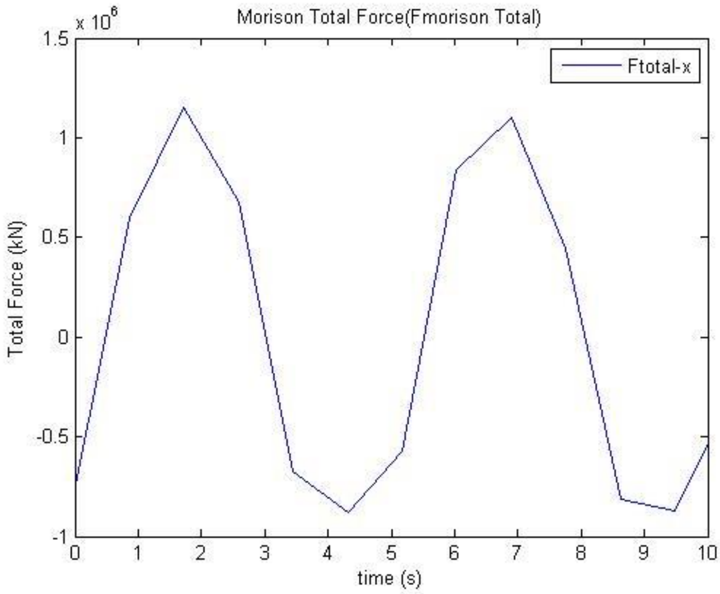


Figure 19 The Applied Morison Force as total force of the mooring line

Since the morison equation that applied at mooring line is assumed as a moving structure, except at anchor point which assumed as zero velocity and acceleration, thus, the morison force equation contain the froude krylov, hydrodynamic mass and drag force terms. From the result above it is observed that the maximum morison force is 5 x 10^5 kN which applied at marker point 11, which located at the bottom part of cylinder. While the maximum morison force that applied as total force is 1.5 x 10^6 Kn.

From both morison results it can be observed that the morison hydrodynamic force that applied at the floating or fixed object become larger at the deeper segment (nMarker point). Since the morison force for floating cylinder structure contain only drag force term, and for mooring line contain the whole froude krylov, hydrodynamic mass and drag terms, it is obesrve that the total force of morison equation for mooring line is obtained larger than for cylinder floating structure. These results with respect to the similar input data of geometrical structure measurement and wave loadcase for both object.

5. DESIGNED MODEL AND WAVE LOADCASES

5.1. Design Model of The Cylindrical Floating Structure

The floater design in this analysis is modelled as a slender (hydrodynamically trasparent) floating cylindrical structure. The sample model of cylindrical structure is designed with respect to the limit diagram of chakrabarti region VI.

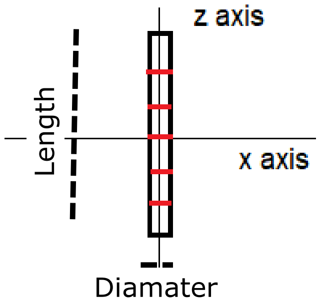


Figure 20 The design description of cylinder floater structure

The body structure is an unconstrained rigid, with the design measurement as follows:

Table 2 Main Dimension Design

Measurements	Value
Cylinder Diameter-D (m)	0.27
Cylinder Length-*l* (m)	12
Draft	6
Total Mass (kg)	200
Sea water density (kg/m)	1025

Table 3 Stiffness and Damping Factor

Factors	Model (Used)
Siffness	26000
Damping	18225

In this analysis, the designed floating cylindrical structure above, will be used for all conditions and lodcases evaluation analysis. The main dimension is created with respect to the non dimensional Keulegan-Carpenter number H/D and the ratio $\pi D/L$ as limit parameter which make distinction regarding the used of hydrodynamic force equation method, where D is the cylinder diameter, H is the wave height and L is the wave length. The detail explanation about the limit parameter is refer to chapter 2.3.

5.2. Mooring Configurations

The configuration of mooring analysis in this report is performed based on several possible conditions. The description of mooring line configuration is present below.

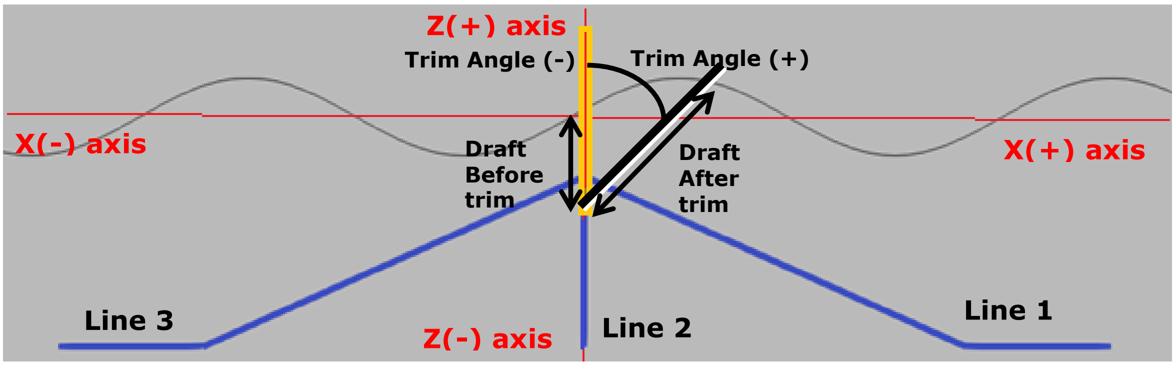
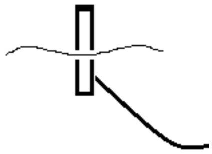
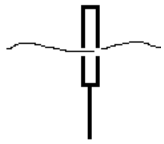
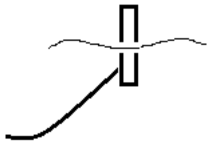
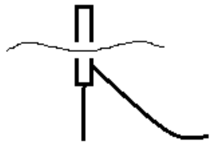
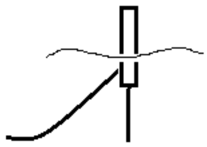
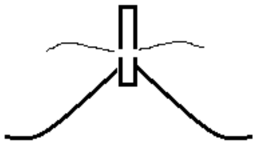
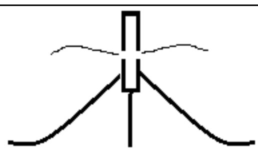


Figure 21 Description of Mooring Line Configuration

These conditions are developed to execute the comparative study of mooring system configurations and the floater response bahaviour. The evaluation of these mooring configurations are performed by time domain analysis using OCN Simflex program. The mooring configuration conditions are described as follows :

Table 4 Mooring Line Configurations

Conditions	Mooring Lines	Model
Condition 1	Line 1	
Condition 2	Line 2	
Condition 3	Line 3	
Condition 4	Line 1 and 2	
Condition 5	Line 2 and 3	
Condition 6	Line 1 and 3	
Condition 7	Line 1, 2 and 3	

The mooring configuration conditions are designed in 7 possible conditions by using 3 mooring lines configuration. The table below defines the fairlead and anchor point coordinates relative to global earth reference coordinate system:

Table 5 Mooring systems fairlead in local body coordinate and anchor point in global coordinate

Fairlead Point	**X axis (m)**	**Y axis (m)**	**Z axis (m)**
Line 1	0.0	0.0	-3.13
Line 2	0.0	0.0	-3.13
Line 3	0.0	0.0	-3.13
Anchor Point	**X axis (m)**	**Y axis (m)**	**Z axis (m)**
Line 1	-36.59	0.0	-16
Line 1	0.0	0.0	-16
Line 2	36.59	0.0	-16

The mooring line has the following properties, which are constant for the whole line :

Table 6 Mooring Line Characteristics

Measurements	**Value**
Line Type	Chain
Length Line 1 and 3 (m)	39.1
Length Line 2 (m)	12.8
Diameter (m)	0.04
Density (kg/m)	7000

5.3. Wave Loadcases

The loads considered here are composed of hydrodynamic drag induced by waves, buoyancy and gravity. The wave load loadcases are established in order to compare the floater bahaviour in regular airy wave loads. The evaluation of wave loadcases are performed by time domain analysis in OCN-Simflex. The applied configurations of the wave load components are composed of several loadcases conditions as present as follows :

Table 7 Loadcases Simulations for Superpose waves analysis

Loadcases	L1	L2	L3	L4	L5	L6	L7	L8	L9
Depth-d (m)	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Wave Height-H (m)	5.4	7.0	80	5.4	7.0	8.0	5.4	7.0	8.0
Amplitude-A (m)	**2.7**	**3.5**	**4.0**	**2.7**	**3.5**	**4.0**	**2.7**	**3.5**	**4.0**
Period-T (s)	**5.0**	**5.0**	**5.0**	**10.0**	**10.0**	**10.0**	**15.0**	**15.0**	**15.0**
Frequency-f (Hz)	0.2	0.2	0.2	0.07	0.07	0.07	0.07	0.07	0.07
Horizontal Velocity-v (m/s)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Omega-ω	**1.3**	**1.3**	**1.3**	**0.6**	**0.6**	**0.6**	**0.4**	**0.4**	**0.4**
Wave Numb. (rad/m)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Wave Length-L (m)	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
H/D **(>=20)**	**20.0**	**25.0**	**28.6**	**20.0**	**25.0**	**28.6**	**20.0**	**25.0**	**28.6**
$\pi D/L$ **(<=0.03)**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**

From the designed main dimension and the wave loadcases above, it is known that non dimensional H/D is greater than 20, and $\pi D/L$ is less than 0.03, means that the designed main dimension is satisfy the requirement of morison hydrodynamic force equation method. The cylindrical floating structure and airy wave is designed in order to satisfy the requirement limit diagram of chakrabarti in region VI regard to figure 5, therefore, this anaysis is computed by only using the drag term of the hydrodynamic morison equation.

The other limitation of the input value of the loadcases above such amplitude and period are obtained also by limitation of range value which able to be run by OCN Simflex, for example, if the input amplitude is more than 4 m, it might be able to be run with period 10 s and 15 s but, when the amplitude is applied together with period 5 s, it is failed and can not be run by OCN Simflex. The detail explanation about the limit parameter is defined in chapter 2.

6. TIME DOMAIN ANALYSIS RESULT

The response result is computed by OCN Simflex program, while for postprocessing result is using Paraview program. The motion response is presented as the displacement of offset area at x and z in (+) and (-) axis . The maximum tension of mooring line induced by Horizontal Airy wave load configuration. There are 2 configuration of the simulation, those are configurations of mooring line and configurations of airy wave loadcases. As introduced earliear in section 5.3 and 5.2, the cylindrical model with mooring line configurations are induced by horizontal airy wave loadcases. In this section, some findings of the simulation is done and will be explained in next part.

The results also present the draft and trim of cylindr floating structure, in order to get more clear visualization, the draft and trim description are described as figure 21.

6.1. Results and Comparison of Displacement Motion Response

In order to introduce an understanding of how the airy wave loads acting on the structure, the displacement caused by the movement of the structure will be presented in this cahpter. The results are presented in two type, first is the overall maximum displacement result in it’s time step. The second is the displacement response of time step no. 73.

The first results will show the maximum probability result of displacement response for the overall condition in all wave load cases. From this information, it can be observed the maximum probability displacement for each mooring design condition at each wave load case. However the relation of displacement and wave loadcases with different wave amplitude and period can not be observed, since the variation of the results may vary depend on the time step of their maximum displacement in each condition and loadcase. Therefore, the second displacement result of time step no. 73 are choosen to be presented to show the relation between the displacement at each condition at each loadcase. Basicly the displacement result at time step no. 73 is choosen randomly. The trim and draft also provide in order to observe the detail condition and the draft which presented below, show the submerged draft after trim, and this is with respect to local body coordinate. The first displacement result, based on comprehensive studies as collected in appendix, which present the overall probability maximum displacement response are presented as follows :

Table 8 Maximum Displacement Result

Result	Condition 1				Condition 2				Condition 3			
	max. X (+)	min. X (-)	max. Z (+)	min. Z (-)	max. X (+)	min. X (-)	max. Z (+)	min. Z (-)	max. X (+)	min. X (-)	max. Z (+)	min. Z (-)
Loadcase	3	all	9	6	3	8	all	3	3	7	5	9
Displ.	29.9	-1.0	4.0	-4.0	3.5	-3.5	0.0	-3.6	0.2	-38.9	4.3	-3.9
Trim	78.8	0.0	87.4	84.1	83.5	21.8	0.0	69.4	71.1	61.1	74.4	88.1
Draft	12.0	12.0	3.5	6.9	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Time Step	94	0	83	67	7	66	0	74	5	97	45	35

Loadcases	Condition 4				Condition 5				Condition 6			
	max. X (+)	min. X (-)	max. Z (+)	min. Z (-)	max. X (+)	min. X (-)	max. Z (+)	min. Z (-)	max. X (+)	min. X (-)	max. Z (+)	min. Z (-)
Loadcase	6	8	all	9	9	all	all	4	3	8	all	6
Displ.	1.9	-2.9	0.0	-7.0	8.5	-1.0	0.0	-4.8	-0.3	-13.2	0.0	-6.4
Trim	64.1	-8.2	0.0	-7.4	64.3	0.0	0.0	-51.8	63.1	-21.7	0.0	0.0
Draft	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Time Step	95	28	0	30	92	0	0	37	5	46	0	0

Loadcases	Condition 7			
	max. X (+)	min. X (-)	max. Z (+)	min. Z (-)
Loadcase	3	8	all	9
Displ.	1.6	-3.3	0.0	-8.7
Trim	59.0	-14.1	0.0	-10.9
Draft	12.0	12.0	12.0	12.0
Time Step	6	26	0	29

From the first result above, it can be obserserved that the maximum and minimum probability displacement at x axis is 29.9 m at condition 1 and -38.9 m at condition 3.

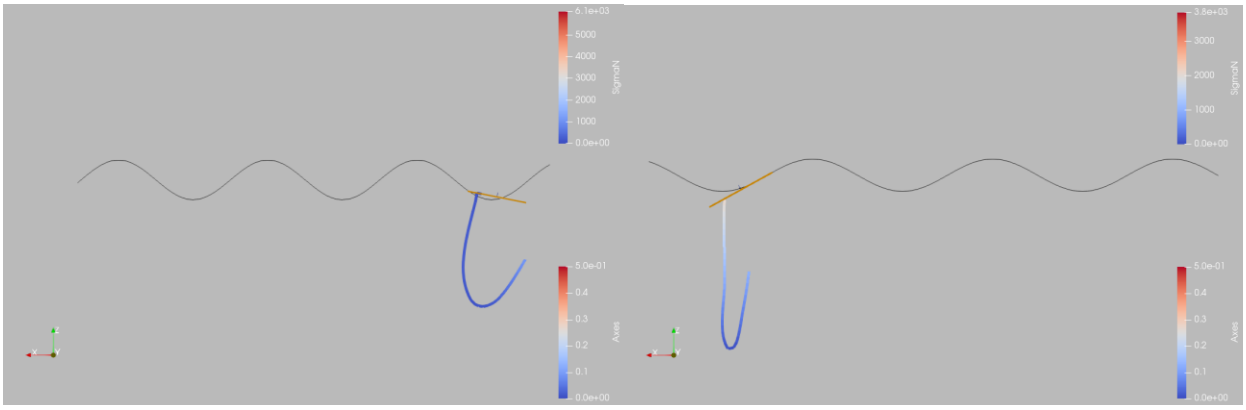


Figure 22 Maximum and minimum probability displacement at x axis, at condition 1 (left), and at condition 3 (right)

While the maximum and minimum probability displacement at z axis is 4.3 m at condition 3 and -7 m at condition 4.

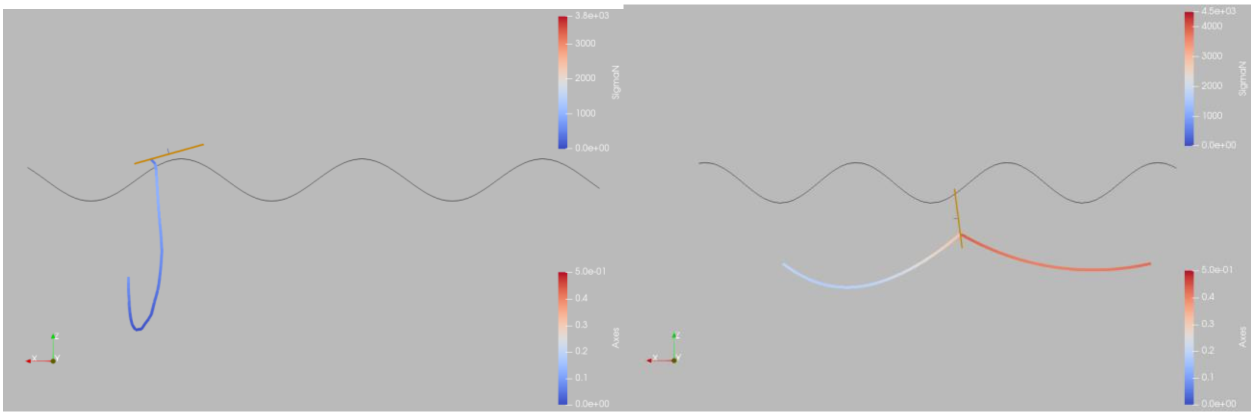


Figure 23 Maximum and minimum probability displacement at z axis, at condition 3 (left), and at condition 4 (right)

The second results will show the probability displacement response of body structure at time step no. 73, this kind of result is presented in order to observe the relation between the displacement response of each mooring condition at each loadcase. The second result is presented as follows :

Table 9 Displacement Result of time step 73 of all conditions and loadcases

Loadcases		Cond. 1		Cond. 2		Cond. 3		Cond. 4		Cond. 5		Cond. 6		Cond. 7	
		X (m)	Y (m)	X (m)	Y (m)	X (m)	Y (m)	X (m)	Y (m)	X (m)	Y (m)	X (m)	Y (m)	X (m)	Y (m)
Loadcase 1	**Displ.**	13.1	-0.8	0.9	-2.0	-31	-1.4	-1.3	-4.2	2.5	-1.1	-11	-4.3	-1.7	-5.7
A = 2.7 m	**Trim**	60.7	60.7	69.7	69.7	104.4	104.4	1.4	1.4	-8.3	-8.3	-10.6	-10.6	0.4	0.4
T = 5 s	**Draft**	10.7	6.4	7.2	12.0	12.0	8.5	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

Loadcase 2	**Displ.**	22.0	-1.3	1.6	-2.5	-29	-1.9	1.0	-3.0	3.3	-1.3	-10	-3.6	-1.6	-6.1
A = 3.5 m	**Trim**	56.2	56.2	79.6	79.6	104.6	104.6	42.2	42.2	6.0	6.0	-5.0	-5.0	0.7	0.7
T = 5 s	**Draft**	11.0	6.7	4.4	12.0	12.0	7.9	7.9	11.2	11.2	12.0	12.0	12.0	12.0	12.0
Loadcase 3	**Displ.**	22.5	-1.8	4.0	-1.6	-28	-2.3	1.0	-3.3	4.0	-1.6	-10	-3.6	-1.6	-6.3
A = 4.0 m	**Trim**	57.4	57.4	43.4	43.4	100.9	100.9	48.9	48.9	20.6	20.6	9.1	9.1	0.8	0.8
T = 5 s	**Draft**	10.5	5.6	12.0	12.0	12.0	12.0	8.5	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Loadcase 4	**Displ.**	12.1	-0.9	2.9	-1.9	-31	-0.8	0.5	-2.9	2.9	-1.9	-12	-4.5	-1.1	-4.0
A = 2.7 m	**Trim**	60.9	60.9	80.6	80.6	103.8	103.8	26.2	26.2	-12.6	-12.6	-18.8	-18.8	1.7	1.7
T = 10 s	**Draft**	8.6	8.6	9.1	6.8	6.8	12.0	12.0	9.4	9.4	12.0	12.0	12.0	12.0	12.0
Loadcase 5	**Displ.**	13.5	0.0	5.0	-3.3	-29	-2.1	1.3	-3.5	5.0	-3.3	-9.7	-2.6	-0.6	-4.3
A = 3.5m	**Trim**	53.0	53.0	89.4	89.4	105.5	105.5	42.1	42.1	49.1	49.1	-15.8	-15.8	9.9	9.9
T = 10 s	**Draft**	3.9	8.2	12.0	11.9	11.9	12.0	12.0	8.6	8.6	12.0	12.0	12.0	12.0	12.0
Loadcase 6	**Displ.**	15.0	1.2	5.2	-4.4	-28	-2.7	1.5	-3.8	3.6	-1.2	-6.5	-1.8	0.3	-4.5
A = 4.0 m	**Trim**	36.6	36.6	92.8	92.8	104.7	104.7	49.1	49.1	65.8	65.8	18.3	18.3	22.9	22.9
T = 10 s	**Draft**	6.7	12.0	12.0	11.5	11.5	12.0	12.0	6.5	6.5	12.0	12.0	12.0	12.0	12.0
Loadcase 7	**Displ.**	13.7	-2.0	4.2	-1.5	-32	1.1	0.0	-1.9	3.3	-0.7	-11	-4.1	-0.4	-3.6
A = 2.7 m	**Trim**	79.1	79.1	31.3	31.3	74.8	74.8	17.2	17.2	44.6	44.6	-3.8	-3.8	13.6	13.6
T = 15 s	**Draft**	12.0	8.7	3.7	10.5	10.5	12.0	12.0	12.0	7.8	11.9	12.0	12.0	11.9	11.9
Loadcase 8	**Displ.**	16.3	-2.6	3.5	-1.2	-30	1.1	0.3	-2.0	3.5	-1.2	-6.4	-2.2	-0.1	-3.8
A = 3.5 m	**Trim**	79.5	79.5	32.6	32.6	68.9	68.9	21.8	21.8	14.7	14.7	26.1	26.1	17.4	17.4
T = 15 s	**Draft**	12.0	8.7	9.2	11.2	11.2	12.0	12.0	9.3	9.3	12.0	12.0	12.0	12.0	12.0
Load case 9	**Displ.**	18.2	-2.9	3.2	-1.1	-30	0.9	-0.2	-2.4	3.2	-1.1	-5.4	-2.7	0.0	-3.9
A = 4.0 m	**Trim**	82.0	82.0	32.7	32.7	63.0	63.0	23.5	23.5	11.5	11.5	43.4	43.4	18.9	18.9
T = 15 s	**Draft**	12.0	8.7	8.5	11.7	11.7	12.0	12.0	7.8	12.0	12.0	11.9	11.9	12.0	12.0

From the summary result above, it can be observed that in the same period with variation of wave amplitude loadcases, the increasing amplitude will increase the displacement response. For the same wave amplitude with variation of period, the increasing period will decrease the displacement response of cylinder floating structure, however this point mostly satisfy for such a stable mooring design condition, such mooring condition 4 and 7.

Among the other mooring condition, condition no. 1 and 3 show a big displacement than the other because the mooring condition is only 1 line which anchored at the right side for condition 1 and at the left side for condition 3. While for condition 2, with 1 line is anchored exactly under the floating cylinder, present the smalest movement, theoretically it should only produce very small displacement or almost no movement, but from the resut above, it yield such a value of displacement response at x and z axis, because the line at fairlead/suspention point is designed not exactly at the bottom of cylinder, but 2 m more above the bottom point of cylinder, thus, in the running system at OCN Simflex, it may caused such a value of movement at x axis.

The displacement response for mooring condition 4 compared with condition 7, it shows that at the small period the displacement response of the cylinder of mooring condition 4 is smaller than condition 7, while at the large period of wave loadcase show that the displacement response of the cylinder of mooring condition 7 is smaller that mooring condition 4. These phenomenon may happen because at small period the condition 7 with 3 mooring line, the displacement at z axis at small period is around 6 m below water level, this may cause the structure moving a lot because of the slackening of the mooring line. While the displacement at z axis at large period is around 4 m below water level, which cause the robability of movement of the structure is smaller because of the mooring line is pulled. The detail result shown in appendix A.

6.2. Results and Comparison of Mooring Tensions Response

The same type of results for mooring line tension comparison result are presented as displacement response result. There are 2 type of result, first is the overall maximum displacement result in it's time step. The second is the displacement response of time step no. 73. The trim and draft also provide in order to observe the detail condition and the draft which presented below, show the submerged draft after trim, and this is with respect to local body coordinate.

The first result, based on comprehensive studies as collected in appendix, which present the overall probability maximum tension response are presented as follows :

Table 10 Maximum Tension Result

Result	Cond. 1	Cond. 2	Cond. 3	Cond. 4		Cond. 5		Cond. 6		Condition 7		
	Line 1	Line 2	Line 3	Line 1	Line 3	Line 1	Line 2	Line 2	Line 3	Line 1	Line 2	Line 3
Loadcase	3	1	1	3	8	2	2	3	6	3	3	9
Max. Tens.	6,074.6	8,341.5	13,875.9	5,199.9	3,986.3	12,404.9	4,445.6	7,030.8	3,093.7	5,055.0	889.2	3,337.9
Trim	74.4	82.3	87.5	41.6	11.3	58.3	-2.7	9.1	32.3	27.1	41.0	14.7
Draft	12.0	12.0	4.3	12.0	10.6	12.0	3.4	12.0	12.0	12.0	8.6	12.0
Time Step	30	83	44	19	39	64	80	73	86	18	17	9

From the above result, it can be observed that the maximum tension probability is found at condition 3 with loadcase 1. In this case, the tension mostly caused by the huge trim of the cylindrical structure which the stability is in unstable position not because of the pulling mooring line which caused by the large displacement.

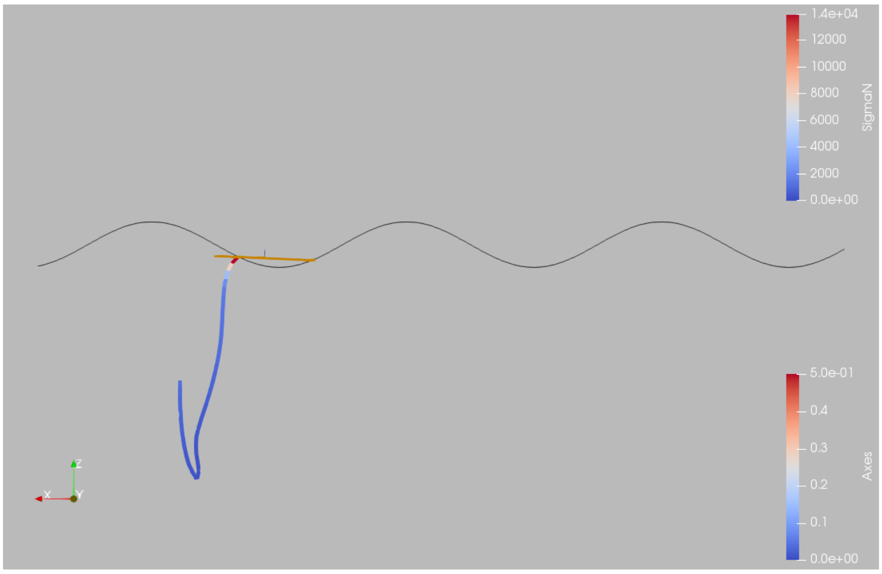


Figure 24 Maximum tension of mooring linenat condition 3

The second results will show the probability mooring line tension response of body structure at time step no. 73, this kind of result is presented in order to observe the relation between the mooring line tension response of each mooring condition at each loadcase. The second result is presented as follows :

Table 11 Mooring Line Tension Result of time step 73 of all conditions and loadcases

Loadcases		Cond 1	Cond 2	Cond 3	Cond. 4		Cond. 5		Cond. 6		Cond. 7		
		Line 1	Line 2	Line 3	Line 1	Line 3	Line 1	Line 2	Line 2	Line 3	Line 1	Line 2	Line 3
Load case 1	Tension	3,035.8	1,948.2	5,075.6	2,765.2	2,010.0	629.6	187.5	3,939.6	1,885.6	3,174.0	643.7	2,185.8
	Trim	60.7	69.7	104.4	1.4	1.4	-8.3	-8.3	-10.6	-10.6	0.4	0.4	0.4
	Draft	10.7	6.7	7.2	12.0	12.0	8.5	8.5	12.0	12.0	12.0	12.0	12.0
Load case 2	Tension	2,930.2	1,146.4	3,087.8	2,798.6	1,963.2	739.8	69.2	5,328.9	1,146.8	3,113.1	633.4	2,173.9
	Trim	56.2	79.6	104.6	42.2	42.2	6.0	6.0	-5.0	-5.0	0.7	0.7	0.7
	Draft	10.5	6.4	4.4	8.5	8.5	7.9	7.9	11.2	11.2	12.0	12.0	12.0
Load case 3	Tension	2,913.7	656.9	1,175.3	2,677.2	2,114.4	728.5	115.4	7,030.8	617.6	3,103.1	628.9	3,096.1
	Trim	57.4	43.4	100.9	48.9	48.9	20.6	20.6	9.1	9.1	0.8	0.8	0.8
	Draft	11.0	5.6	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Load case 4	Tension	2,652.4	2,149.5	444.6	2,502.8	2,015.8	1,086.0	552.7	3,337.1	1,845.6	2,737.3	540.5	2,066.9
	Trim	60.9	80.6	103.8	26.2	26.2	-12.6	-12.6	-18.8	-18.8	1.7	1.7	1.7
	Draft	8.6	8.6	9.1	6.8	6.8	12.0	12.0	9.4	9.4	12.0	12.0	12.0
Load case 5	Tension	2,712.9	965.5	207.7	2,567.0	2,066.5	1,996.7	471.4	3,904.2	1,179.9	2,519.7	492.5	1,966.7
	Trim	53.0	89.4	105.5	42.1	42.1	49.1	49.1	-15.8	-15.8	9.9	9.9	9.9
	Draft	3.9	8.2	12.0	11.9	11.9	12.0	12.0	8.6	8.6	12.0	12.0	12.0
Load case 6	Tension	2,859.1	610.6	173.1	2,621.7	2,121.6	2,441.8	850.1	4,376.8	650.2	2,260.6	429.1	1,920.0
	Trim	36.6	92.8	104.7	49.1	49.1	65.8	65.8	18.3	18.3	22.9	22.9	22.9
	Draft	6.7	12.0	12.0	11.5	11.5	12.0	12.0	6.5	6.5	12.0	12.0	12.0
Load case 7	Tension	2,037.7	2,560.0	1,413.0	2,768.1	2,830.1	1,764.0	417.8	3,388.5	1,553.2	2,869.9	705.7	2,912.9
	Trim	79.1	31.3	74.8	17.2	17.2	44.6	44.6	-3.8	-3.8	13.6	13.6	13.6
	Draft	12.0	8.7	9.2	10.5	10.5	12.0	12.0	12.0	12.0	11.9	11.9	11.9
Load case 8	Tension	2,432.0	2,216.7	1,358.5	2,679.7	2,824.1	1,460.8	260.7	2,483.7	2,389.8	2,831.6	709.2	3,032.2
	Trim	79.5	32.6	68.9	21.8	21.8	14.7	14.7	26.1	26.1	17.4	17.4	17.4
	Draft	12.0	8.7	8.5	11.2	11.2	12.0	12.0	9.3	9.3	12.0	12.0	12.0
Load case 9	Tension	2,490.3	1,963.6	1,437.5	2,605.0	2,837.7	1,328.6	224.2	1,987.1	2,565.3	2,819.2	709.6	3,100.5
	Trim	82.0	32.7	63.0	23.5	23.5	11.5	11.5	43.4	43.4	18.9	18.9	18.9
	Draft	12.0	8.7	3.7	11.7	11.7	12.0	12.0	7.8	7.8	12.0	12.0	12.0

With the incoming wave from the right side at x axis, the floating structure with 1 mooring line condition, the mooring line 1 which anchored at the right side of structure as presented in figure 17 at condition 1, mostly experience the highest tension among the other single line configuration. This is due to the incoming wave here bring the structure more to the left side. For 2 mooring line configuration, since the incoming wave come from right side, for condition 5, the highest tension is experienced by line 1. While for condition

6, the highest tension is experienced by line 2 at all loadcases. For condition 4 with 2 line configuration at both side right and left is compared with condition 7 with the same configuration and 1 additional mooring line exactly under the floating structure. The highest tension is experienced by line 1 for both condition, but only for loadcase 1 to 6 with period 5 s and 10 s. While for loadcase 7 to 9 with higher period 15 s, the highest tension is experienced by line 3. This is because the loadcase with small period, bring the structure mostly going to the right side, while with large period, bring the structure mostly going to the left side because the process become slower. However, the highest tension at line 1 in condition 7 is higher than in condition 4. This is because line 1 should taking into account the appearance of line 2 at condition 7, which bring the effect of it's weight, where the line 2 here is in slackening position also. Taking such a sample result from condition 4 and 7 ay laodcase 7, 8 and 9 also show that the decreasing trim of line 1 yield to the increasing tension of line 1. The detail result shown in appendix A.

6.3. Results and Comparison of Stability

The results for mooring line stability response comparison result are presented as the stability response of time step no. 73, which is choosen randomly. All results are presented in the same time step in order to present the relation between the stability response at each condition and loadcase at same time step. Fg is gravity force and Fb is buoyancy force. The stability results at below table provide the buoyancy and gravity force in order to present the comparison study of the trim angle response of structure at each condition and loadcase. The drafts in table below are presented as the draft before trim response of cylinder structure.

Table 12 Stability Result of time step 73 of all conditions and Loadcases

Loadcases		Cond. 1	Cond. 2	Cond. 3	Cond. 4	Cond. 5	Cond. 6	Cond. 7
Load Case 1	Trim (deg)	60.7	69.7	104.4	1.4	-8.3	-10.6	0.4
	Draft (m)	5.9	4.8	1.6	9.1	4.3	12.7	10.7
	Fg	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0
	Fb	3,372.4	2,735.6	896.1	5,237.4	2,499.3	7,327.4	6,177.0
Load Case 2	Trim (deg)	56.2	79.6	104.6	42.2	6.0	-5.0	0.7
	Draft (m)	7.4	4.4	1.2	4.7	4.0	13.0	10.6
	Fg	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0
	Fb	4,251.2	2,547.0	716.4	2,703.5	2,276.0	7,481.6	6,112.9
Load Case 3	Trim (deg)	57.4	43.4	100.9	48.9	20.6	9.1	0.8
	Draft (m)	8.7	3.5	1.3	7.3	3.7	14.1	13.1
	Fg	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0
	Fb	4,982.1	2,026.6	726.1	4,191.1	2,156.4	8,098.6	7,556.2
Load Case 4	Trim (deg)	60.9	80.6	103.8	26.2	-12.6	-18.8	1.7
	Draft (m)	0.7	5.2	2.0	8.8	5.1	12.8	9.7
	Fg	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0
	Fb	416.7	2,999.5	1,161.2	5,091.3	2,941.5	7,378.8	5,609.1
Load Case 5	Trim (deg)	53.0	89.4	105.5	42.1	49.1	-15.8	9.9
	Draft (m)	0.7	4.7	2.7	8.7	5.9	11.7	9.9
	Fg	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0
	Fb	430.6	2,698.2	1,531.1	5,008.8	3,383.9	6,715.6	5,678.8
Load Case 6	Trim (deg)	36.6	92.8	104.7	49.1	65.8	18.3	22.9
	Draft (m)	1.4	4.1	2.9	8.6	5.3	11.5	9.7
	Fg	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0
	Fb	811.4	2,344.6	1,669.9	4,950.1	3,068.7	6,618.1	5,603.9
Load Case 7	Trim (deg)	79.1	31.3	74.8	17.2	44.6	-3.8	13.6
	Draft (m)	1.2	7.0	2.3	10.1	8.1	10.8	11.9
	Fg	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0
	Fb	688.4	4,051.8	1,325.9	5,818.7	4,634.0	6,226.9	6,875.4
Load Case 8	Trim (deg)	79.5	32.6	68.9	21.8	14.7	26.1	17.4
	Draft (m)	0.3	6.8	4.3	10.8	7.9	9.2	12.6
	Fg	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0
	Fb	189.2	3,908.9	2,487.8	6,210.6	4,522.5	5,302.3	7,267.7
Load Case 9	Trim (deg)	82.0	32.7	63.0	23.5	11.5	43.4	18.9
	Draft (m)	0.2	7.0	5.8	11.2	8.0	8.2	12.7
	Fg	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0	1,962.0
	Fb	97.4	4,019.8	3,335.5	6,427.5	4,585.8	4,696.9	7,325.3

Theoretically, it is assumed that the structure is in stable condition if the buoyancy force equal to the gravity force, the buoyancy center gravity should above the gravity force also. From the stability result above, it is observed that when buoyancy force less than gravity force, the increasing buoyancy force yield to smaller trim at the same draft. While when the buoyancy force more than gravity force, the increasing buoyancy force yield to bigger trim at the same draft. These phenomenon happen because the buoyancy force try to achieve the same value of gravity force to get a stable condition by the trim of the floating body it self.

For the condition with 1 mooring line, such condition 1 ,2 and 3, the condition 3 at period 5 s and 10 s, show the unstable result, therefore it yield to largest trim among the other condition. While the condition 3 at loadcases with period 15 s, the conditions is more stable and at these period, condition 2 show the smallest trim. For condition 4 with 2 mooring line at both side compare with condition 7 with the same condition and additional mooring line at the center, the larger draft of condition 7, yield to smaller trim angle than condition 4.

7. CONCLUSION AND FURTHER STUDIES

7.1. Conclusions

The hydrodynamic interaction effect and dynamic response are the major consideration in the design of floating structures. The hydrodynamic load calculation is necessary to be obtained in order to analyze the response. A set of morison hydrodynamic algorithm is used and presented by Matlab program, the morison hydrodynamic computation method is selected because of the shape of floating structure considered as slender transparant structure. The set of algorithm in Matlab is to test the plausibility of the developed algorithm and to be used as reference documentation for deeper understanding for author and other researcher also.

A sample model of cylinder transparent structure and wave loadcases are designed in order to satisfy the region VI of diagram chakrabarti. This model is used in order to execute the comparative study of floating structure response induced by horizontal airy wave using hydrodynamic morison method.

From the comparative study of the response result, it can be assumed that, in the same period with variation of wave amplitude loadcases, the increasing amplitude will increase the displacement response. For the same wave amplitude with variation of period, the increasing period will decrease the displacement response of cylinder floating structure. Regarding the mooring line tension, the line tension 1 increase when the trim and draft before trim of strucure decrease, and the largest tension will be observed at the mooring line which anchored at same direction with the incoming wave. Regarding the stability, when buoyancy force less than gravity force, the increasing buoyancy force yield to smaller trim at the same draft. While when the buoyancy force more than gravity force, the increasing buoyancy force yield to bigger trim at the same draft. These phenomenon happen because the buoyancy force try to achieve the equal value of gravity force to get a stable condition by the trim of the floating body it self. For condition 4 with 2 mooring line at both side compare with condition 7 with the same condition and additional mooring line at the center, the larger draft of condition 7, yield to smaller trim angle than condition 4. Means that, the addtional mooring line at center and exactly positioned under the structure, will yield to more stable effect for the floating cylindrical structure.

7.2. Further Studies

Further studies are needed to study the response of cylinder floating structure as follows :

- Comparison of motion response result using more than one program as evaluation
- Study the used of morison equation in large floating structure hydroynamic load calculation and also by using fast fourier transform in order to combine the hydrodynamic load equation in frequency domain.

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APPENDIXES A. THE MOORING DISPLACEMENT AND TENSION RESPONSE RESULT

Loadcases		Condition 1				Condition 2				Condition 3			
		max. X (+)	max. X (-)	max. Y (+)	max. Y (-)	max. X (+)	max. X (-)	max. Y (+)	max. Y (-)	max. X (+)	max. X (-)	max. Y (+)	max. Y (-)
Loadcase 1	**Displ.**	25.2	-1.0	2.1	-2.7	2.3	-1.0	0.0	-2.8	-0.6	-33.5	2.8	-2.6
	Trim	52.6	0.0	37.5	86.4	77.8	8.8	8.8	83.2	67.5	61.9	27.0	89.2
	Draft	12.0	12.0	9.0	5.1	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	100	0	56	51	8	2	2	35	5	98	41	66
Loadcase 2	**Displ.**	28.5	-1.0	1.6	-3.5	3.1	-1.0	0.0	-3.3	-0.1	-33.0	2.6	-3.4
	Trim	49.2	0.0	35.7	89.6	84.0	4.9	9.1	69.9	70.2	59.6	16.6	88.0
	Draft	12.0	12.0	7.8	5.3	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	100	0	56	41	7	1	2	64	5	79	51	85
Loadcase 3	**Displ.**	29.9	-1.0	1.3	-3.9	3.5	-1.0	0.0	-3.6	0.2	-33.5	1.0	-3.9
	Trim	78.8	0.0	35.0	89.0	83.5	5.3	9.8	69.4	71.1	69.6	38.7	88.3
	Draft	12.0	12.0	7.7	8.2	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	94	0	56	42	7	1	2	74	5	68	37	85
Loadcase 4	**Displ.**	15.0	-1.0	1.5	-2.4	2.3	-3.4	0.0	-2.9	-1.0	-37.4	0.8	-2.5
	Trim	85.8	0.0	51.1	88.6	69.2	13.2	5.7	85.8	0.0	53.8	68.1	89.1
	Draft	9.5	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	83	0	99	9	39	24	1	11	0	86	49	24
Loadcase 5	**Displ.**	16.2	-1.0	1.6	-3.4	2.6	-3.4	0.0	-3.2	-1.0	-37.8	4.3	-3.8
	Trim	84.7	0.0	39.3	88.3	72.8	35.3	0.0	89.1	0.0	45.4	74.4	56.9
	Draft	7.8	12.0	12.0	7.7	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	62	0	77	67	95	86	0	11	0	86	45	34
Loadcase 6	**Displ.**	16.9	-1.0	1.9	-4.0	3.1	-3.5	0.0	-3.5	-1.0	-37.9	4.0	-3.9
	Trim	81.5	0.0	32.7	84.1	88.8	11.0	0.0	66.2	0.0	41.5	48.1	63.2
	Draft	2.4	12.0	12.0	6.9	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	42	0	74	67	95	86	0	94	0	86	47	25
Loadcase 7	**Displ.**	14.7	-1.0	1.5	-2.5	2.4	-3.4	0.0	-2.8	-1.0	-38.9	3.0	-2.5
	Trim	89.6	0.0	53.5	89.7	64.6	20.9	0.0	86.0	0.0	61.1	63.3	63.1
	Draft	9.8	12.0	12.0	8.7	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	93	0	85	71	58	98	0	16	0	97	34	96
Loadcase 8	**Displ.**	17.3	-1.0	2.0	-3.4	2.7	-3.5	0.0	-3.2	-1.0	-38.8	2.5	-3.3
	Trim	66.8	0.0	52.1	87.9	89.9	21.8	0.0	89.5	0.0	53.1	87.6	89.3
	Draft	6.4	12.0	10.8	5.3	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	76	0	78	66	78	66	0	15	0	97	23	34
Loadcase 9	**Displ.**	25.7	-1.0	4.0	-3.9	3.2	-3.4	0.0	-3.6	-1.0	-38.7	2.0	-3.9
	Trim	82.4	0.0	87.4	84.4	88.6	20.6	0.0	88.6	0.0	48.9	79.7	88.1
	Draft	6.8	12.0	3.5	9.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	91	0	83	66	15	66	0	24	0	97	23	35

Loadcases		Condition 4				Condition 5				Condition 6			
		max. X (+)	max. X (-)	max. Y (+)	max. Y (-)	max. X (+)	max. X (-)	max. Y (+)	max. Y (-)	max. X (+)	max. X (-)	max. Y (+)	max. Y (-)
Loadcase 1	**Displ.**	0.4	-2.6	0.0	-5.6	5.6	-1.0	0.0	-4.3	-1.0	-11.4	0.0	-5.0
	Trim	28.6	-16.2	0.0	-8.3	46.8	0.0	0.0	-47.7	0.0	-11.1	0.0	20.4
	Draft	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	6	77	0	30	9	0	0	57	0	54	0	22
Loadcase 2	**Displ.**	1.7	-1.1	0.0	-4.7	6.3	-1.0	0.0	-3.4	-0.6	-12.7	0.0	-5.5
	Trim	63.6	3.8	0.0	55.1	51.5	0.0	0.0	40.1	59.8	-20.1	0.0	-20
	Draft	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	74	11	0	7	67	0	0	17	5	34	0	34
Loadcase 3	**Displ.**	1.7	-1.1	0.0	-4.7	6.5	-1.0	0.0	-3.8	-0.3	-11.4	0.0	-5.3
	Trim	67.9	7.9	0.0	61.5	45.2	0.0	0.0	49.7	63.1	-10.5	0.0	31.7
	Draft	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	74	11	0	7	29	0	0	17	5	54	0	89
Loadcase 4	**Displ.**	1.2	-2.6	0.0	-6.1	7.3	-1.0	0.0	-4.8	-1.0	-12.8	0.0	-5.7
	Trim	44.7	-6.2	0.0	-6.2	48.8	0.0	0.0	-51.8	0.0	-19.6	0.0	-19
	Draft	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	34	20	0	20	61	0	0	37	0	31	0	31
Loadcase 5	**Displ.**	1.8	-2.4	0.0	-5.8	7.7	-1.0	0.0	-4.2	-1.0	-10.6	0.0	-5.8
	Trim	62.1	-3.9	0.0	40.6	60.0	0.0	0.0	59.3	0.0	-12.8	0.0	34.1
	Draft	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	33	21	0	14	82	0	0	53	0	34	0	64
Loadcase 6	**Displ.**	1.9	-2.2	0.0	-6.1	8.0	-1.0	0.0	-4.5	-1.0	-10.9	0.0	-6.4
	Trim	64.1	-5.9	0.0	48.2	63.9	0.0	0.0	59.3	0.0	-16.0	0.0	0.0
	Draft	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	95	21	0	14	82	0	0	74	0	96	0	0
Loadcase 7	**Displ.**	0.7	-2.9	0.0	-6.6	7.8	-1.0	0.0	-3.7	-1.0	-12.6	0.0	-5.4
	Trim	32.6	-11.3	0.0	- 11.2	48.6	0.0	0.0	60.8	0.0	-20.2	0.0	- 20.2
	Draft	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	47	28	0	29	91	0	0	46	0	47	0	47
Loadcase 8	**Displ.**	1.4	-2.9	0.0	-6.9	8.3	-1.0	0.0	-4.4	-1.0	-13.2	0.0	-6.3
	Trim	49.7	-8.2	0.0	-8.3	59.0	0.0	0.0	65.6	0.0	-21.7	0.0	-21
	Draft	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	79	28	0	30	92	0	0	46	0	46	0	46
Loadcase 9	**Displ.**	1.7	-2.8	0.0	-7.0	8.5	-1.0	0.0	-4.8	-1.0	-12.6	0.0	-6.3
	Trim	57.6	-7.8	0.0	-7.4	64.3	0.0	0.0	68.5	0.0	-20.3	0.0	28.4
	Draft	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
	Time Step	79	29	0	30	92	0	0	46	0	47	0	34

Loadcases		Condition 7			
		max. X (+)	max. X (-)	max. Y (+)	max. Y (-)
Loadcase 1	**Displ.**	0.2	-2.7	0.0	-6.6
	Trim	26.0	-12.5	0.0	-2.3
	Draft	12.0	12.0	12.0	12.0
	Time Step	6	28	0	21
Loadcase 2	**Displ.**	1.2	-2.8	0.0	-7.1
	Trim	51.6	-13.6	0.0	-0.3
	Draft	12.0	12.0	12.0	12.0
	Time Step	7	38	0	31
Loadcase 3	**Displ.**	1.6	-2.9	0.0	-7.3
	Trim	59.0	-15.5	0.0	0.9
	Draft	12.0	12.0	12.0	12.0
	Time Step	6	96	0	41
Loadcase 4	**Displ.**	-0.2	-2.7	0.0	-7.7
	Trim	15.6	-11.7	0.0	-9.5
	Draft	12.0	12.0	12.0	12.0
	Time Step	9	18	0	20
Loadcase 5	**Displ.**	0.3	-2.8	0.0	-8.2
	Trim	24.7	-5.6	0.0	-8.4
	Draft	12.0	12.0	12.0	12.0
	Time Step	10	20	0	83
Loadcase 6	**Displ.**	0.7	-2.7	0.0	-7.4
	Trim	36.7	-4.4	0.0	-3.7
	Draft	12.0	12.0	12.0	12.0
	Time Step	12	20	0	21
Loadcase 7	**Displ.**	0.2	-3.3	0.0	-7.7
	Trim	20.7	-17.2	0.0	-13
	Draft	12.0	12.0	12.0	12.0
	Time Step	77	25	0	60
Loadcase 8	**Displ.**	0.7	-3.3	0.0	-8.4
	Trim	30.7	-14.1	0.0	-12
	Draft	12.0	12.0	12.0	12.0
	Time Step	78	26	0	29
Loadcase 9	**Displ.**	0.9	-3.2	0.0	-8.7
	Trim	37.3	-12.1	0.0	-11
	Draft	12.0	12.0	12.0	12.0
	Time Step	79	27	0	29

Loadcases		Cond. 1	Cond. 2	Cond. 3	Cond. 4		Cond. 5		Cond. 6		Cond. 7		
		Line 1	Line 2	Line 3	Line 1	Line 3	Line 1	Line 2	Line 2	Line 3	Line 1	Line 2	Line 3
Load Case 1	**Max.Tens**	4,120.0	8,341.5	13,875.9	4,513.7	3,895.5	3,497.5	2,098.6	5,566.7	2,792.5	3,847.6	817.5	3,193.5
	Trim	85.3	82.3	87.5	27.9	3.3	32.9	-3.4	-1.6	20.4	26.6	2.0	3.1
	Draft	12.0	12.0	4.3	10.2	8.7	10.7	6.0	12.0	12.0	8.5	5.6	12.0
	Time Stp	33	83	44	8	12	10	22	24	22	7	2	13
Load Case 2	**Max.Tens**	4,491.7	5,501.1	4,237.8	5,199.9	3,924.1	12,404.9	4,445.6	6,596.8	2,933.0	4,886.8	843.0	3,268.4
	Trim	56.2	81.1	79.7	33.1	32.6	58.3	-2.7	1.2	24.9	26.9	26.9	3.5
	Draft	12.0	12.0	12.0	12.0	7.8	12.0	3.4	12.0	12.0	12.0	8.5	12.0
	Time Stp	88	87	22	19	9	64	80	92	60	9	9	22
Load Case 3	**Max.Tens**	6,074.6	5,546.6	5,176.8	5,199.9	3,924.1	4,417.7	2,620.6	7,030.8	3,030.6	5,055.0	889.2	3,280.0
	Trim	74.4	55.4	64.0	41.6	43.0	14.9	45.2	9.1	38.3	27.1	41.0	5.2
	Draft	12.0	12.0	12.0	12.0	7.5	11.6	3.3	12.0	12.0	12.0	8.6	12.0
	Time Stp	30	50	21	19	9	20	29	73	40	18	17	32
Load Case 4	**Max.Tens**	3,118.3	5,161.1	3,227.2	4,363.1	3,895.1	2,943.5	2,453.1	4,125.9	2,556.4	3,832.3	816.4	3,039.0
	Trim	51.6	49.5	82.5	-5.0	-6.2	-7.0	49.6	-8.9	23.1	-9.5	0.3	2.2
	Draft	10.9	12.0	6.8	12.0	11.3	10.6	4.4	10.9	12.0	11.9	11.5	12.0
	Time Stp	15	20	16	22	20	45	99	92	87	20	26	27
Load Case 5	**Max.Tens**	3,741.0	6,893.4	3,788.4	4,256.0	3,917.6	2,937.8	2,718.8	5,334.2	3,028.6	4,025.6	827.7	3,130.0
	Trim	42.6	64.1	44.1	-2.2	7.8	47.9	45.3	-1.1	13.7	-4.9	3.1	10.1
	Draft	12.0	12.0	12.0	12.0	8.6	12.0	4.5	11.7	12.0	12.0	11.1	12.0
	Time Stp	15	20	68	22	26	99	85	30	24	21	26	28
Load Case 6	**Max.Tens**	4,312.4	6,978.8	4,233.5	4,525.6	3,967.2	3,091.3	2,711.7	5,957.3	3,093.7	3,952.0	833.8	3,189.3
	Trim	48.2	14.6	76.1	23.1	14.9	47.7	53.3	-2.5	32.3	-2.2	4.8	14.8
	Draft	4.7	12.0	6.8	10.4	8.0	10.6	4.8	12.0	12.0	12.0	10.6	12.0
	Time Stp	93	83	16	39	27	23	79	51	86	43	26	70
Load Case 7	**Max.Tens**	2,752.2	5,084.9	3,839.8	4,281.8	3,888.6	2,871.5	2,505.7	3,779.1	2,457.2	4,007.0	824.8	3,272.1
	Trim	49.2	53.0	80.6	-8.2	3.7	16.1	46.7	-7.8	38.0	-10.7	3.6	9.8
	Draft	9.7	12.0	12.0	11.6	10.9	10.4	6.4	12.0	7.2	11.8	12.0	12.0
	Time Stp	20	91	19	32	69	32	85	53	9	93	70	9
Load Case 8	**Max.Tens**	4,291.9	7,494.5	3,972.9	4,455.1	3,986.3	2,994.4	2,751.8	3,931.0	2,848.0	4,100.6	823.3	3,325.9
	Trim	56.0	57.1	78.9	-6.2	11.3	31.3	46.4	55.5	26.5	-9.9	1.0	13.2
	Draft	11.0	12.0	12.0	11.6	10.6	10.6	6.9	9.2	12.0	11.8	12.0	12.0
	Time Stp	77	91	20	63	39	65	83	21	69	61	37	9
Load Case 9	**Max.Tens**	4,301.8	3,907.1	4,210.9	4,495.7	3,959.8	2,983.7	2,650.1	4,249.5	3,078.9	4,161.6	824.3	3,337.9
	Trim	75.1	59.1	44.8	-5.3	12.4	43.4	45.6	59.5	31.0	-8.8	1.9	14.7
	Draft	12.0	12.0	12.0	11.6	10.7	10.6	7.0	8.4	12.0	11.7	12.0	12.0
	Time Stp	81	91	70	63	39	97	52	23	67	61	37	9

APPENDIXES B. MATLAB CODES OF MORISON HYDRODYNAMIC LOAD ALGORITHM FOR CYLINDER FLOATING STRUCTURE

ABREVIATIATIONS

xyzKar = xyz-Kardan angles

T = Transformation Matrix

N = amount of time variant

rMaLoc = positions of markers on body

ampli = amplitude

rRef = Position of body Ref. Global sys.

vRef = Velocity of the body

Ut4D = wave velocity at XYZ global axis

omRef = Angular velocity of the body

dUt4D = wave acceleration at XYZ global axis

nMarkers = Number of markers

u_rel4D = relative velocity at XYZ global axis

r_CSYS_0 = Global Positions of markers

dUt_totx2D = final acc. wrto wave elev at X local axis

v_CSYS_0 = Global velocity of markers

u_totx2D = final vel. wrto wave elev at X local axis

k = wave elevation

u_totz2D = final vel. wrto wave elev at Z local axis

z_eta2D = Marker points in z axis wrto Wave elevation

eta2D = wave elevation for each marker point

Id = Identity to filter all results wrto wave elevation

Re_U = Reynold Number to obtain added mass and drag coefficient in horizontal dir.

Kc_U = Keulegan Number to obtain added mass and drag coefficient in horizontal dir.

Cm_U = Added Mass Coefficient

Cd_U = Drag Coefficient

Fmor = Morison Force of nMarkers at X and time variant

Fmorx_t = Morison Force-x Total of at X and time variant

Fmorz_t = Morison Force-z Total of at X and time variant

Fb2D = Bouyancy Force Total of at X and time variant

Ftx2D = Total Force-x of at X and time variant

Ftz2D = Total Force-x of at X and time variant

Ftx3D = Total Force of nMarkers at X and time variant

Ftz3D = Total Force of nMarkers at X and time variant

MAIN CALCULATION

```
% Step1.Calculate transformation matrix
xyzKar    = [0, 0, 0];                      % input XYZ-Kardan angles
[T] = F1_calcTransMatXYZKar(xyzKar);
% Step2.Calc. Marker Position and velocity new projection at global coord.
lCylinder = 12;                              % input Length of cylinder
nMarkers  = 11;                             % input Number of markers on
cylinder start from the top of cylinder to bottom in z
vRef = [1 ;0; 0];                           % input a given sample value
velocity of body
rRef = [0 ;0; 0];                           % input Global coordinates of
body reference system
omRef = [0; 0; 0];                          % input Angular velocity of the
body
% Step3. calculate wave elevation
phi = 3.14;
period = 5;%2;4                             %input period
lambda = 30;%1;24.67                      %input lambda
ampli = 2.7;%2;10                            %input wave amplitude
depth = 16;%50;10                           %input depth of sea
omega = 2*pi/period;                        %input omega formulation
k = 2*pi/lambda;                            %input wave number (k)
formulation
nstep = 30;                                     %input value of (x) and (t)
limit quantity
tmax = 25;                                  %input value of (t) maximum
tmin = 0;                                   %input value of (t) maximum
t = linspace(tmin,tmax,nstep);
% Step7.Added Mass Coefficient
nu = 1e-6;                                          %input kinematic
viscosity
DCylinder = 2.7;                                      %input cylinder
diameter
% Step8.Calculate Morison forces acting on cylinder segments/markers
rho = 1025;%input
DCylinder = 2.7;                                      %input value of
cylinder diameter

%%%%%%%%%%%%%%%%%%%%   HYDRODYNAMIC LOAD ALGORITHM STEPS   %%%%%%%%%%%%%%%%

% Step2.Calc. Marker Position and velocity new projection at global coord.
% ==(Function.2)
rMaLoc = [   zeros(1,nMarkers); zeros(1,nMarkers); ...
             linspace(lCylinder/2, -lCylinder/2, nMarkers) ];%input
```

```
[r_CSYS_0,v_CSYS_0] = F2_calcMarkerPositionsAndVelocity(rRef, rMaLoc,
T,vRef,omRef,nMarkers);%function.eq.

% Inputs

% Step3. calculate wave elevation
% ==(no function)
z = r_CSYS_0(3,:);                          %all z coord. marker point at
global system
x = r_CSYS_0(1,:)

for istep=1:nstep
    for i=1:nMarkers
        eta2d(i,istep) = ampli.*cos((k.*x(i))-(omega.*t(istep)));
    end
end
eta_1 = reshape(eta2d,[nMarkers*nstep,1]);%step1
z_1 = repmat(z',[nstep,1]);%step2
z_1(z_1>eta_1) = NaN;%step3
eta_2 = reshape(z_1,[nMarkers,nstep]);%step4
eta_3 = max(eta_2);%step5
eta = eta_3';%step6

% create 'Id' for filtering results process wrto wave elevation
eta_add=[100;eta];

for istep=1:nstep
    for i=1:nMarkers
        for it=1:(nstep+1)
            z_add0=repmat(z,[it,1]);
            z_add(it,i) = z_add0(it,i);
            Id(it,:)=z_add(1,i) > eta_add(it,1);
            z_add(Id,i) = NaN;
        end
    end
end

% Step4. Flow Velocities and Acceleration
% ==(Function.3)
[u,amp]=F3_calcFlowVelocities(ampli,omega,k,depth,t,nMarkers,r_CSYS_0,nstep)

% Step5.Calculate relative flow velocities
% ==(Function.4)
[u_rel] = F4_calcRelativeFlowVelocities(v_CSYS_0,nMarkers,u,nstep)

% Step6.Flow Acc. and Relative Vel. and Transformation to Body Coordinate
wrto wave elevation
% ==(Function.5)
[u_totx,u_totz]=F5_calcVelAndAccTransWrtoWaveElev(nMarkers,nstep,u_rel,z_add,
eta_add)

z_add(1,:) = [];
eta_add(1,:) = [];


% Step7.Added Mass Coefficient
%==(no function)
Re_U1 = amp(1,1:nMarkers).*(DCylinder/nu);                    %calcuate (Re)
based on hor.vel. amplitude
```

```
Kc_U1 = amp(1,1:nMarkers).*(period/DCylinder);              %calcuate (Kc)
based on hor.vel. amplitude
Re_U = max(Re_U1);
Kc_U = max(Kc_U1);
%Aproach by Clauss
if (Re_U>=100000)||(Kc_U<10)
        Cm_U = 2.0;
        Cd_U = 0.6;
elseif (Re_U>=100000)||(Kc_U>=10)
        Cm_U = 1.5;
        Cd_U = 0.6;
elseif (Re_U<100000)||(Kc_U<10)
        Cm_U = 2.0;
        Cd_U = 1.2;
elseif (Re_U<100000)||(Kc_U>=10)
        Cm_U = 1.5;
        Cd_U = 1.2;
end

% Step8.Calculate Morison forces acting on cylinder segments/markers
%==(Function.6)
dz = diff(r_CSYS_0 (3,(1:2)));                          %input differences for
each point of Markers at submerged body at z axis

[Fmorx_t,Fmorz_t,Fmor_nx,Fmor_nz] =
F6_calcMorisonEquationForce(nMarkers,rho,DCylinder,dz,u_totx,u_totz,Cd_U,nste
p);

% Plotting result
figure(1)
plot(t,Fmorx_t)
legend('Ftotal-x')
xlabel('time (s)');
ylabel('Total Force (kN)');
xlim([0 10])
title('Morison Total Force(Fmorison Total)');

figure(2)
plot(t,Fmor_nx(:,1),t,Fmor_nx(:,2),t,Fmor_nx(:,3),t,Fmor_nx(:,4),t,Fmor_nx(:,
5),t,Fmor_nx(:,6),t,Fmor_nx(:,7),t,Fmor_nx(:,8),t,Fmor_nx(:,9),t,Fmor_nx(:,10
),t,Fmor_nx(:,11))
legend('Fmarker-1','Fmarker-2','Fmarker-3','Fmarker-4','Fmarker-5','Fmarker-
6','Fmarker-7','Fmarker-8','Fmarker-9','Fmarker-10','Fmarker-11')
xlabel('time (s)');
ylabel('nMarkers Force (kN)');
xlim([0 10])
title('Morison Force(Fmorison nMarkers)');
```

F1 TRANSFORMATION MATRIX ALGORITHM

```
function [T] = F1_calcTransMatXYZKar(xyzKar)
% Inputs
% xyzKar: (3) vector containing the alpha, beta and gamma xyz-Kardan angles
%
% Outputs
% T: (3x3) Transformation matrix

    %inputs
    al = xyzKar(1);
```

```
    be = xyzKar(2);
    ga = xyzKar(3);
    %Outputs
    T = [   cos(be)*cos(ga)  , cos(be)*sin(ga)  , sin(be); ...
            cos(al)*sin(ga)  + sin(al)*sin(be)*cos(ga), ...
            cos(al)*cos(ga)  - sin(al)*sin(be)*sin(ga), ...
            -sin(al)*cos(be); ...
            sin(al)*sin(ga)  - cos(al)*sin(be)*cos(ga), ...
            sin(al)*cos(ga)  + cos(al)*sin(be)*sin(ga), ...
            cos(al)*cos(be)  ...
        ];

end
 End
```

F2 MARKER POSITION AND VELOCITY ALGORITHM

```
function [r_CSYS_0,v_CSYS_0,dv_CSYS_0] =
F2_calcMarkerPositionsAndVelocity(rRef, rMaLoc,
T,vRef,omRef,nMarkers,omRef2,dvRef,omRef3)
% Inputs
%    rRef        : Position of body reference system with retspect to CSYS_0
%    rMaLoc      : Local positions of markers on body. Dimension (3 x number of
markers)
%    T           : Transformation matrix_type from body to global coordinate
%    vRef        : Velocity of the body (a given sample value here)
%    omRef       : Angular velocity of the body
%    nMarkers    : Number of markers on cylinder
%
% Outputs
%    r_CSYS_0 : Positions of markers with respect to global coordinate system.
%                Dimension (3 x number of markers)
%    v_CSYS_0    : Velocities of markers with respect to global coordinate
system.
%                Dimension (3 x number of markers


    for ix = 1:nMarkers
        r_CSYS_0(:,ix) = rRef + T*rMaLoc(:,ix);
        v_CSYS_0(:,ix) = vRef + cross(omRef,T*rMaLoc(:,ix));

    end
end
```

F3 WAVE FLOW VELOCITIES ALGORITHM

```
function
[u,amp]=F3_calcFlowVelocities(ampli,omega,k,depth,t,nMarkers,r_CSYS_0,nstep)
% Inputs
%    ampli         : Wave Amplitude
%    omega         : Wave angular frequency
%    k             : Wave number
%    z             : z coordinates of nMarkers already wrto wave elevation
%    depth         : distance from water still water level to seabed
%    x             : varian of x value, same ammount with time varian value
%    time          : varian of time value, same ammount with x varian value
%    nMarkers      : input Number of markers on cylinder start from the top of
cylinder to bottom in z
%    N             : input value of (x) and (t) limit quantity
%    r_CSYS_0      : Positions of markers with respect to global coordinate
system.
```

```
%                   Dimension (3 x number of markers)
%
% Outputs
%   amp2D           : Amplitude for flow velocity calc. at (x,y,z) axis, used
%                   also to obtain Coeff. drag & added mass
%   Ut4D            : Wave velocities at (x,y,z) axis in global coordinate
%   dUt4D           : Wave acceleration at (x,y,z) axis in global coordinate

% output :

for i=1:nMarkers
    for istep=1:nstep
        phi(istep) = k*r_CSYS_0(1,i) + omega*t(istep);    % Phase
        sigma = omega;                    % No mean velocity

        amp(1,i) = ampli.*( cosh(k*(r_CSYS_0(1,i)+depth))./sinh(k*depth) );
        amp(3,i) = ampli.*( sinh(k*(r_CSYS_0(3,i)+depth))./sinh(k*depth) );

        u(1,i,istep) = sigma*amp(1,i).*cos(phi(istep));
        u(3,i,istep) = sigma*amp(3,i).*sin(phi(istep));

    end
end

end
```

F4 RELATIVE FLOW VELOCITIES ALGORITHM

```
function [u_rel] = F4_calcRelativeFlowVelocities(v_CSYS_0,nMarkers,u,nstep)
% Inputs
%   v_CSYS_0     : Velocities of markers with respect to global coordinate
system
%                  Dimension (3 x number of markers)
%   nMarkers     : input Number of markers on cylinder start from the top of
cylinder to bottom in z
%   Ut           : Wave velocities at (x,y,z) axis in global coordinate
%   N            : input value of (x) and (t) limit quantity
%
% Outputs
%   u_rel        : Relative Horizontal wave velocities at (x,y,z) axis at
%                  global coordinate (wave velocities - body proj.
%                  velocities)

%Equation

for istep=1:nstep
    for i=1:nMarkers
        u_rel(1,i,istep) = u(1,i,istep) - v_CSYS_0(1,i);
        u_rel(3,i,istep) = u(3,i,istep) - v_CSYS_0(3,i);
    end
end
end
end
```

F5_VELOCITY TRANSFORMATION AND FILTERING WITH RESPECT TO WAVE ELEVATION

```
%
[utot_x2D,utot_z3D,u_totx2D,u_totz2D,Idu,utot_z2D]=F5_calcVelAndAccTransWrtoW
aveElev(nMarkers,nstep,xyzKar,u_rel,z_add,eta_add,omRef,vRef,r_CSYS_0,T)
% Inputs
%   nMarkers    : input Number of markers on cylinder start from the top of
cylinder to bottom in z
%   N           : input value of (x) and (t) limit quantity
%   xyzKar      : (3) vector containing the alpha, beta and gamma xyz-Kardan
angles
%   dUt         : wave acceleration at (x,y,z) axis in global coord.
%   u_rel       : Relative Horizontal wave velocities at (x,y,z) axis
%   z_eta1      : Marker points in z axis, here with additional value at
first
%                 coloumn as one of filtering result process wrto wave
elevation
%   eta1        : wave elevation for each marker point, here with additional
value at first
%                 coloumn as one of filtering result process wrto wave
elevation
%   Tb          : Transformation matrix from global to body coordinate
%
% Outputs
%   u_totx      : Horizontal wave velocities at x axis wrto wave elevation &
in body coord.
%   u_totz      : Vertical wave velocities at z axis wrto wave elevation & in
body coord.
%   dUt_totx    : Horizontal wave accelerations at x axis wrto wave elevation
%                 & in body coord

% output :


utot_x2D = [];
utot_z2D = [];

for istep=1:nstep
    for i=1:nMarkers
        utot_x3D(1,i,istep) = u_rel(1,i,istep);
        utot_z3D(1,i,istep) = u_rel(3,i,istep);

    end
%     %convert from 3D to 2D matrix
      utot_x2D = cat(1,utot_x2D,utot_x3D(:,:,istep));
      utot_z2D = cat(1,utot_z2D,utot_z3D(:,:,istep));
%     %Prepare input for Filtering the result wrto wave elevation
      utot_xadd = [utot_x2D(1,:);utot_x2D];
      utot_zadd = [utot_z2D(1,:);utot_z2D];
        u_totx = [utot_xadd];
        u_totz = [utot_zadd];

    for it=1:(nstep)+1
        for i=1:nMarkers
            %Filtering the process wrto wave elevtion
            Idu(it,:) = z_add(1,i) > eta_add(it,1);
```

```
            u_totx(Idu,i) = NaN;
            u_totz(Idu,i) = NaN;
        end
    end
%     %delete unecessary element (the first row element)
    u_totx(1,:) = [];
    u_totz(1,:) = [];
end
end
```

F6 HYDRODYNAMIC MORISON EQUATION

```
function [Fmorx_t,Fmorz_t,Fmor_nx,Fmor_nz] =
F6_calcMorisonEquationForce(nMarkers,rho,DCylinder,dz,u_totx,u_totz,Cd_U,nste
p)
% Inputs
%   n_eta      : Number of marker point at body wrto wave elevation
%   rho        : sea water density
%   Cm_U       : added mass coeff. wrto wave elevation
%   DCylinder  : diameter cylider
%   dz         : differences for each point of Markers at submerged body at z
axis
%   dUdt       : Horizontal wave accelerations wrto wave elevation
%   Cd_U       : drag coeff. wrto wave elevation
%   u_tot      : horizontal rel.vel.after tranformation to body coord.sys.
%   v_tot      : vertical rel.vel.after tranformation to body coord.sys.
%
% Outputs
%   Fmor       : Hydrodynamic force of Morison equation

Fmorx2D = [];
Fmorz2D = [];
for istep=1:nstep
    for i=1:nMarkers
        dragx(i,istep) =
(0.5*rho*Cd_U*DCylinder*dz).*(abs(u_totx(istep,i))).*(u_totx(istep,i));%===Dr
ag Force horizontal
        dragz(i,istep) =
(0.5*rho*Cd_U*DCylinder*dz).*(abs(u_totz(istep,i))).*(u_totz(istep,i));%===Dr
ag Force vertical
        Fmorx(i,istep) = dragx(i,istep);
        Fmorz(i,istep) = dragz(i,istep);

    end
end
Fmorx(isnan(Fmorx))=0;
Fmorz(isnan(Fmorz))=0;

Fmorx_t=(sum(Fmorx))';% Total force-x (sum) at each X and time variant
Fmorz_t=(sum(Fmorz))';% Total force-z (sum) at each X and time variant

Fmor_nx=Fmorx';
Fmor_nz=Fmorz';
end
```

APPENDIXES C. MATLAB CODES OF MORISON HYDRODYNAMIC LOAD ALGORITHM FOR MOORING LINE

MAIN CALCULATION

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%                 HYDRODYNAMIC LOAD OF STRUCTURES                    %%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%   MAIN INPUT OF ALL DATA   %%%%%%%%%%%%%%%%%%%%%%%%

% Step1.Calculate transformation matrix
xyzKar    = [0, 0, 0];                    % input XYZ-Kardan angles
[T] = F1_calcTransMatXYZKar(xyzKar);
% Step2.Calc. Marker Position and velocity new projection at global coord.
xLine = 10;
zLine = 6.6;
sLine = ((xLine^2)+(zLine^2))^0.5;
nMarkers  = 11;                            % input Number of markers on
cylinder start from the top of cylinder to bottom in z
vRef = [1 ;0; 0];                          % input a given sample value
velocity of body
rRef = [0 ;0; 0];                          % input Global coordinates of
body reference system
dvRef = [1 ;0; 0];
omRef = [0; 0; 0];                         % input Angular velocity of the
body
omRef2 = 2.*omRef;
omRef3 = omRef.*omRef;
% Step3. calculate wave elevation
phi = 3.14;
period = 5;%2;4                            %input period
lambda = 30;%1;24.67                     %input lambda
ampli = 2.7;%2;10                           %input wave amplitude
depth = 16;%50;10                          %input depth of sea
omega = 2*pi/period;                       %input omega formulation
k = 2*pi/lambda;                           %input wave number (k)
formulation
nstep = 30;                                    %input value of (x) and (t)
limit quantity
tmax = 25;                                 %input value of (t) maximum
tmin = 0;                                  %input value of (t) maximum
t = linspace(tmin,tmax,nstep);
% Step7.Added Mass Coefficient
nu = 1e-6;                                         %input kinematic
viscosity
DCylinder = 2.7;                                     %input cylinder
diameter
% Step8.Calculate Morison forces acting on cylinder segments/markers
rho = 1025;%input
DCylinder = 2.7;                                     %input value of
cylinder diameter

%%%%%%%%%%%%%%%%%%%%   HYDRODYNAMIC LOAD ALGORITHM STEPS   %%%%%%%%%%%%%%%%

% Step2.Calc. Marker Position and velocity new projection at global coord.
% ==(Function.2)
rMaLoc = [ linspace(0, xLine, nMarkers); zeros(1,nMarkers); ...
            linspace(0, -zLine, nMarkers) ];%input
```

```
[r_CSYS_0,v_CSYS_0,dv_CSYS_0] = F2_calcMarkerPositionsAndVelocity(rRef,
rMaLoc, T,vRef,omRef,nMarkers,omRef2,dvRef,omRef3)

% Inputs

% Step3. calculate wave elevation
% ==(no function)
z = r_CSYS_0(3,:);                          %all z coord. marker point at
global system
x = r_CSYS_0(1,:)

for istep=1:nstep
    for i=1:nMarkers
        eta2d(i,istep) = ampli.*cos((k.*x(i))-(omega.*t(istep)));
    end
end
eta_1 = reshape(eta2d,[nMarkers*nstep,1]);%step1
z_1 = repmat(z',[nstep,1]);%step2
z_1(z_1>eta_1) = NaN;%step3
eta_2 = reshape(z_1,[nMarkers,nstep]);%step4
eta_3 = max(eta_2);%step5
eta = eta_3';%step6

% create 'Id' for filtering results process wrto wave elevation
eta_add=[100;eta];

for istep=1:nstep
    for i=1:nMarkers
        for it=1:(nstep+1)
            z_add0=repmat(z,[it,1]);
            z_add(it,i) = z_add0(it,i);
            Id(it,:)=z_add(1,i) > eta_add(it,1);
            z_add(Id,i) = NaN;
        end
    end
end

% Step4. Flow Velocities and Acceleration
% ==(Function.3)
[u,du,amp]=F3_calcFlowVelocities(ampli,omega,k,depth,t,nMarkers,r_CSYS_0,iste
p)

% Step5.Calculate relative flow velocities
% ==(Function.4)
[u_rel,du_rel] =
F4_calcRelativeFlowVelocities(v_CSYS_0,nMarkers,u,du,nstep,dv_CSYS_0)

% Step6.Flow Acc. and Relative Vel. and Transformation to Body Coordinate
wrto wave elevation
% ==(Function.5)
[u_totx,u_totz,du_totx,du_totz,du_totwx,du_totwz]=F5_calcVelAndAccTransWrtoWa
veElev(nMarkers,nstep,u_rel,z_add,eta_add,du_rel,du)

z_add(1,:) = [];
eta_add(1,:) = [];


% Step7.Added Mass Coefficient
%==(no function)
```

```
Re_U1 = amp(1,1:nMarkers).*(DCylinder/nu);                    %calcuate (Re)
based on hor.vel. amplitude
Kc_U1 = amp(1,1:nMarkers).*(period/DCylinder);                %calcuate (Kc)
based on hor.vel. amplitude
Re_U = max(Re_U1);
Kc_U = max(Kc_U1);
%Aproach by Clauss
if (Re_U>=100000)||(Kc_U<10)
        Cm_U = 2.0;
        Cd_U = 0.6;
elseif (Re_U>=100000)||(Kc_U>=10)
        Cm_U = 1.5;
        Cd_U = 0.6;
elseif (Re_U<100000)||(Kc_U<10)
        Cm_U = 2.0;
        Cd_U = 1.2;
elseif (Re_U<100000)||(Kc_U>=10)
        Cm_U = 1.5;
        Cd_U = 1.2;
end

% Step8.Calculate Morison forces acting on cylinder segments/markers
%==(Function.6)
dz = diff(r_CSYS_0 (3,(1:2)));                          %input differences for
each point of Markers at submerged body at z axis

[Fmorx_t,Fmorz_t,Fmor_nx,Fmor_nz] =
F6_calcMorisonEquationForce(nMarkers,rho,Cm_U,DCylinder,dz,u_totx,u_totz,Cd_U
,nstep,du_totwx,du_totwz,du_totx,du_totz)%function.eq.

% Plotting result
figure(1)
plot(t,Fmorx_t)
legend('Ftotal-x')
xlabel('time (s)');
ylabel('Total Force (kN)');
xlim([0 10])
title('Morison Total Force(Fmorison Total)');

figure(2)
plot(t,Fmor_nx(:,1),t,Fmor_nx(:,2),t,Fmor_nx(:,3),t,Fmor_nx(:,4),t,Fmor_nx(:,
5),t,Fmor_nx(:,6),t,Fmor_nx(:,7),t,Fmor_nx(:,8),t,Fmor_nx(:,9),t,Fmor_nx(:,10
),t,Fmor_nx(:,11))
legend('Fmarker-1','Fmarker-2','Fmarker-3','Fmarker-4','Fmarker-5','Fmarker-
6','Fmarker-7','Fmarker-8','Fmarker-9','Fmarker-10','Fmarker-11')
xlabel('time (s)');
ylabel('nMarkers Force (kN)');
xlim([0 10])
title('Morison Force(Fmorison nMarkers)');
```

F1 TRANSFORMATION MATRIX ALGORITHM

```
function [T] = F1_calcTransMatXYZKar(xyzKar)
% Inputs
% xyzKar: (3) vector containing the alpha, beta and gamma xyz-Kardan angles
%
% Outputs
% T: (3x3) Transformation matrix
```

```
    %inputs
    al = xyzKar(1);
    be = xyzKar(2);
    ga = xyzKar(3);
    %Outputs
    T = [   cos(be)*cos(ga)  , cos(be)*sin(ga)  , sin(be); ...
            cos(al)*sin(ga)  + sin(al)*sin(be)*cos(ga), ...
            cos(al)*cos(ga)  - sin(al)*sin(be)*sin(ga), ...
            -sin(al)*cos(be); ...
            sin(al)*sin(ga)  - cos(al)*sin(be)*cos(ga), ...
            sin(al)*cos(ga)  + cos(al)*sin(be)*sin(ga), ...
            cos(al)*cos(be)  ...
        ];

end
```

F2 MARKER POSITION, ACCELERATION AND VELOCITY ALGORITHM

```
function [r_CSYS_0,v_CSYS_0,dv_CSYS_0] =
F2_calcMarkerPositionsAndVelocity(rRef, rMaLoc,
T,vRef,omRef,nMarkers,omRef2,dvRef,omRef3)
% Inputs
%   rRef        : Position of body reference system with retspect to CSYS_0
%   rMaLoc      : Local positions of markers on body. Dimension (3 x number of
markers)
%   T           : Transformation matrix_type from body to global coordinate
%   vRef        : Velocity of the body (a given sample value here)
%   omRef       : Angular velocity of the body
%   nMarkers    : Number of markers on cylinder
%
% Outputs
%   r_CSYS_0 : Positions of markers with respect to global coordinate system.
%               Dimension (3 x number of markers)
%   v_CSYS_0    : Velocities of markers with respect to global coordinate
system.
%               Dimension (3 x number of markers


    for ix = 1:nMarkers
        for iv = 1:3
        r_CSYS_0(:,ix) = rRef + T*rMaLoc(:,ix);
        v_CSYS_0(:,ix) = vRef + cross(omRef,T*rMaLoc(:,ix));

        dv_CSYS_0(:,ix) = dvRef +
(2.*cross(omRef2,T*v_CSYS_0(:,ix)))+cross(omRef,rMaLoc(:,ix))+cross(omRef3,rM
aLoc(:,ix));

        end
    end
    v_CSYS_0(:,nMarkers) = [0];
    dv_CSYS_0(:,nMarkers) = [0];
end
```

F3 WAVE FLOW VELOCITIES ALGORITHM

```
function
[u,du,amp]=F3_calcFlowVelocities(ampli,omega,k,depth,t,nMarkers,r_CSYS_0,nste
p)
```

```
% Inputs
%   ampli        : Wave Amplitude
%   omega        : Wave angular frequency
%   k            : Wave number
%   z            : z coordinates of nMarkers already wrto wave elevation
%   depth        : distance from water still water level to seabed
%   x            : varian of x value, same ammount with time varian value
%   time         : varian of time value, same ammount with x varian value
%   nMarkers     : input Number of markers on cylinder start from the top of
cylinder to bottom in z
%   N            : input value of (x) and (t) limit quantity
%   r_CSYS_0     : Positions of markers with respect to global coordinate
system.
%                  Dimension (3 x number of markers)
%
% Outputs
%   amp2D          : Amplitude for flow velocity calc. at (x,y,z) axis, used
%                  also to obtain Coeff. drag & added mass
%   Ut4D           : Wave velocities at (x,y,z) axis in global coordinate
%   dUt4D          : Wave acceleration at (x,y,z) axis in global coordinate

% output :

for i=1:nMarkers
    for istep=1:nstep
        phi(istep) = k*r_CSYS_0(1,i) + omega*t(istep);   % Phase
        sigma = omega;                 % No mean velocity

        amp(1,i) = ampli.*( cosh(k*(r_CSYS_0(1,i)+depth))./sinh(k*depth) );
        amp(3,i) = ampli.*( sinh(k*(r_CSYS_0(3,i)+depth))./sinh(k*depth) );

        u(1,i,istep) = sigma*amp(1,i).*cos(phi(istep));
        u(3,i,istep) = sigma*amp(3,i).*sin(phi(istep));
        du(1,i,istep) = (sigma^2)*amp(1,i).*sin(phi(istep));
        du(3,i,istep) = -(sigma^2)*amp(3,i).*cos(phi(istep));
    end
end

end
```

F4 RELATIVE FLOW VELOCITIES AND ACCELERATION ALGORITHM

```
function [u_rel,du_rel] =
F4_calcRelativeFlowVelocities(v_CSYS_0,nMarkers,u,du,nstep,dv_CSYS_0)
% Inputs
%   v_CSYS_0      : Velocities of markers with respect to global coordinate
system
%                   Dimension (3 x number of markers)
%   nMarkers      : input Number of markers on cylinder start from the top of
cylinder to bottom in z
%   Ut            : Wave velocities at (x,y,z) axis in global coordinate
%   N             : input value of (x) and (t) limit quantity
%
% Outputs
%   u_rel         : Relative Horizontal wave velocities at (x,y,z) axis at
%                   global coordinate (wave velocities - body proj.
%                   velocities)

%Equation
```

```
for istep=1:nstep
    for i=1:nMarkers
        u_rel(1,i,istep) = u(1,i,istep) - v_CSYS_0(1,i);
        u_rel(3,i,istep) = u(3,i,istep) - v_CSYS_0(3,i);
        du_rel(1,i,istep) = du(1,i,istep) - dv_CSYS_0(1,i);
        du_rel(3,i,istep) = du(3,i,istep) - dv_CSYS_0(3,i);
    end
end
end
```

F5 VELOCITY AND ACCELERATION TRANSFORMATION AND FILTERING WITH RESPECT TO WAVE ELEVATION

```
function
[u_totx,u_totz,du_totx,du_totz,du_totwx,du_totwz]=F5_calcVelAndAccTransWrtoWa
veElev(nMarkers,nstep,u_rel,z_add,eta_add,du_rel,du)
%
[utot_x2D,utot_z3D,u_totx2D,u_totz2D,Idu,utot_z2D]=F5_calcVelAndAccTransWrtoW
aveElev(nMarkers,nstep,xyzKar,u_rel,z_add,eta_add,omRef,vRef,r_CSYS_0,T)
% Inputs
%   nMarkers    : input Number of markers on cylinder start from the top of
cylinder to bottom in z
%   N           : input value of (x) and (t) limit quantity
%   xyzKar      : (3) vector containing the alpha, beta and gamma xyz-Kardan
angles
%   dUt         : wave acceleration at (x,y,z) axis in global coord.
%   u_rel       : Relative Horizontal wave velocities at (x,y,z) axis
%   z_eta1      : Marker points in z axis, here with additional value at
first
%                 coloumn as one of filtering result process wrto wave
elevation
%   eta1        : wave elevation for each marker point, here with additional
value at first
%                 coloumn as one of filtering result process wrto wave
elevation
%   Tb          : Transformation matrix from global to body coordinate
%
% Outputs
%   u_totx      : Horizontal wave velocities at x axis wrto wave elevation &
in body coord.
%   u_totz      : Vertical wave velocities at z axis wrto wave elevation & in
body coord.
%   dUt_totx    : Horizontal wave accelerations at x axis wrto wave elevation
%                 & in body coord

% output :


utot_x2D = [];
utot_z2D = [];
dutot_x2D = [];
dutot_z2D = [];
dutotw_x2D = [];
dutotw_z2D = [];
%r_CSYS_add = horzcat(r_CSYS_0,[NaN;NaN;NaN])% needed to make differencess of
ix and im for calc. process

for istep=1:nstep
```

```
    for i=1:nMarkers
        utot_x3D(1,i,istep) = u_rel(1,i,istep);
        utot_z3D(1,i,istep) = u_rel(3,i,istep);

        dutot_x3D(1,i,istep) = du_rel(1,i,istep);
        dutot_z3D(1,i,istep) = du_rel(3,i,istep);

        dutotw_x3D(1,i,istep) = du(1,i,istep);
        dutotw_z3D(1,i,istep) = du(3,i,istep);
    end
%      %convert from 3D to 2D matrix
       utot_x2D = cat(1,utot_x2D,utot_x3D(:,:,istep));
       utot_z2D = cat(1,utot_z2D,utot_z3D(:,:,istep));
       dutot_x2D = cat(1,dutot_x2D,dutot_x3D(:,:,istep));
       dutot_z2D = cat(1,dutot_z2D,dutot_z3D(:,:,istep));
       dutotw_x2D = cat(1,dutotw_x2D,dutotw_x3D(:,:,istep));
       dutotw_z2D = cat(1,dutotw_z2D,dutotw_z3D(:,:,istep));
%      %Prepare input for Filtering the result wrto wave elevation
       utot_xadd = [utot_x2D(1,:);utot_x2D];
       utot_zadd = [utot_z2D(1,:);utot_z2D];
       dutot_xadd = [dutot_x2D(1,:);dutot_x2D];
       dutot_zadd = [dutot_z2D(1,:);dutot_z2D];
       dutotw_xadd = [dutotw_x2D(1,:);dutotw_x2D];
       dutotw_zadd = [dutotw_z2D(1,:);dutotw_z2D];
%        utot_xadd(:,nMarkers) = [];
%        utot_zadd(:,nMarkers) = [];
        u_totx = [utot_xadd];
        u_totz = [utot_zadd];
        du_totx = [dutot_xadd];
        du_totz = [dutot_zadd];
        du_totwx = [dutotw_xadd];
        du_totwz = [dutotw_zadd];

    for it=1:(nstep)+1
        for i=1:nMarkers
            %Filtering the process wrto wave elevtion
            Idu(it,:) = z_add(1,i) > eta_add(it,1);

            u_totx(Idu,i) = NaN;
            u_totz(Idu,i) = NaN;
            du_totx(Idu,i) = NaN;
            du_totz(Idu,i) = NaN;
            du_totwx(Idu,i) = NaN;
            du_totwz(Idu,i) = NaN;
        end
    end
%      %delete unecessary element (the first row element)
    u_totx(1,:) = [];
    u_totz(1,:) = [];
    du_totx(1,:) = [];
    du_totz(1,:) = [];
    du_totwx(1,:) = [];
    du_totwz(1,:) = [];
end
end
```

F6 HYDRODYNAMIC MORISON EQUATION

```
function [Fmorx_t,Fmorz_t,Fmor_nx,Fmor_nz] =
F6_calcMorisonEquationForce(nMarkers,rho,Cm_U,DCylinder,dz,u_totx,u_totz,Cd_U
,nstep,du_totwx,du_totwz,du_totx,du_totz)
```

```
% Inputs
%    n_eta       : Number of marker point at body wrto wave elevation
%    rho         : sea water density
%    Cm_U        : added mass coeff. wrto wave elevation
%    DCylinder   : diameter cylider
%    dz          : differences for each point of Markers at submerged body at z
axis
%    dUdt        : Horizontal wave accelerations wrto wave elevation
%    Cd_U        : drag coeff. wrto wave elevation
%    u_tot       : horizontal rel.vel.after tranformation to body coord.sys.
%    v_tot       : vertical rel.vel.after tranformation to body coord.sys.
%
% Outputs
%    Fmor        : Hydrodynamic force of Morison equation

Fmorx2D = [];
Fmorz2D = [];
for istep=1:nstep
    for i=1:nMarkers
        froudx(i,istep) = rho*pi*1/4*(DCylinder^2)*dz.*du_totwx(istep,i);
        froudz(i,istep) = rho*pi*1/4*(DCylinder^2)*dz.*du_totwz(istep,i);
        Amassx(i,istep) = rho*Cm_U*1/4*(DCylinder^2)*dz.*du_totx(istep,i);
        Amassz(i,istep) = rho*Cm_U*1/4*(DCylinder^2)*dz.*du_totz(istep,i);
        dragx(i,istep) =
(0.5*rho*Cd_U*DCylinder*dz).*(abs(u_totx(istep,i))).*(u_totx(istep,i));%===Dr
ag Force horizontal
        dragz(i,istep) =
(0.5*rho*Cd_U*DCylinder*dz).*(abs(u_totz(istep,i))).*(u_totz(istep,i));%===Dr
ag Force vertical
        Fmorx(i,istep) = froudx(i,istep) + Amassx(i,istep) + dragx(i,istep);
        Fmorz(i,istep) = froudz(i,istep) + Amassz(i,istep) + dragz(i,istep);

    end
end
Fmorx(isnan(Fmorx))=0;
Fmorz(isnan(Fmorz))=0;

Fmorx_t=(sum(Fmorx))';% Total force-x (sum) at each X and time variant
Fmorz_t=(sum(Fmorz))';% Total force-z (sum) at each X and time variant

Fmor_nx=Fmorx';
Fmor_nz=Fmorz';
end
```

APPENDIXES D. OCN SIM-FLEX INPUT CODES

F1 FLD FILE (WAVE LOAD)

```
# Common
properties=============================================================
#
==========================================================================
====
# Fluid density [kg/m^3]
rho = 1025.0

# Type of velocity field
calculation============================================
#   Types of velocity fields (fieldType)
#       1 - Non-moving fluid
#       2 - Constant, uniform velocity field
#       3 - Linear Airy waves
#
==========================================================================
====
fieldType = 3   # Airy wave theory

# Actual wave parameters
omega  = 1.3    # Angular frequency
lambda = 30.0   # Wave length
depth  = 16.0   # Water depth
amp    = 2.7    # Wave amplitude

# Superposed constant uniform velocity field
u = 1.0
v = 0.0
w = 0.0


# Hydrodynamic
forces===========================================================
#
==========================================================================
====
# Apply simple, mass-proportional damping. 1:true, <>1:false
simpDamp = 0
#dampFac  = 0.25


# Coefficient tables
===========================================================
#
==========================================================================
====
nCTables = 1

[CTable__1]
fName = ropeCoeffs.matr
```

F2 MBD FILE (FLOATING STRUCTURE)

Mooring Condition 7

```
[SUBVARS]
# Substitution variables
========================================================
#
================================================================================
====
nSubVars = 0


[CSYS]
# Inertial frames
===============================================================
#
================================================================================
====
[CSYS__0]
nMarkers = 3

[Marker__1]
rMa = 0.0 0.0 -16.0

[Marker__2]
rMa = 73.18 0.0 -16.0

[Marker__3]
rMa = 36.59 0.0 -16.0


[ROPES]
# Ropes
=================================================================================
#   Local longitudinal axis: z!
#
================================================================================
====
nRopes = 5          # Total number of ropes

[ROPE__1]
length    = 10.0
diam      = 0.04
rho       = 7000
nElems    = 10
joint.refBody   = CSYS__0
joint.refMarker = 1
alpha0    = 0.0
beta0     = 90.0
alpha_d0  = 0.0
beta_d0   = 0.0
IDCTable  = 1

[ROPE__2]
length    = 29.1
diam      = 0.04
rho       = 7000
nElems    = 29
joint.refBody   = ROPE__1
```

```
joint.refMarker = 10
alpha0    = 0.0
beta0     = -24.0
alpha_d0  = 0.0
beta_d0   = 0.0
IDCTable  = 1

[ROPE__3]
length    = 10.0
diam      = 0.04
rho       = 7000
nElems    = 10
joint.refBody   = CSYS__0
joint.refMarker = 2
alpha0    = 0.0
beta0     = -90.0
alpha_d0  = 0.0
beta_d0   = 0.0
IDCTable  = 1

[ROPE__4]
length    = 29.1
diam      = 0.04
rho       = 7000
nElems    = 29
joint.refBody   = ROPE__3
joint.refMarker = 10
alpha0    = 0.0
beta0     = 24.0
alpha_d0  = 0.0
beta_d0   = 0.0
IDCTable  = 1


[ROPE__5]
length    = 12.8645
diam      = 0.04
rho       = 7000
nElems    = 12
joint.refBody   = CSYS__0
joint.refMarker = 3
alpha0    = 0.0
beta0     = 0.0
alpha_d0  = 0.0
beta_d0   = 0.0
IDCTable  = 1


[RBODIES]
# Rigid bodies
=================================================================
#
==========================================================================
====
nRigids = 1


[RBODY__1]
mass   = 200.0
```

```
I_1    = 100.0    0.0    0.0
I_2    = 0.0    100.0   0.0
I_3    = 0.0    0.0    100.0

vol  = 0.2              # Ignored if loadTye = 2
rCOB = 0.0 0.0 0.0      # Ignored if loadTye = 2

r0   = 36.59 0.0 0.0
phi0 = 0.0 0.0 0.0

nMarkers = 3
rMa_x = -0.0058  0.0058    0.0
rMa_y = 0.0      0.0       0.0
rMa_z = -3.13549 -3.13549  -3.13549

loadType = 2    # Buoy
lBuoy    = 12    # Length of buoy
dBuoy    = 0.27  # Diameter of buoy
CDLat    = 1.2  # Lateral drag coefficient
CDLong   = 1.2  # Longitudinal drag coefficient
nDivBuoy = 20   # Number of divisions for numerical integration of
hydrodynamic forces


[CONSTRAINTS]
# Implicit constraints between ropes
===========================================
#
===========================================================================
====
nConstr = 0 # Total number of implicit loop closing constraints in the
system.


[SPRINGS]
# Force elements
===============================================================
#
===========================================================================
====
nSprings  = 3   # Total number of springs in the system

[SPRING__1]
c  = 26000.0
d  = 18225.0
node1.refBody   = ROPE__2
node1.refMarker = 29
node2.refBody   = RBODY__1
node2.refMarker = 1

[SPRING__2]
c  = 26000.0
d  = 18225.0
node1.refBody   = ROPE__4
node1.refMarker = 29
node2.refBody   = RBODY__1
node2.refMarker = 2
```

```
[SPRING__3]
c  = 26000.0
d  = 18225.0
node1.refBody   = ROPE__5
node1.refMarker = 12
node2.refBody   = RBODY__1
node2.refMarker = 3
```

F3 ROPE COEFFICIENT

```
nRows = 91
nCols = 4

   0.000  0.000000e+00  0.01  0.01
   2.000  4.187940e-02  0.01  0.01
   4.000  8.370777e-02  0.01  0.01
   6.000  1.254342e-01  0.01  0.01
   8.000  1.670077e-01  0.01  0.01
  10.000  2.083778e-01  0.01  0.01
  12.000  2.494940e-01  0.01  0.01
  14.000  2.903063e-01  0.01  0.01
  16.000  3.307648e-01  0.01  0.01
  18.000  3.708204e-01  0.01  0.01
  20.000  4.104242e-01  0.01  0.01
  22.000  4.495279e-01  0.01  0.01
  24.000  4.880840e-01  0.01  0.01
  26.000  5.260454e-01  0.01  0.01
  28.000  5.633659e-01  0.01  0.01
  30.000  6.000000e-01  0.01  0.01
  32.000  6.359031e-01  0.01  0.01
  34.000  6.710315e-01  0.01  0.01
  36.000  7.053423e-01  0.01  0.01
  38.000  7.387938e-01  0.01  0.01
  40.000  7.713451e-01  0.01  0.01
  42.000  8.029567e-01  0.01  0.01
  44.000  8.335900e-01  0.01  0.01
  46.000  8.632078e-01  0.01  0.01
  48.000  8.917738e-01  0.01  0.01
  50.000  9.192533e-01  0.01  0.01
  52.000  9.456129e-01  0.01  0.01
  54.000  9.708204e-01  0.01  0.01
  56.000  9.948451e-01  0.01  0.01
  58.000  1.017658e+00  0.01  0.01
  60.000  1.039230e+00  0.01  0.01
  62.000  1.059537e+00  0.01  0.01
  64.000  1.078553e+00  0.01  0.01
  66.000  1.096255e+00  0.01  0.01
  68.000  1.112621e+00  0.01  0.01
  70.000  1.127631e+00  0.01  0.01
  72.000  1.141268e+00  0.01  0.01
  74.000  1.153514e+00  0.01  0.01
  76.000  1.164355e+00  0.01  0.01
  78.000  1.173777e+00  0.01  0.01
  80.000  1.181769e+00  0.01  0.01
  82.000  1.188322e+00  0.01  0.01
  84.000  1.193426e+00  0.01  0.01
  86.000  1.197077e+00  0.01  0.01
  88.000  1.199269e+00  0.01  0.01
  90.000  1.200000e+00  0.01  0.01
```

```
  92.000  1.199269e+00  0.01  0.01
  94.000  1.197077e+00  0.01  0.01
  96.000  1.193426e+00  0.01  0.01
  98.000  1.188322e+00  0.01  0.01
 100.000  1.181769e+00  0.01  0.01
 102.000  1.173777e+00  0.01  0.01
 104.000  1.164355e+00  0.01  0.01
 106.000  1.153514e+00  0.01  0.01
 108.000  1.141268e+00  0.01  0.01
 110.000  1.127631e+00  0.01  0.01
 112.000  1.112621e+00  0.01  0.01
 114.000  1.096255e+00  0.01  0.01
 116.000  1.078553e+00  0.01  0.01
 118.000  1.059537e+00  0.01  0.01
 120.000  1.039230e+00  0.01  0.01
 122.000  1.017658e+00  0.01  0.01
 124.000  9.948451e-01  0.01  0.01
 126.000  9.708204e-01  0.01  0.01
 128.000  9.456129e-01  0.01  0.01
 130.000  9.192533e-01  0.01  0.01
 132.000  8.917738e-01  0.01  0.01
 134.000  8.632078e-01  0.01  0.01
 136.000  8.335900e-01  0.01  0.01
 138.000  8.029567e-01  0.01  0.01
 140.000  7.713451e-01  0.01  0.01
 142.000  7.387938e-01  0.01  0.01
 144.000  7.053423e-01  0.01  0.01
 146.000  6.710315e-01  0.01  0.01
 148.000  6.359031e-01  0.01  0.01
 150.000  6.000000e-01  0.01  0.01
 152.000  5.633659e-01  0.01  0.01
 154.000  5.260454e-01  0.01  0.01
 156.000  4.880840e-01  0.01  0.01
 158.000  4.495279e-01  0.01  0.01
 160.000  4.104242e-01  0.01  0.01
 162.000  3.708204e-01  0.01  0.01
 164.000  3.307648e-01  0.01  0.01
 166.000  2.903063e-01  0.01  0.01
 168.000  2.494940e-01  0.01  0.01
 170.000  2.083778e-01  0.01  0.01
 172.000  1.670077e-01  0.01  0.01
 174.000  1.254342e-01  0.01  0.01
 176.000  8.370777e-02  0.01  0.01
 178.000  4.187940e-02  0.01  0.01
 180.000  1.469576e-16  0.01  0.01
```

F4 MAIN CODE

```
# Case name
====================================================================
#
==============================================================================
====
nameOfCase = C7


# Solver configuration
=========================================================
```

```
#
===========================================================================
====
solType = 4
tEnd    = 50.0
nOut    = 500
tStep   = 0.001


# Global configuration
=========================================================
#
===========================================================================
====
g = 0.0 0.0 -9.81


# Fluid model data
=============================================================
#
===========================================================================
====
fluidModel        = C7.fld

# Output water surface elevation. Water surface elevation is written
# from XMin to XMax  at nDiv discrete positions.
writeWaterSurface = 1       # Create additional output for water surface?
0: false, 1: true
xMin              = -5.0
xMax              = 90.0
nDiv              = 95



# Multibody structural configuration
===========================================
#
===========================================================================
====
multibodyData = C7.mbd


# Multibody solver configuration
===============================================
#
===========================================================================
====
constr_kp = 100
constr_ki = 100
constr_kd = 100
```