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Analysis of Motions and Anchor Line Forces for Floating Production Units

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for

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ANALYSIS OF MOTIONS AND ANCHOR LINE FORCES FOR FLOATING PRODUCTION UNITS

Ship shaped units for floating production, storage and offloading (FPSOs) will normally have a turret structure where anchor lines and production risers are linked to the floater. Dynamic interaction between line forces and floater motions will take place; motions will introduce line forces, but the line forces will also influence the motions. Simultaneous computation of motions and line forces is hence wanted, but requires time domain models for both vessel motions and line forces, and also a system for real time communication between the two programs. MARINTEK has developed this type of software based on SIMO and RIFLEX, and also the umbrella software SIMA for communication between the programs and user interface. The purpose of the present project is to study methods for design analysis of anchor systems, and to investigate the performance of uncoupled analyses versus fully coupled models for varying water depth and environmental conditions.

The work might be divided into tasks as follows:

1. Establish a set of analysis models by use of SIMA. The significant wave height should be varied within realistic values for petroleum fields outside Norway.
2. Carry out a set of analyses and compare results from coupled and uncoupled models.

The work may show to be more extensive than anticipated. Some topics may therefore be left out after discussion with the supervisor without any negative influence on the grading.

The candidate should in her/his report give a personal contribution to the solution of the problem formulated in this text. All assumptions and conclusions must be supported by mathematical models and/or references to physical effects in a logical manner.

The candidate should apply all available sources to find relevant literature and information on the actual problem.

The report should be well organised and give a clear presentation of the work and all conclusions. It is important that the text is well written and that tables and figures are used to support the verbal presentation. The report should be complete, but still as short as possible.

The final report must contain this text, an acknowledgement, summary, main body, conclusions and suggestions for further work, symbol list, references and appendices. All figures, tables and equations must be identified by numbers. References should be given by author name and year in the text, and presented alphabetically by name in the reference list. The report must be submitted in two copies unless otherwise has been agreed with the supervisor.

The supervisor may require that the candidate should give a written plan that describes the progress of the work after having received this text. The plan may contain a table of content for the report and also assumed use of computer resources.

From the report it should be possible to identify the work carried out by the candidate and what has been found in the available literature. It is important to give references to the original source for theories and experimental results.

The report must be signed by the candidate, include this text, appear as a paperback, and - if needed - have a separate enclosure (binder, DVD/ CD) with additional material.

Supervisor at NTNU is Professor Carl M. Larsen

Carl M. Larsen

Submitted:	January 2013
Deadline:	10 June 2013

Abstract

The oil industry is expanding its activities into deeper and deeper waters. This creates new challenges in terms of technology and design of floating production units. Floater, mooring lines and risers comprise a dynamic system that respond to environmental loads due to wind, waves and current in a complex way. In deep water, the low-frequent floater motions are significantly influenced by current loading and damping due to the slender structures. These interaction effects become more pronounced as the water depth increases. To achieve accurate predictions of floater motions and mooring line dynamics in deep water, it is essential that the interaction effects are included in the calculations.

Two different methods to calculate on moored floaters are presented: the traditional uncoupled analysis and a coupled analysis. The traditional uncoupled analysis is performed in two steps; first the motions of the floater are calculated, then the dynamic responses in the mooring lines and risers are found by using the floater motions from the first step. The main shortcomings with the traditional uncoupled analysis are the neglection or simplification of the current forces and the low-frequency damping contribution from mooring lines and risers. The effect of these shortcomings will normally increase with increasing water depth. In deep water, a coupled analysis is therefore strongly preferred. In a coupled analysis, the floater motions and mooring line and riser dynamics are calculated simultaneously. The interaction effects are then taken into account and the drawbacks from the uncoupled analysis are avoided.

Both uncoupled and coupled analyses are performed on a floating production unit. The floater is operating in a water depth of 913.5 metre, which is characterized as ‘deep water’. The uncoupled analyses are performed in the programs SIMO and RIFLEX, while the coupled analyses are done in the newly developed software SIMA. The analyses showed that an uncoupled analysis approach overestimates the floater motions and mooring line forces. A coupled analysis should therefore be applied on deep water concepts.

Sammendrag

Oljeindustrien utvider stadig sine aktiviteter og beveger seg ut på større og større vanndyp. Dette skaper utfordringer innenfor teknologi og design av nye konsepter for flytende produksjonsenheter. Fartøy, ankerliner og stigerør utgjør et dynamisk system som responderer på bølger, strøm og vind. På dypt vann blir den lavfrekvente bevegelsen til fartøyet i stor grad påvirket av strøm og demping fra ankerlinene og stigerørene. Disse koblingseffektene mellom fartøy og ankerlinene og stigerørene blir mer tydelige når vanndybden øker. Koblingseffektene må derfor tas med i beregningene for å få nøyaktige resultater for bevegelsene til fartøyet.

To ulike analysemetoder som kan brukes til å gjøre beregninger på et forankret fartøy er presentert i oppgaven: den tradisjonelle ukoblete analysemetoden og en koblet analysemetode. Den tradisjonelle ukoblete analysemetode består av to steg; først blir bevegelsene til fartøyet beregnet, og så blir den dynamiske responsen i ankerlinene og stigerørene funnet ved å bruke bevegelsene fra det første steget. De viktigste begrensningene med en ukoblet analysemetode er neglisjeringen eller forenklingen av det lavfrekvente dempningsbidraget og kreftene fra strømmen på ankerlinene og stigerørene. Effekten av disse begrensningene vil normalt øke med økende vanndyp. På dypt vann er derfor en koblet analysemetode foretrukket. I en koblet analyse blir bevegelsene til fartøyet og responsen i ankerlinene og stigerørene beregnet samtidig. Koblingseffektene blir da inkludert i beregningene og ulempene med den ukoblete analysemetoden blir unngått.

Både ukoblete og koblete analyser har blitt gjort på et forankret fartøy. Vanndypet hvor fartøyet ligger er 913.5 meter, noe som er karakterisert som 'dypt vann'. De ukoblete analysene er gjort i programmene SIMO og RIFLEX, mens de koblete analysene er utført i det nyutviklete programmet SIMA. Analysene viste at en ukoblet analysemetode overestimerer bevegelsene til fartøyet og kreftene i ankerlinene. En koblet analyse bør derfor anvendes når fartøy opererer på store vanndyp.

Acknowledgements

This master thesis has been carried out under the supervision of Professor Carl Martin Larsen at the Department of Marine Technology at the Norwegian University of Science and Technology. I am grateful for the guidance, the encouragement and the support he has shown during the past year; first in connection with my project thesis and now lately in my master thesis.

The work with the master thesis has been instructive. I have acquired good knowledge of floating production units and their responses, but also, and perhaps more important, I have learned that modelling complex floating structures are challenging and a time consuming process. It has been a lot of problems with the analyses, and some problems went on for months. I therefore wish to thank Elizabeth Passano, Andreas Amundsen and Knut Mo at MARINTEK for their help with the analysis programs used in this work. With guidance from them, and Professor Larsen, the project has landed in a satisfactory way and provided reasonable results.

At last, I would like to thank all my friends and fellow students for making the past five years both interesting and enjoyable. It has been lots hard work, but also the best time of my life.

Contents

Nomenclature

Abbreviations

CPU	Central Processing Unit, the time used by the computer for processing instructions
DOF	Degree of Freedom
FE	Finite Element (method)
FFT	Fast Fourier Transform
FPSO	Floating Production Storage and Offloading
HF	High frequency
LF	Low frequency
M	Mean forces
TLP	Tension-leg Platform
WF	Wave frequency

Roman Symbols

$\mathbf{C}$	Damping matrix
C_m	Mass coefficient
C_d	Drag coefficient
D	Diameter of the slender marine structures
$h(\tau)$	Retardation function
H_S	Significant wave height
$\mathbf{M}$	Mass matrix
$\mathbf{r}$	Nodal displacement vector

$\dot{\boldsymbol{r}}$	Velocity vector
$\ddot{\boldsymbol{r}}$	Acceleration vector
$\mathbf{R}^D$	Damping for vector
$\mathbf{R}^E$	External force vector
$\mathbf{R}^I$	Inertia force vector
$\mathbf{R}^S$	Structural reaction force vector
T_P	Peak period
$\boldsymbol{u}$	Flow velocity
$\dot{\boldsymbol{u}}$	Flow acceleration

Greek Symbols

$\Delta \boldsymbol{r}_t$	Delta, incremental nodal displacement vector
$\Delta \dot{\boldsymbol{r}}_t$	Delta, incremental velocity vector
$\Delta \ddot{\boldsymbol{r}}_t$	Delta, incremental acceleration vector
γ	Gamma, peakedness parameter
$(\boldsymbol{\omega})$	Lambda, frequency-dependent added mass
$\mu(\boldsymbol{\omega})$	Lamdba, frequency-dependent damping
ϱ	Rho, density of salt water, 1025kg/m^3

Chapter 1

Introduction

Hydrocarbons are found in deeper and deeper waters, and the numbers of deepwater floating production units are growing rapidly. This results in new technological challenges. The dynamic behaviour of a multi-component offshore structure is a complex problem. To obtain realistic simulations and results, extensive computational efforts are required.

Water depths larger than 400 metre are usually considered as 'deep water'. If the water depth exceeds 1000 metre it is called ultra-deep water. [Ormberg et al., 2002]

The project thesis was mainly a literature study on floating production units, with focus on the three main components: floaters, mooring systems and risers. In addition, it was performed an extensive study on methods for design analysis of mooring systems including calculations on vessel motions and anchor lines dynamics. This will not be repeated in the master thesis, only a brief summary is given when needed.

In this master thesis, the methodology for both a traditional uncoupled analysis and a coupled analysis of a floating production unit is presented. The methodologies are applied to a turret-moored floating production, storage and offloading (FPSO) operating in a water depth of 913.5 metre. The results are compared, and the need for coupled analysis is discussed.

Chapter 2
Floating Production Units

2.1 General

Development of deepwater fields requires advanced structures for production and transport of oil and gas. The structures can include combinations of steel catenary risers, flexible flowlines, top tensioned risers, and hybrid risers, connected to one or more moored floaters such as ships, semisubmersibles, spars and tension-leg platforms (TLPs).

The mooring system is made of a number of cables which are attached both to the floater and to anchors at the sea bed. In a spread mooring system, several pre-tensioned anchor lines are arrayed around the structure to keep it in the desired location. The cables are often composed of two or more lengths of different materials, e.g. chain, wire and rope, to give the cables adequate properties and a convenient configuration.

Mooring lines and risers are often referred to as 'slender structures' due to the small cross-section area compared to the overall structure length.

Ship-shaped vessels will experience significant low-frequency response in the horizontal plane due to the large natural periods in surge, sway and yaw. Ships may be particularly sensitive to surge excitation since the viscous hull damping is very low. This sensitivity is reduced with increasing water depth since the damping contribution from mooring lines and risers become more significant in deeper water. An important feature of moored offshore structures is therefore their slow oscillatory motions.

For ships, the natural periods of heave, roll and pitch will be within the first-order wave-frequency range. This implies that ships experience significant vertical wave-frequency motions. [ITTC, 1999]

	Natural periods [s]					
	Surge	Sway	Heave	Roll	Pitch	Yaw
Ship	>100	>100	5-12	5-30	5-30	>100

Table 1.1 - Natural periods for ship

More information about floating production units can be found in the project thesis [2012].

2.2 Second-order non-linear effects

In actual irregular sea states, the wave forces can usually be divided into the following categories:

- 1st order forces at wave-frequency (WF)
- 2nd order forces
    - Mean wave drift forces (M)
    - Forces at sum frequencies (HF)
    - Forces at difference frequencies (LF)
- Higher order forces
    - Wetted surface effects
    - Ringing
    - Viscous (non-potential) drift forces

The higher order wave forces present in typical offshore environments necessitates non-linear theory in the calculations. The solution of second-order theory results in mean forces, and forces oscillating with sum frequencies and difference frequencies in addition to the linear solution. Sum or difference frequency is either the sum or the difference of two frequencies used in describing the wave spectrum. Higher order wave forces will be disregarded in this context as they are of minor importance for floating vessels. [Faltinsen, 1990]

Due to the first- and second-order wave forces, a moored offshore structure will respond to wind, waves and current with motions on three different time scales: wave-frequency motions (WF), low-frequency motions (LF) and high-frequency motions (HF). The largest wave loads on offshore structures take place at the same frequencies as the waves, causing WF motions of the structure. To avoid large resonant effects, offshore structures are often designed in such a way that the resonant frequencies are shifted well outside the wave-frequency range. [SESAM DeepC, 2005]

As mentioned in the previous section, the mean and slow-varying wave loads may excite LF resonant motions in surge, sway and yaw. The effects of the LF motions and mean forces will increase with increasing water depth. Thus, the second-order wave loads may be of huge importance for deep water moored structures. [Faltinsen and Loeken, 1989 and Naess and Moan, 2013]

The importance of the second-order forces is shown in the figure below.

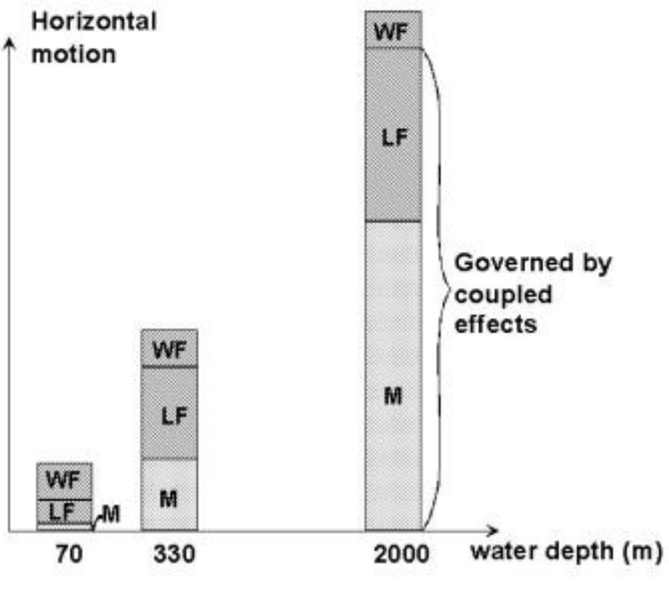


Figure 1.1 - Frequencies present in the horizontal motion for a ship

Chapter 3

Numerical Methods

3.1 Uncoupled approach

In an uncoupled analysis the responses of a floating production system are calculated in two separate steps:

1. Calculation of the floater motions. The motions are often separated into WF and LF motion, and the contribution from mooring lines and risers are either neglected or taken into account in a simplified way.
2. Dynamic response analysis of the mooring lines and risers. The floater motions from step 1 are used as top end displacements in the analysis.

The simplified contribution from the slender structures may result in inaccurate floater motions, where important coupling effects are not properly accounted for. The main shortcomings of an uncoupled approach are:

- Mean loads on mooring lines and risers due to current is normally not accounted for. Particularly in deep water, with strong current and many mooring lines and risers, may the mean loads on the slender structures be pronounced.
- The important damping effect from the mooring and riser system on the LF motion can only be included in a simplified way. As the water depth increases, the damping induced by the mooring lines will affect the motion response of the vessel considerably, and need to be accurately accounted for.

The effect of these simplifications will increase considerably when the water depth increases. This approach may therefore be convenient to use in shallow water. In deep water, where the couplings between floater and mooring lines and risers are particularly pronounced, a separate uncoupled approach may be too inaccurate. [Ormberg et al. 1997, Ormberg and Larsen, 1998, Nestegaard and Krokstad, 1999, Heurtier et al., 2001 and Gurumurthy et al., 2011]

3.2 Coupled analysis

In a fully coupled analysis, the motions of the floater and the dynamic loads in mooring lines and risers are computed simultaneously with a nonlinear approach in the time domain. The force model of the floater is then implemented as nodal forces at the top end of the finite element models of the mooring lines and risers. The WF and LF responses are also calculated simultaneously, and not divided into two separate contributions as in the uncoupled analysis.

The main reason for performing a coupled analysis is to avoid the limitations of the uncoupled approach and take the important coupling effects into account. Consequently, the estimates of the vessel motions and the dynamic responses in the mooring lines and risers will be more accurate.

The main disadvantage with a coupled approach is that the analyses are time consuming and require a large amount of CPU time. [Ormberg et al., 1997, Ormberg and Larsen, 1998, Heurtier et al., 2001, Gurumurthy et al., 2011]

3.3 Coupling effects

The term 'coupling effects' refer to the influence on the floater mean position and dynamic response from slender structure restoring, damping and inertia forces. The restoring force of the mooring and riser system is mainly from current loading.

3.3.1 Current loads on mooring lines and risers

The primary function of the mooring system is to impose the floater with a horizontal stiffness to limit the horizontal motion of the floater. The stiffness forces due to moorings and risers are normally calculated without including the effect of current. The presence of current imposes drag forces on the mooring and riser system, and these drag forces will increase with increasing water depths and larger exposed area of the slender marine structures. Neglecting the current forces will therefore result in incorrect drag forces, and, consequently, inaccurate estimates of the mean offset. [Ormberg et al., 1997 and Ormberg and Larsen, 1998]

In deep water the current forces can often become the dominant environmental load, contributing up to 75 percent of the mean drift forces on a floating production system. This emphasizes the importance of including current loads and drag forces in an accurate manner. [ITTC, 1999]

3.3.2 LF damping from moorings and risers

According to Huse and Matsumoto [1989], the main contributions to damping in general are the structure itself, wave drift and friction on the main structure, as well as drag forces from the mooring lines.

Traditionally it has been customary to neglect mooring line drag as a contribution to the total damping. However, Huse and Matsumoto [1989], Faltinsen [1990], Hermans [1991] and Karimirad [2013] demonstrated that damping due to slender structures significantly influences the horizontal LF motion of a moored vessel. How large this influence is, varies a lot, but Huse and Matsumoto [1989] showed that the LF surge damping of a ship due to the mooring system may be as high as 80 percent of total damping. The damping contribution from mooring lines and risers may therefore be the most important damping source for moored structures.

3.3.3 Inertia forces

The inertia forces are normally neglected in an uncoupled analysis due to the assumption that the total mass of the mooring system is much smaller than the floater mass. However, when the water depth increases, the lengths of the mooring lines and risers will also increase, and result in large masses. Neglecting these masses will result in inaccurate mass calculations and imprecise inertia forces. [Heurtier et al., 2001]

3.4 Use of coupled analysis

The coupling effects will automatically be properly accounted for in a fully coupled analysis, and the shortcomings with an uncoupled analysis are avoided. The use of coupled analysis is therefore particularly relevant for the motion analysis of deep water concepts.

The main disadvantage of a coupled analysis is that it is time consuming. However, the rapid computer hardware development has resulted in much lower computational time now compared to a few years back. A coupled analysis should therefore be a highly relevant method to use in design analysis of floating production units operating in deep water.

3.5 Time-domain analysis

Simultaneous computation of motions and line forces in a coupled analysis requires a time domain analysis. The time domain analysis is based on the following dynamic equilibrium equation:

$$\boldsymbol{R}^I(\boldsymbol{r},\ddot{\boldsymbol{r}},\boldsymbol{t}) + \boldsymbol{R}^D(\boldsymbol{r},\dot{\boldsymbol{r}},\boldsymbol{t}) + \boldsymbol{R}^S(\boldsymbol{r},\boldsymbol{t}) = \boldsymbol{R}^E(\boldsymbol{r},\dot{\boldsymbol{r}},\boldsymbol{t}) \qquad (3.1)$$

Where $\mathbf{R}^I$, $\mathbf{R}^D$ and $\mathbf{R}^S$ represent inertia, damping and internal structural reaction force vectors respectively. $\mathbf{R}^E$ is the external force vector, and $\boldsymbol{r}$, $\dot{\boldsymbol{r}}$ and $\ddot{\boldsymbol{r}}$ are the structural displacement, velocity and acceleration vectors.

Equation (3.1) is a nonlinear differential equation. Nonlinearities are due to the displacement dependencies in the inertia and the damping forces, and the coupling between the external load vector and structural displacement and velocity. In addition, there may be a non-linear relationship between inertial reaction forces and deformations.

The inertia force vector and damping force vector are given as:

$$\boldsymbol{R}^I(\boldsymbol{r},\ddot{\boldsymbol{r}},\boldsymbol{t}) = \boldsymbol{M}(\boldsymbol{r})\ddot{\boldsymbol{r}} \qquad (3.2)$$

$$\boldsymbol{R}^D(\boldsymbol{r},\dot{\boldsymbol{r}},\boldsymbol{t}) = \boldsymbol{C}(\boldsymbol{r})\dot{\boldsymbol{r}} \qquad (3.3)$$

M is the system matrix, which includes structural mass, mass accounting for internal fluid flow and hydrodynamic mass. **C** is the system damping matrix that includes contributions from internal structural damping and hydrodynamic damping.

The external load vector accounts for weight and buoyancy, forced displacement due to support vessel motions, drag and wave acceleration terms in Morison equation and specified nodal forces. The internal reaction force vector is calculated based on instantaneous state of stress in the elements.

The numerical solution of the dynamic equilibrium equation is based on an incremental procedure using the Newmark β-family method which considers a constant time step throughout the analysis. Newton-Raphson's step by step integration method is used to assure equilibrium between internal and external forces at every step.

The nonlinearities that affect the system are taken into account by introducing the tangential mass, damping and stiffness matrices at the start of the increment, and implementing the residual force vector from the previous time step. The linearized incremental equation of motion is then given by:

$$\boldsymbol{M}_t \Delta \ddot{\boldsymbol{r}}_t + \boldsymbol{C}_t \Delta \dot{\boldsymbol{r}}_t + \boldsymbol{K}_t \Delta \boldsymbol{r}_t = \boldsymbol{R}^E_{t+\Delta t} - (\boldsymbol{R}^I_t + \boldsymbol{R}^D_t + \boldsymbol{R}^S_t) \tag{3.4}$$

Where $\Delta \boldsymbol{r}_t$, $\Delta \dot{\boldsymbol{r}}_t$ and $\Delta \ddot{\boldsymbol{r}}_t$ are incremental nodal displacements, velocities and accelerations respectively. All force vectors are established by assembly of element contributions and specified discrete nodal forces.

In a coupled analysis the floater is introduced as a nodal component in the finite element method model. The body forces are computed for each time step and are included in the external vector, $\mathbf{R}^E$. The exception is the vessel mass and the frequency independent part of added mass, which are included in the system mass matrix. [RIFLEX Theory Manual, 2012]

Chapter 4

Methods of Analysis

Three different analysis techniques, two uncoupled and one coupled technique, will be studied further. The methods are mainly taken from Ormberg et al. [1998].

4.1 Uncoupled Vessel Motion Analysis

In a vessel motion analysis, the primary purpose is to give a good description of the vessel motion. The slender structure response is not so important in this kind of analysis. The mooring lines are therefore included in a simplified way, often with a crude finite element (FE) model.

The vessel motion analysis will be performed in the MARINTEK program SIMO.

4.2 Uncoupled Slender Structure Analysis

In a slender structure analysis are the slender elements represented by a detailed FE model. The floater motions are applied as external loading in terms of forced boundary displacements on the slender structures. Thus, the floater motions must be known prior to the slender structure analysis. Direct wave- and current loading on the slender structure are included in the analysis.

The slender structure analysis will be performed in the MARINTEK program RIFLEX.

4.4 Coupled System Analysis

In a fully coupled analysis are the vessel force model introduced in the detailed FE model of the slender structure system. A non-linear time-domain approach is required to give adequate representation of the dynamic behaviour of the coupled vessel and slender structure system. This approach yields dynamic equilibrium between the forces acting on the floater and the slender structure response at every time step. It will therefore be no need for assessment of the LF damping from the slender structures, as this contribution is automatically included in the slender structure response. The current load on the mooring lines and risers are included in the detailed FE model. The output from such analyses will be floater motions as well as a detailed slender structure response description.

The fully coupled analysis will be done in the MARINTEK program SIMA.

Chapter 5

Software Programs

A short description of the three programs used in the analyses is given below.

5.1 SIMO

SIMO is a computer program for simulation of motions and station-keeping behaviour of complex systems of floating vessels and suspended loads.

The vessel properties are described with a set of coefficients. The hydrodynamic coefficients like added mass and radiation damping, first-order wave force and second-order mean drift forces are usually obtained from a diffraction/radiation solver such as WADAM or WAMIT. The hydrodynamic coefficients are frequency dependent, and, consequently, calculated in the frequency domain. The forces are converted to time domain by using the fast Fourier transform (FFT):

$$h(\tau) = \frac{1}{\pi}\int_0^{\infty}[\lambda(\omega)\cos(\omega\tau) - \omega\mu(\omega)\sin(\omega\tau)]\, d\omega \qquad (5.1)$$

Here h(τ) are the retardation function, and $\boldsymbol{\lambda}(\boldsymbol{\omega})$ and $\mu(\boldsymbol{\omega})$ are the frequency-dependent added mass and damping respectively.

Wind and current forces are computed by a set of direction dependent coefficients. The coefficients can include both linear and quadratic forces.

Since the purpose of SIMO is to give good descriptions of the floater motion, the slender structures can only be included with a crude FE model. The mooring lines are assumed to form catenaries, and are modelled by the catenary equations.

Risers cannot be correctly modelled in SIMO. The simple FE model available makes it impossible to model the stiffness of the risers properly. The risers are therefore absent in the 'vessel motion analyses'. On the other hand, compared to the mooring lines, risers are assumed to be of minor importance for the vessel motion characteristic. [Johannessen and Wanvik, 2002 and SIMO Theory manual, 2012]

5.2 RIFLEX

RIFLEX is a computer program for analysis of flexible risers and other slender structures, such as mooring lines, pipelines and conventional steel risers. RIFLEX is developed by MARINTEK, and the program is based on a nonlinear finite element formulation.

A global analysis of slender marine structures includes two aspects: static analysis and dynamic analysis. The static analysis determines the equilibrium configuration of the system, and the dynamic analysis gives the riser and mooring line response due to the support vessel motions, wave induced loads and currents.

The mooring lines and risers are represented by a detailed FE model. Each slender element consists of two supernodes, one node at the coordinate for the anchor and one node on the surface vessel. The supernodes are connected by simple lines. The system topology is therefore uniquely determined by the connectivity between the number of defined supernodes and lines. Each line may be built up by several segments with different lengths and properties. This is to ensure a convenient configuration of the mooring lines and risers.

The surface vessel cannot be modelled as carefully as the slender structures, and the floater motions must be given as input to the analysis. (RIFLEX Theory Manual, 2012)

5.3 SIMA

SIMA is developed as a Joint Industry Project by MARINTEK and Statoil, and is based on SIMO and RIFLEX. SIMA is a unique modelling, analysis and post-processing program especially developed for coupled global response of deep water floating systems.

In a fully coupled analysis SIMA provides an interface between SIMO and RIFLEX. The force model of the floater from SIMO is implemented as nodal forces at the top end of the FE model of the mooring lines and risers from RIFLEX. A dynamic time domain approach is used in the calculations. The vessel node forces will then be in equilibrium with the slender structures at all times, and the LF damping and current forces from the mooring lines and risers are automatically included in an accurate manner.

Chapter 6

The Analyzed System

6.1 System description

The FPSO to be analyzed is turret-moored and operates in a water depth of 913.5 m, which is characterised as 'deep water'. It has 4 lazy wave risers and 12 catenary mooring lines paired in groups of three and three, see Figure. 6.1.

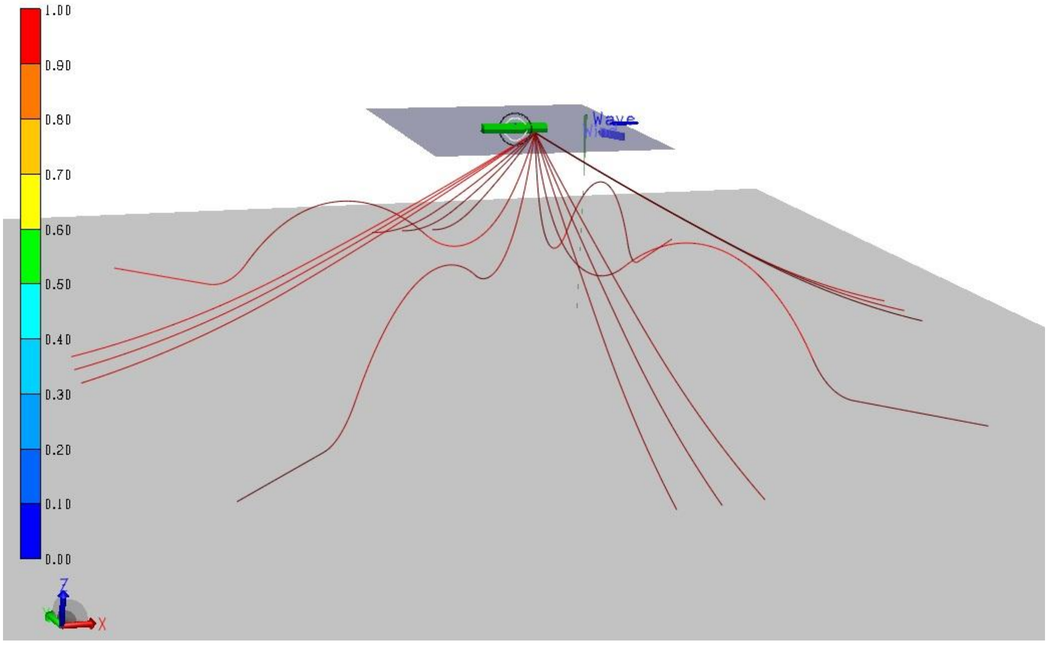


Figure 6.1 - Graphic view of the analyzed system

The main particulars of the FPSO:

Length	275 m
Breadth	45 m
Height	35 m
Draft	20.42 m
Displacement	240 300 tonnes
Distance from midship to centre of the turret	91.45 m

Table 6.1 - Main particulars of the analyzed FPSO

The mechanical properties of the mooring lines and risers:

MOORING LINES		**RISERS**
Segment 1		
Length No. of FEM elements Mass per unit length Hydrodynamic diameter Axial stiffness	45.7 m 1 178 kg/m 0.089 m 794 850 kN	820 m 40 235 kg/m 0.300 m 50 000 000 kN
Segment 2		
Length No. of FEM elements Mass per unit length Hydrodynamic diameter Axial stiffness	1127.8 m 20 38 kg/m 0.091 m 689 860 kN	1050 m 50 282 kg/m 0.650 m 50 000 000 kN
Segment 3		
Length No. of FEM element Mass per unit length Hydrodynamic diameter Axial stiffness	914.4 m 19 178 kg/m 0.089 m 794 850 kN	775 m 40 235 kg/m 0.300 m 50 000 000 kN
Pre-tension	37 400 kN	-

Table 6.2 - Mechanical properties of the mooring lines and risers in the analyses

The data used in the analyses is from a testcase given by MARINTEK.

The geometry of the system and the direction of wind, waves and current are shown on the figures below:

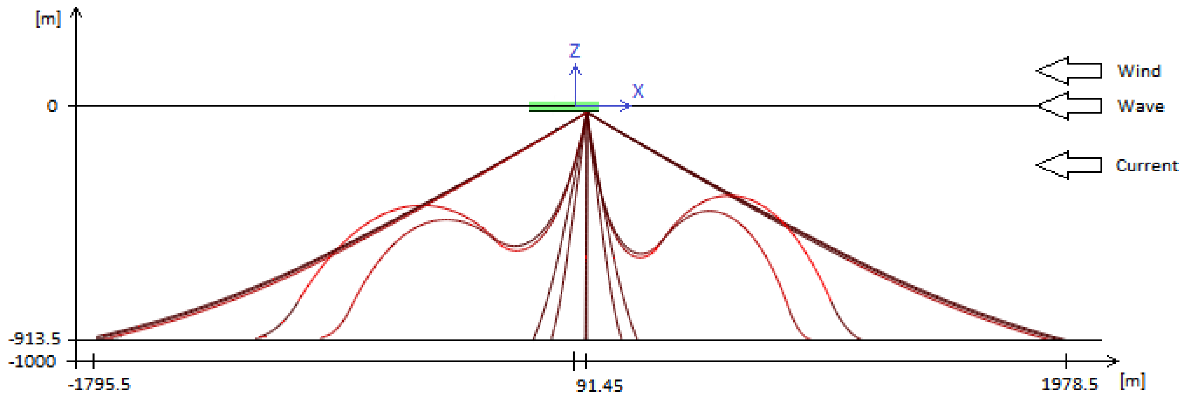


Table 6.2 - Overview of the analyzed system

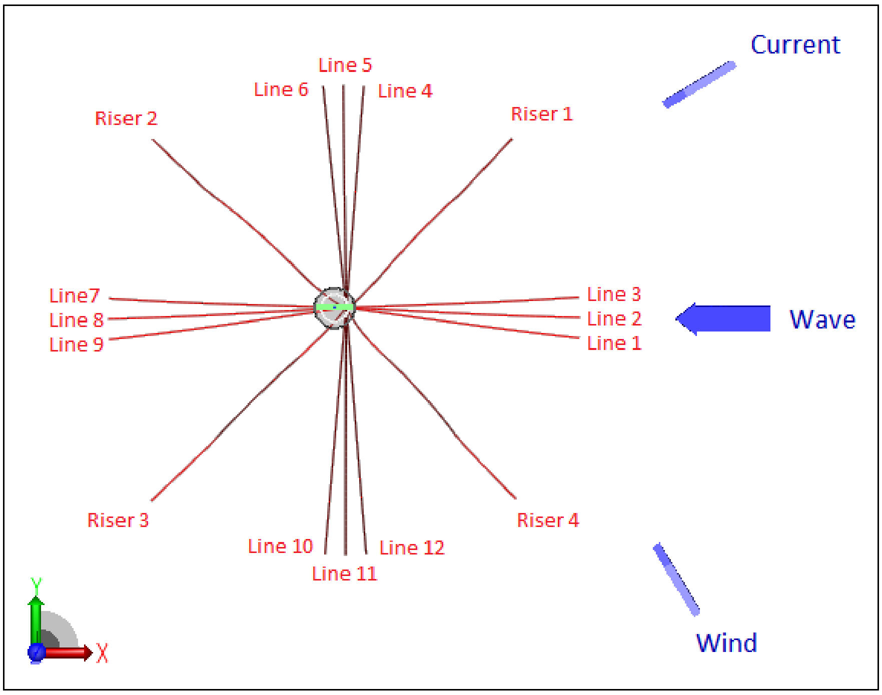


Figure 6.3 - Overview of the positions of the mooring lines and risers, and direction of wind, waves and current

6.2 System modelling

When modelling a floating system the following parts have to be accounted for in order to obtain accurate response analysis.

- Environmental effects describing wind, waves and current
- Large volume bodies to represent the floating structure
- Slender structures to present the mooring lines and risers

6.2.1 Environmental loads

The moored FPSO will experience the following environmental forces:

- Sea state: Irregular waves generated by the 3-parameter JONSWAP spectrum
  - Significant wave height, H_S: 9-15m
  - Peak period, T_P: 14.0 s
  - Peakedness parameter, γ: 2.5
  - Wave direction: 180 deg

- Wind specification: ISO 19901-1 (NPD) wind spectrum
  - Wind propagation direction: 121 deg
  - Reference height for wind velocity: 0.025 m
  - 1 hour average velocity: 41.13 m/s
  - Surface drag coefficient: 0.02

- Current specification: Current in 3 levels
  - Current level 1:
    - Global z-coordinate: 0.0 m
    - Propagation direction: 211 deg
    - Velocity: 1.293 m/s
  - Current level 2:
    - Global z-coordinate: -261.82 m
    - Propagation direction: 211 deg
    - Velocity: 0.091 m/s
  - Current level 3:
    - Global z-coordinate: -913.5 m
    - Propagation direction: 211 deg
    - Velocity: 0.091 m/s

6.2.2 Large volume bodies

The floater is a large volume body presented by a 6 DOF rigid body motion model. The motion of the large volume body will mainly come from the environmental loads. The interaction effects between the floater and the waves are described by a set of coefficients for inertia, damping and excitation forces. Both linear and quadratic forces are included in these coefficients. [SIMO Theory manual, 2012]

6.2.3 Slender structures

Slender structures are modelled by a FE model. The following physical effects will contribute to loads on the mooring lines and risers:

- Weight and inertia, governed by line mass
- Hydrostatic forces, dependent on pressure gradients
- Hydrodynamic forces, dependent on wave , current and structure motions
- Forced motion of line, dependent on vessel motions

The hydrodynamic forces are calculated according to a generalized Morison's equation, where the added mass and drag coefficients are specified for each element [RIFLEX Theory Manual, 2012]:

$$\boldsymbol{F} = \boldsymbol{F_{Inertia}} + \boldsymbol{F_{Drag}} = C_m \rho \frac{\pi}{4} D^2 \dot{\boldsymbol{u}} + C_d \frac{1}{2} \rho D \boldsymbol{u} |\boldsymbol{u}| \qquad (6.1)$$

Chapter 7

The Analyses

The analyses comprise a turret-moored FPSO operating in a water depth of 913.5 m. The FPSO experiences sea states with varying significant wave heights within realistic values for petroleum fields outside the coast of Norway:

Case 1: H_S = 12.19 m

Case 2: H_S = 15 m

Case 3: H_S = 9 m

Case 2 and 3 are performed to see how the wave height influences the coupling effects.

7.1 Uncoupled analysis

In a vessel motion analysis in SIMO are the floater motions calculated from vessel coefficients, transfer functions and retardation functions. This information is given as input before the analysis. The floater data used in the analysis is given by MARINTEK.

The slender structure analysis utilizes the motion time series obtain in the vessel motion analysis. The time series are exported from SIMO, and MATLAB is used to generate text files of the motion time series that can be read by RIFLEX.

The modelling of the mooring lines and risers are based on the input files from MARINTEK. However, several modifications are done to get to the wanted configurations and results.

Both the SIMO analysis and the RIFLEX analysis are run through SIMA.

7.2 Coupled analysis

The coupled analysis uses the same input data and component properties as the above analyses. The results should therefore be comparable with the results from the uncoupled analyses, and direct conclusions can be draw from the time series.

7.3 Simulation time

Ormberg et al. [1997] showed that a simulation length of approximately 1h is needed for the LF damping to stabilize. The simulation length in the analyses is 3800s, which is longer than 1h. Hence, the analyses should give reliable estimates of the floater motions and line forces. However, the simulation length is too short to represent a real sea state, and extreme value analyses cannot be performed.

Chapter 8

Results and Discussions

Three sets of analyses, two uncoupled and one coupled analysis, have been performed on a turret-moored FPSO. The FPSO experiences three different significant wave heights: H_S = 12.19m, H_S = 15 m and H_S = 9m. Time series of the motions are compared for each case.

Three different motion time series is presented:

- HF motion (HF is here the frequency corresponding to the incident waves)
- HF + LF motion without wind
- HF + LF motion with wind

I addition, the motion spectra, standard deviations, line forces and CPU time are studied.

8.1 Case 1

8.1.1 Motion time series

Only the last 400s of each time series is presented below. This is to make the paths of the graphs more apparent. In the last 400s the LF damping should have stabilized, and the time series will give a good indication of the total motions of the FPSO. The complete motion time series can be found in Appendix A.

SIMO

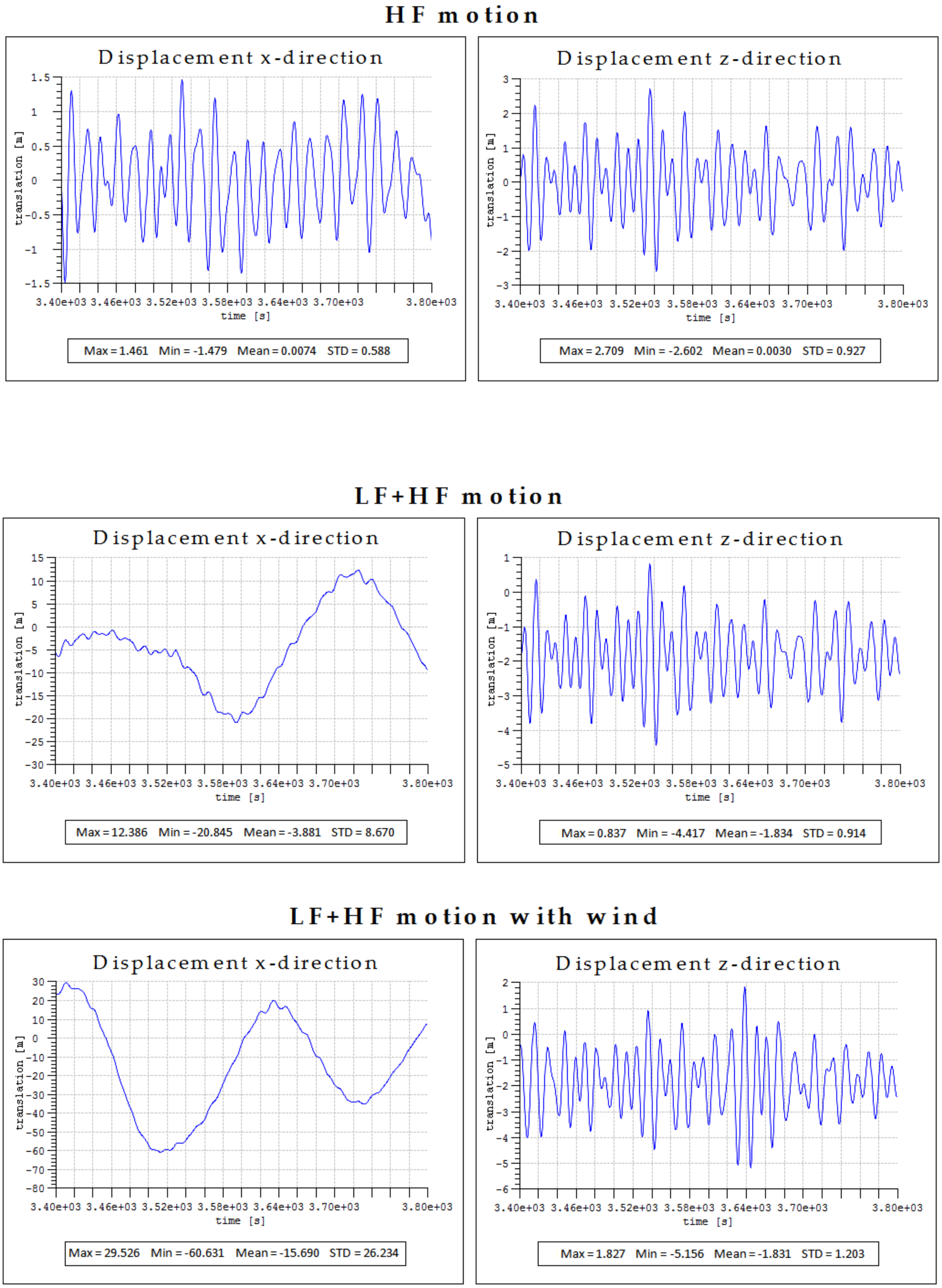


Figure 8.1 - The surge and heave motion from SIMO, H_S = 12.19m

RIFLEX

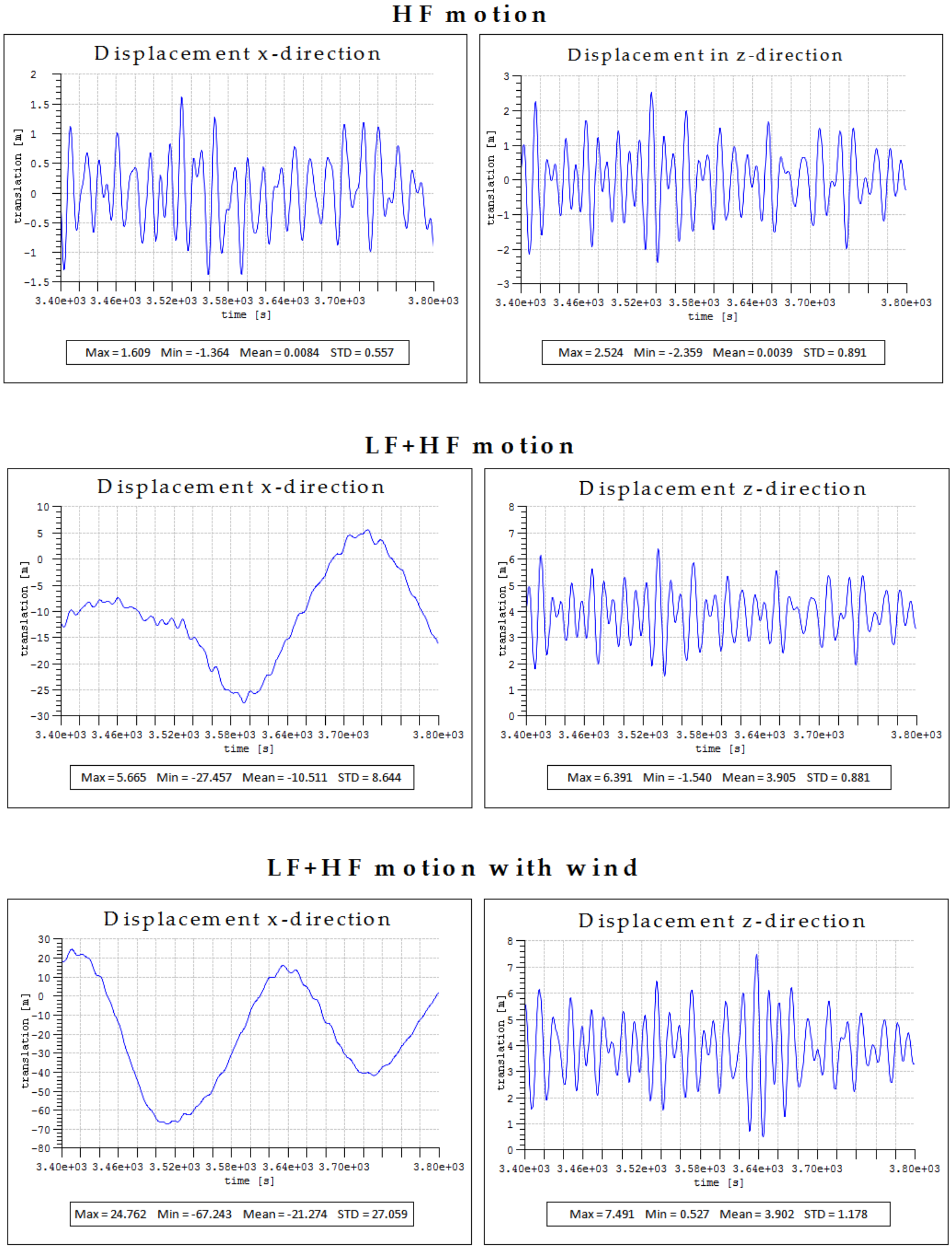


Figure 8.2 - The surge and heave motion from RIFLEX, Hs = 12.19m

SIMA

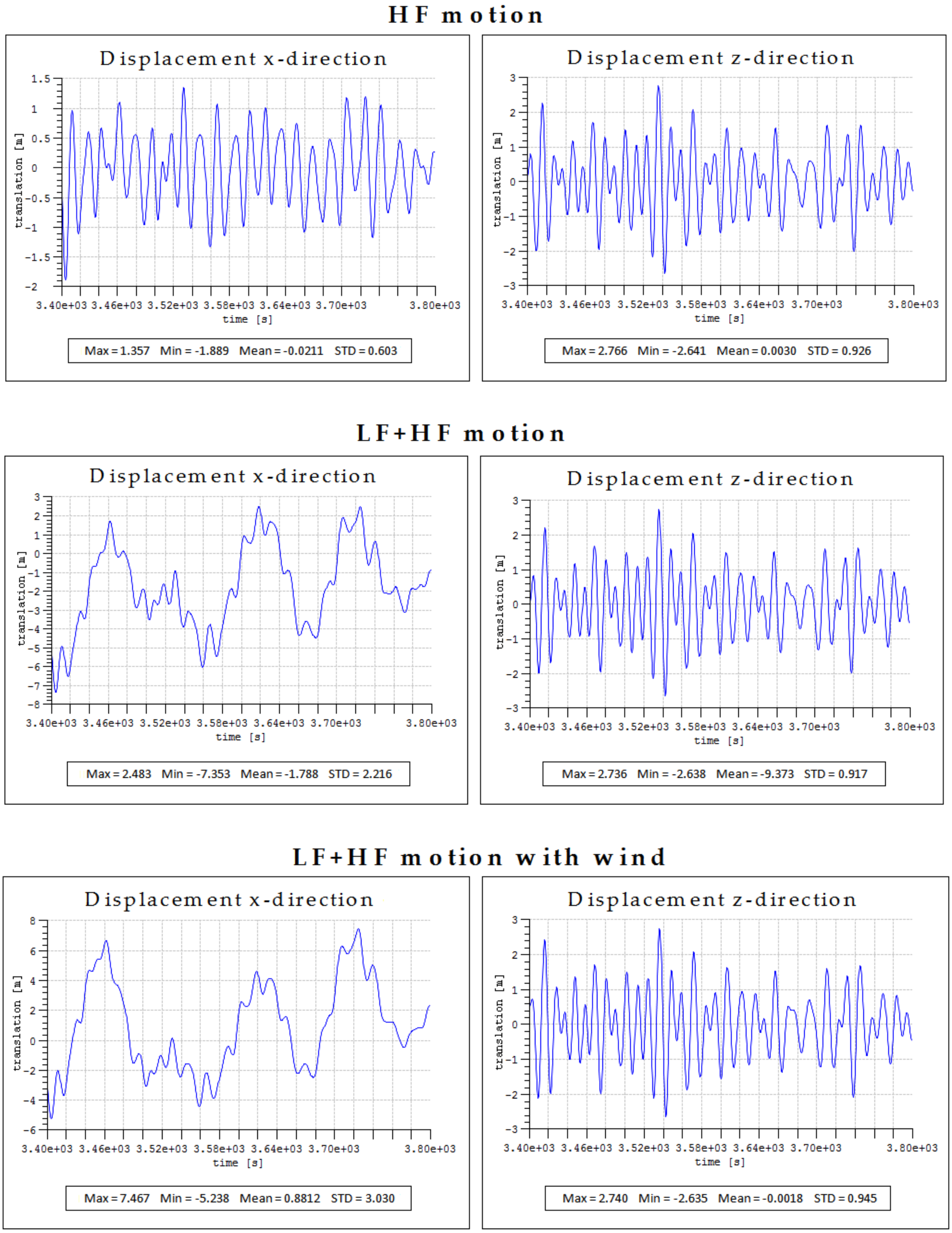


Figure 8.3 - The surge and heave motion from SIMA, Hs = 12.19m

Surge

The figures presented show that the graphs obtained in SIMO and in RIFLEX have the same tendencies, which is naturally as RIFLEX utilizes the motion time series from SIMO in the calculations. Hence, the two uncoupled analyses will give very similar results.

The graphs show that the surge motion is dominated by the LF motion. A small HF motion is observed, but it is of minor importance compared to the LF motion.

The time series of the total motion (HF+LF motion) clearly show the importance of taking LF damping and current loads on the slender structures into account. The standard deviation is 25 percent smaller in the coupled analysis where the coupling effects are considered than in the uncoupled analyses.

By including the wind forces, the importance of including the coupling effects become even more evident. The maximum response increases considerably in the uncoupled analyses when wind is included. Only a small increase in the maximum response is observed in the coupled analysis.

According to the 22nd ITTC report [1999] the maximum allowable offset is typically 10 percent of the water depth. The analyzed FPSO is operating in a water depth of 913.5m, which means that the offset should not be larger than 90m. The graphs show that the surge motions from the uncoupled analyses are approximately 90m when wind is considered, which is on the limit. The surge motion from the coupled analysis is well within the limit.

Heave

The graphs indicate that the HF motion dominates the heave motion. All the three programs SIMO, RIFLEX and SIMA give very similar results for the heave motion. Hence, the HF motion is not significantly affected by the coupling effects. It can also be seen that wind forces have a negligible effect on the heave motion.

8.1.2 Motion spectra

SIMO

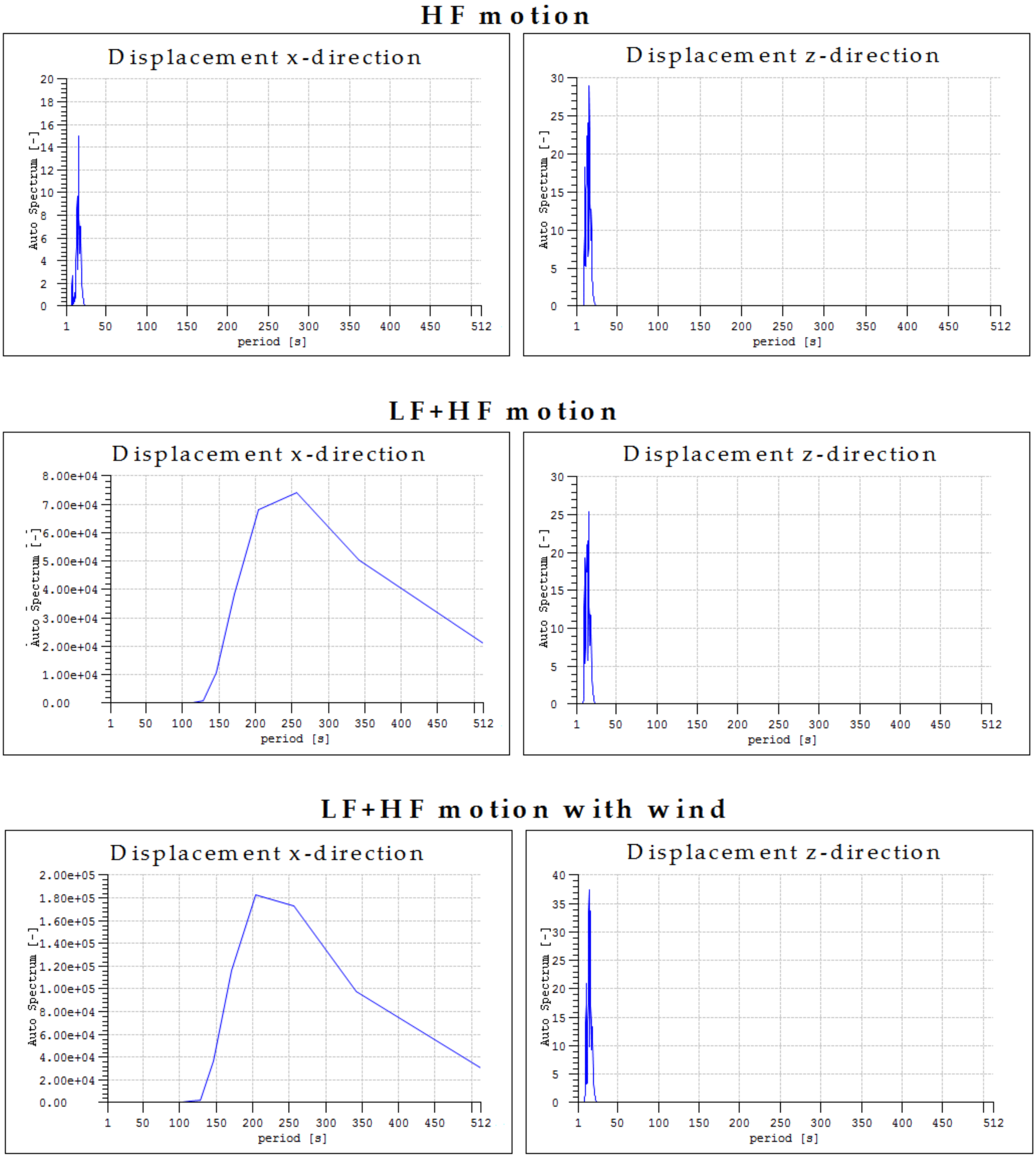


Figure 8.4 - Motion spectra from SIMO, Hs = 12.19m

RIFLEX

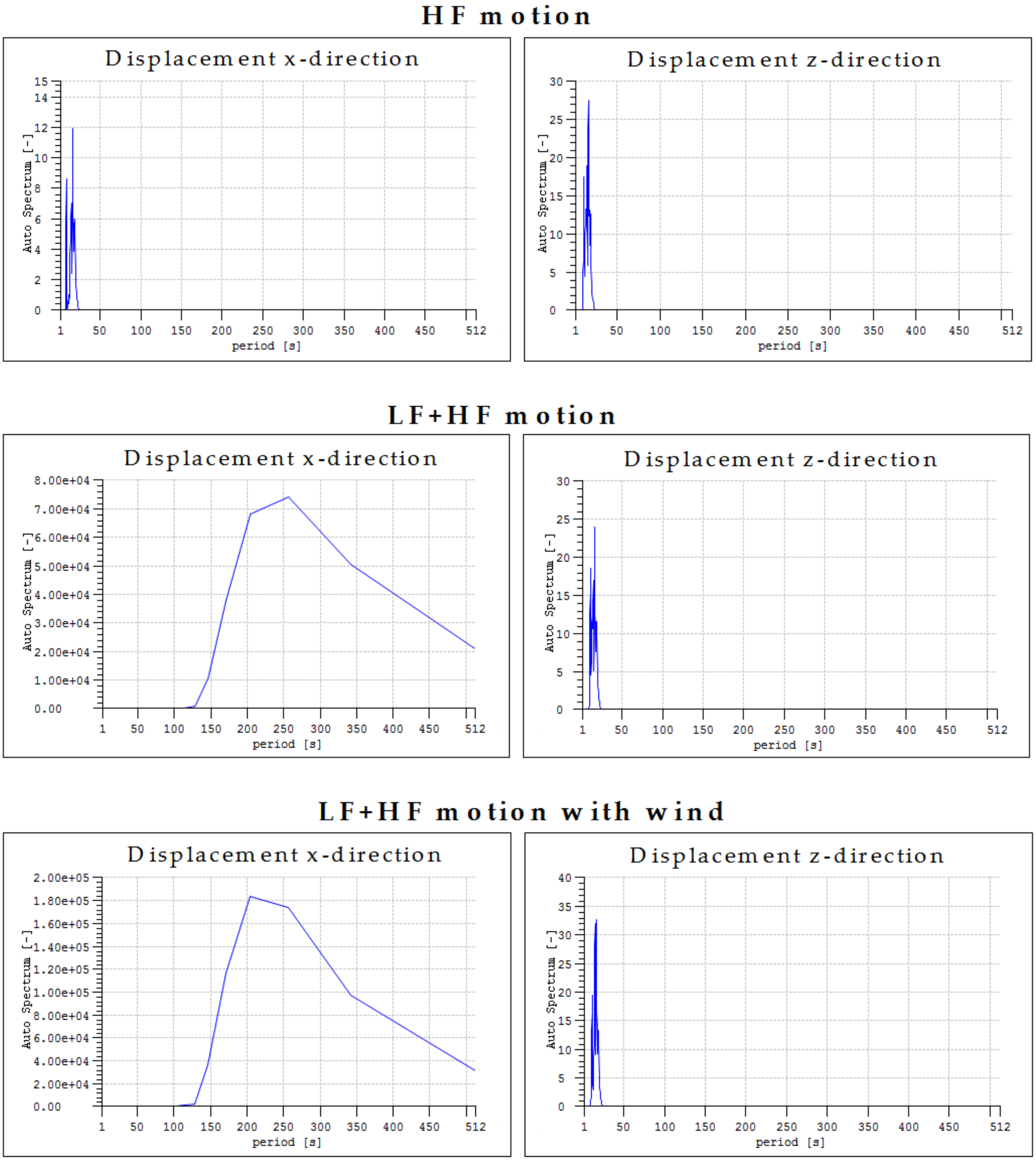


Figure 8.5 - Motion spectra from RIFLEX, Hs = 12.19m

SIMA

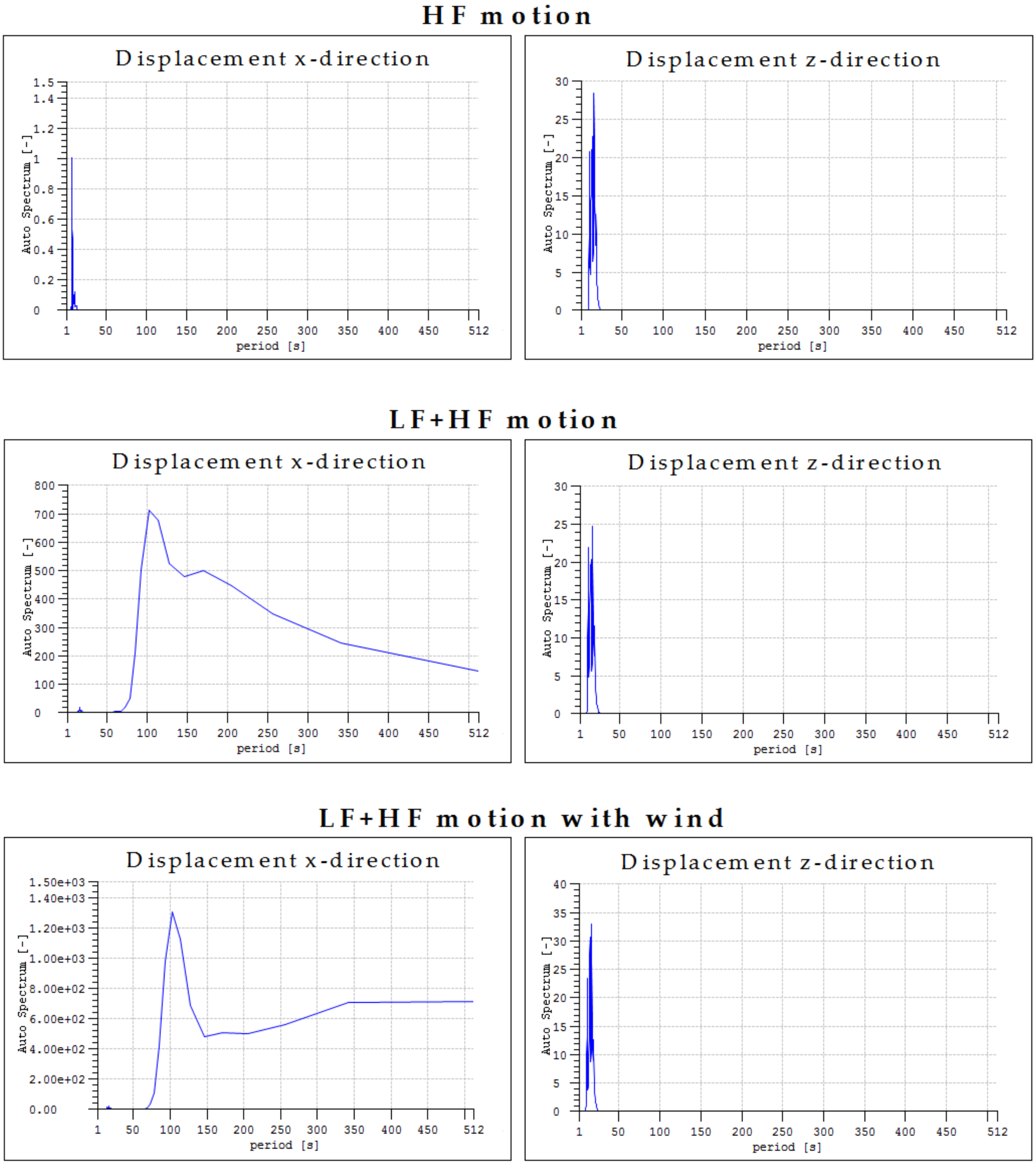


Figure 8.6 - Motion spectra from SIMA, Hs = 12.19m

The spectra show which frequencies, or periods, that are present in the motions of the FPSO. The spectra indicate the same as the motion time series; the surge motion is governed by the LF motion, while the heave motion is dominated by the HF motion. This is a reasonable result as the natural period in surge is large, typically larger than 100s, and the natural period in heave is relatively short and within the first-order wave-frequency range.   The LF motion is also significantly smaller in the spectra from the coupled analysis than in the spectra from the two uncoupled analyses.

In the motion time series, it is observed a small HF motion in addition to the LF motion in surge. This HF motion is so small compared to the LF motion that it is not present in the total motion spectra from the uncoupled analyses. A small contribution is seen in the spectra from the coupled analyses.

8.2 Case 2 & 3

The results from case 2 and 3 indicate the same as case 1. The uncoupled analyses severely overpredict the surge motion, and the importance of including the LF damping and current loads on the mooring lines and risers are again emphasized. The motion time series and the spectra for case 2 and 3 can be found in Appendix B and C respectively.

8.3 Standard deviation

The standard deviation of the motion time series for all three cases are plotted together to see how the significant wave height affects the results from the analyses.

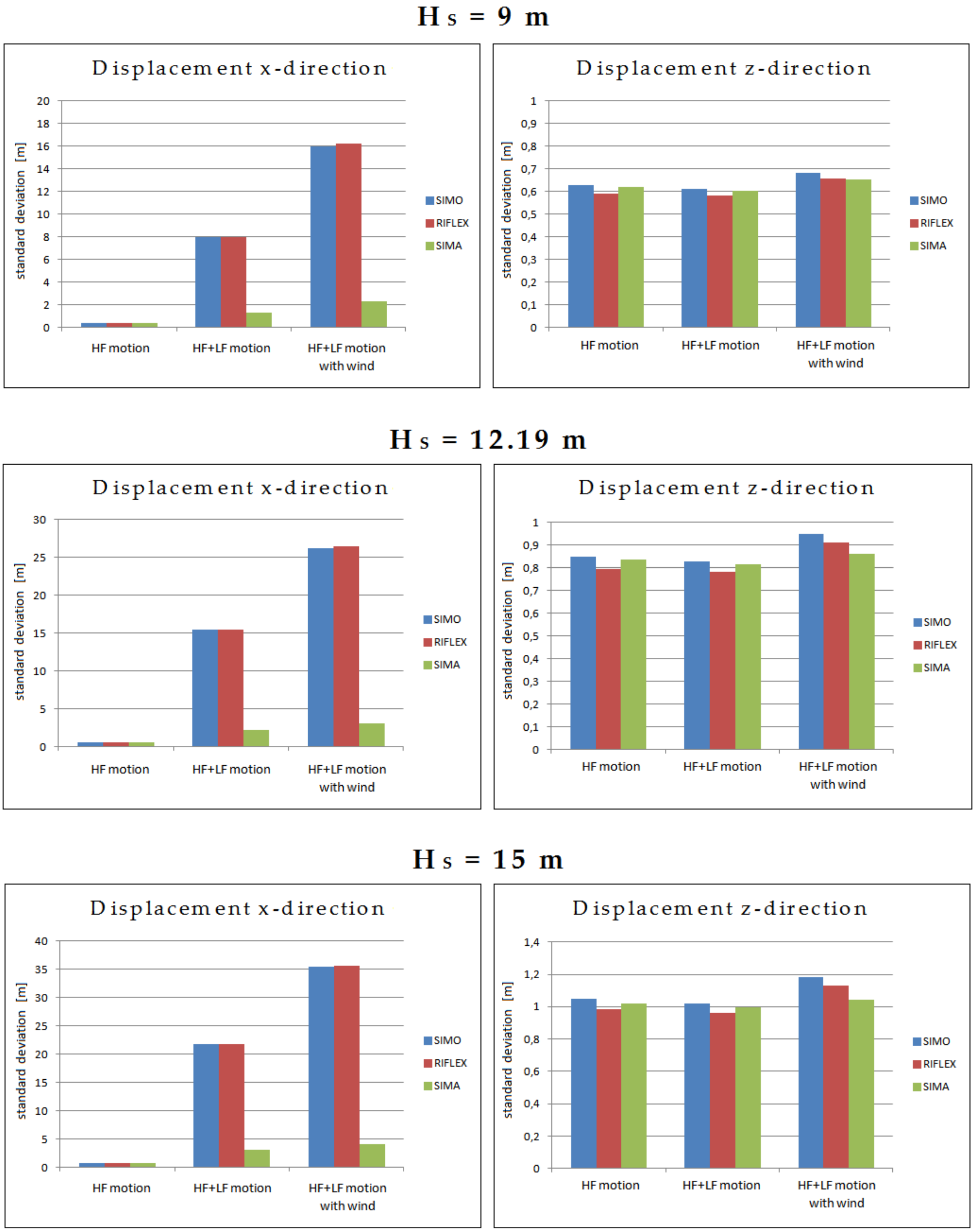


Figure 8.7 - Comparison of the standard deviation for surge and heave motion

The plots of the standard deviation emphasize the conclusions that have been drawn above. The uncoupled and coupled analyses give similar estimates of the HF motions. This is seen both in the surge and heave motion. Hence, the standard deviations also show that the HF motions are not significantly affected by the coupling effects or wind forces.

The uncoupled analyses severely overestimate the total surge motion. Again it is emphasized that including the LF damping and current loads on mooring lines and risers in a simplified way is not adequate in deep water analysis.

The significant wave height influences the surge motion to a much greater extent than the heave motion. The standard deviation of the surge motions increases considerably when the wave height is increased by 3 metre. The heave motions experience a small increase when the wave height is increased. The importance of including the LF damping and current forces on the mooring lines and risers in an accurate manner will therefore increase with increasing wave height.

8.4 Line forces

The results presented are from Case 1 when wind is included in the calculations.

8.4.1 Mooring lines

The forces in three mooring lines with different angles relative to the wave propagation direction are compared. The mooring lines considered are number 2, 5 and 8, see Figure 8.8.

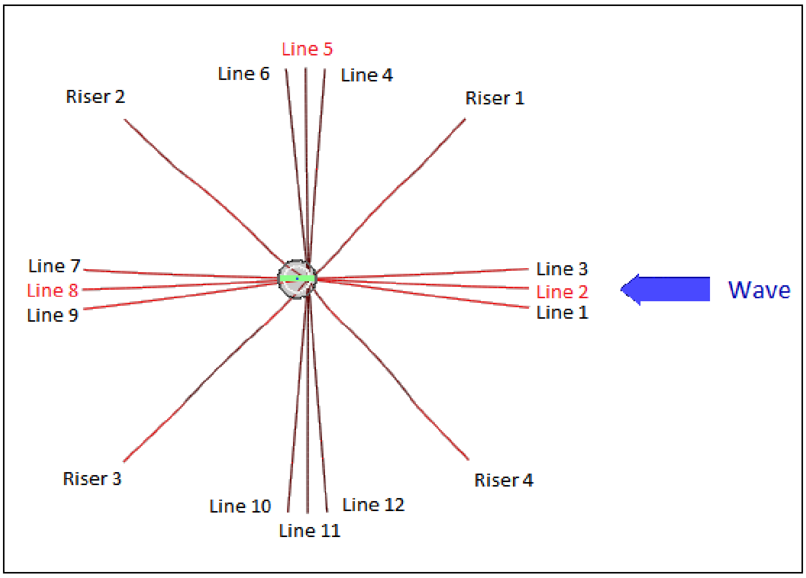


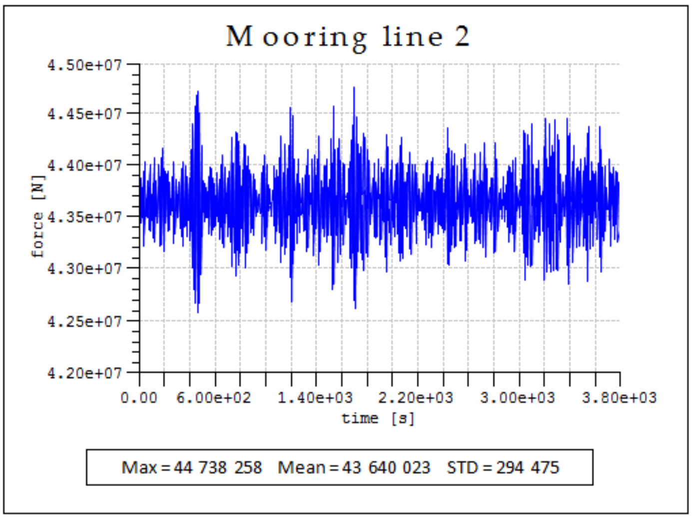
Figure 8.8 - Overview of the analyzed mooring lines

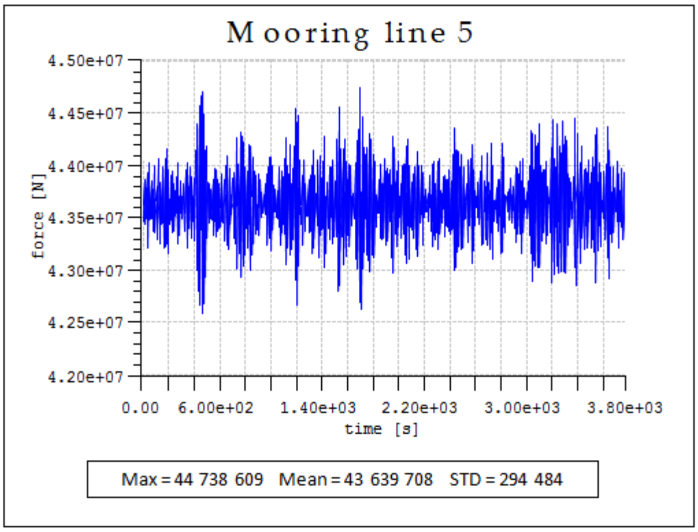
The graphs below show that both the uncoupled analyses overestimate the forces in the mooring lines. Especially the vessel motion analyses in SIMO result in too large forces. The forces are approximately 10 times larger than the forces from the coupled SIMA analyses. The forces are also almost identical for all three mooring lines. It should be some variations in the forces as the position of the mooring line relative to the wave direction has an influence. The effect of the crude FE model of the mooring lines used in the vessel motion analyses is therefore particularly pronounced in the obtained forces.

The forces from the RIFLEX analysis have large variations compared the coupled analysis, which is a consequence of the large and overestimated surge motions.

Both the uncoupled RIFLEX analysis and the coupled SIMA analysis show that mooring line 8 has the lowest forces. This is expected due to the position of the mooring line relative to the wave direction. The average force is highest for mooring line 2, however, the maximum force is almost equally high for both mooring line 2 and 5.

SIMO





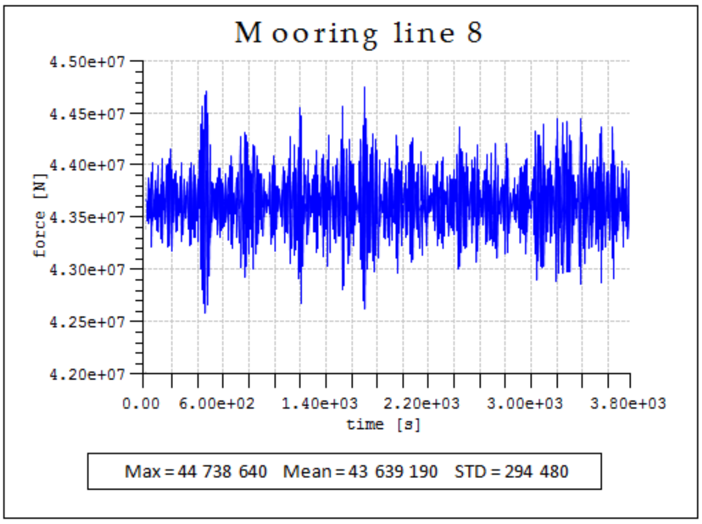


Figure 8.9 - Mooring line forces from SIMO, H_S = 12.19m and wind included

RIFLEX

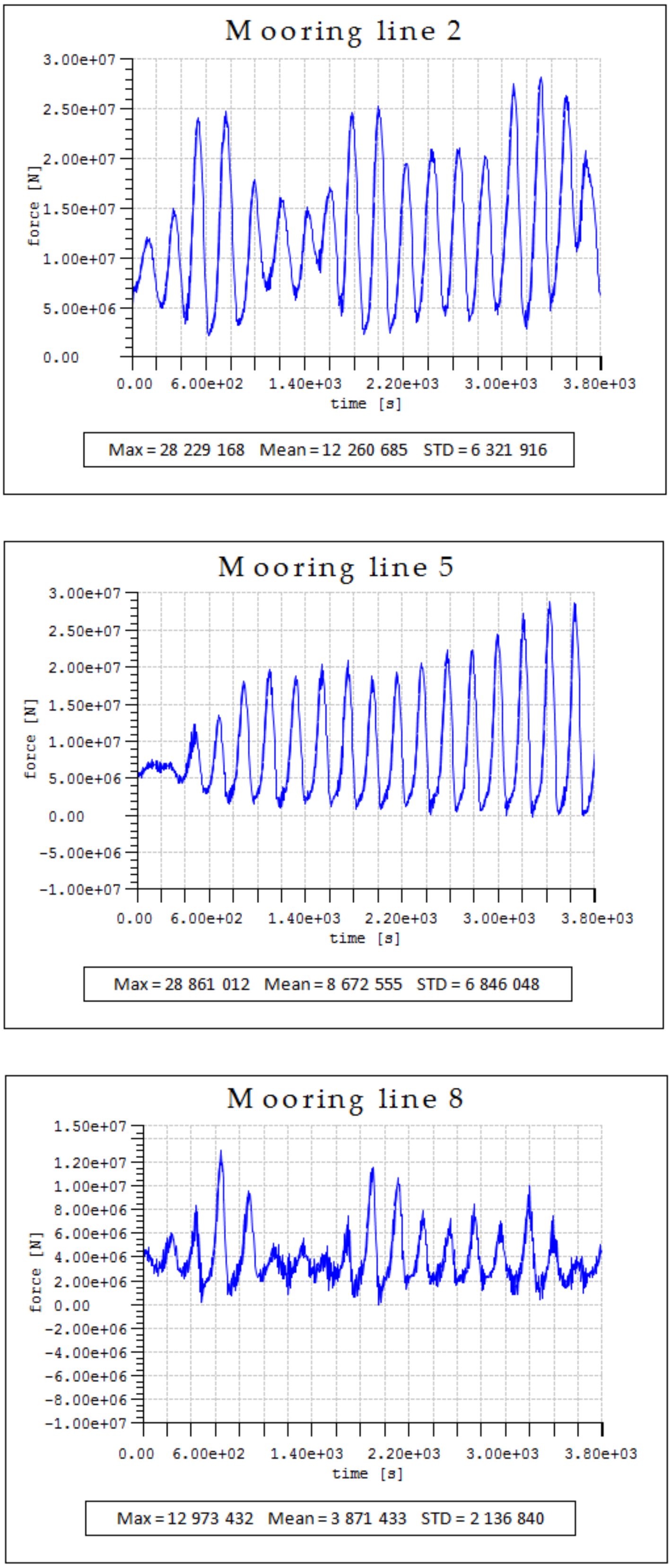
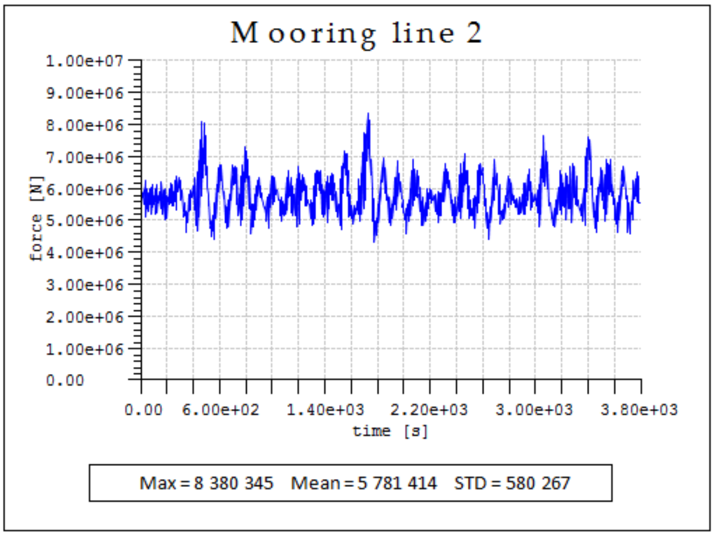
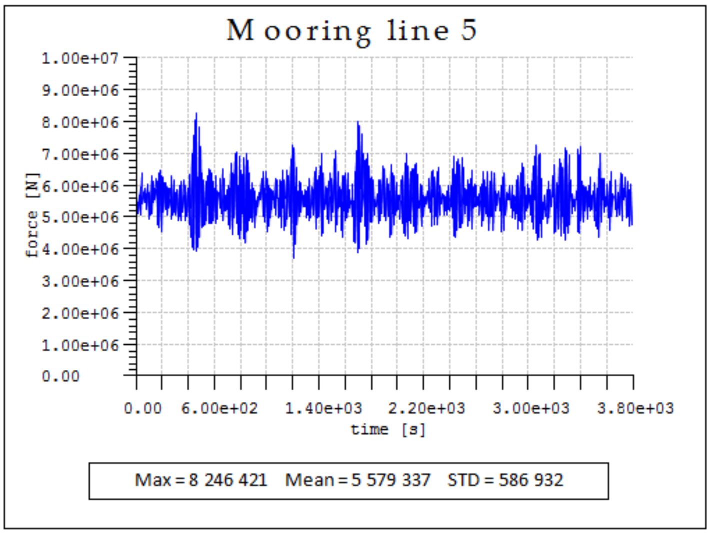


Figure 8.10 - Mooring line forces from RIFLEX, H_S = 12.19m and wind included

SIMA





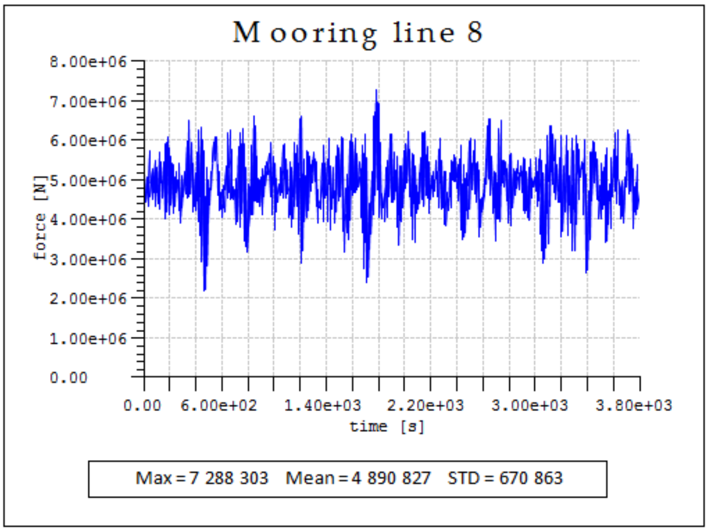


Figure 8.11 - Mooring line forces from SIMA, Hs = 12.19m and wind included

8.4.2 Risers

The forces in two risers with different angles relative to the wave propagation direction are also presented. Since risers cannot be modelled in SIMO, only the results from RIFLEX and SIMA are compared. The risers considered are number 1 and 2, see Figure 8.12.

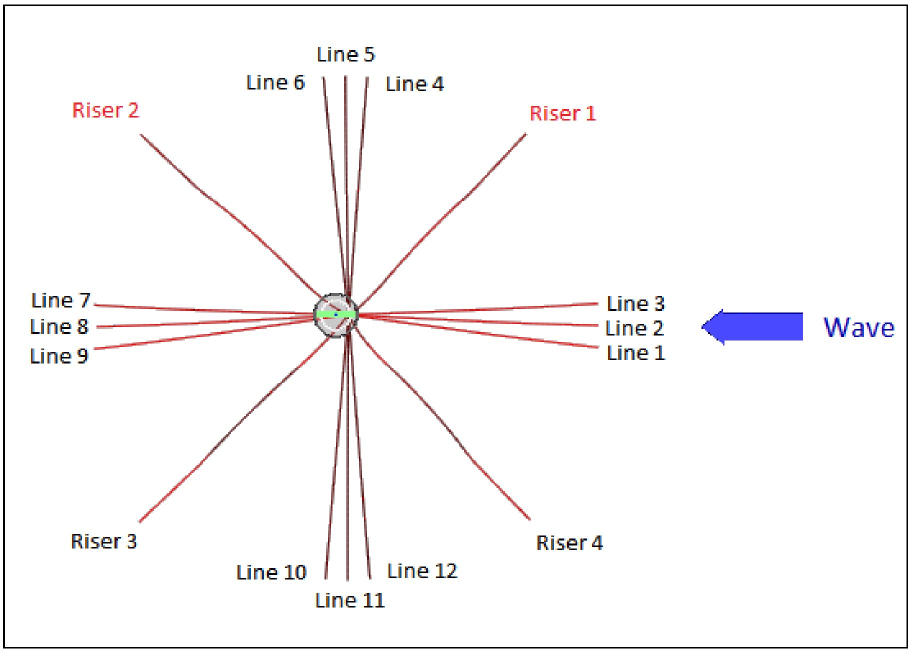


Figure 8.12 - Overview of the analyzed risers

The below figures indicate that riser forces obtain with an uncoupled and a coupled analysis are very similar. Hence, the overprediction of the surge motion from the uncoupled analysis does not affect the riser forces.

The position of the riser relative to the wave direction also has limited influence on the results.

RIFLEX

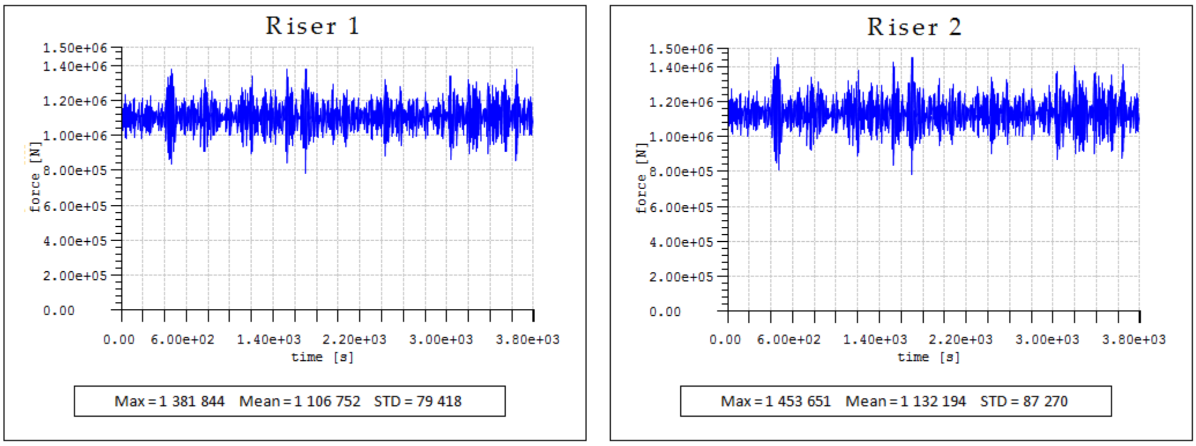


Figure 8.13 - Riser forces from RIFLEX, H_S = 12.19m and wind included

SIMA

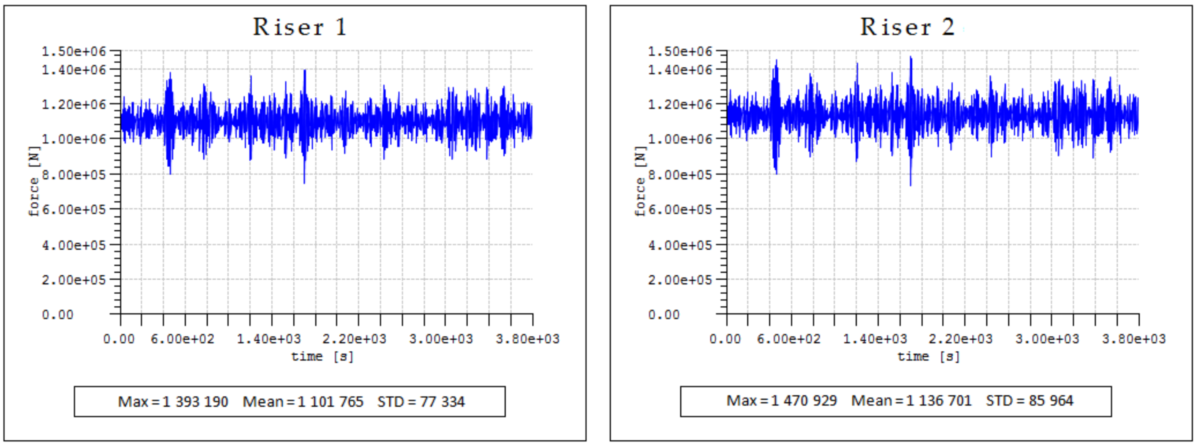


Figure 8.14 - Riser forces from SIMA, H_S = 12.19m and wind included

8.5 CPU time

The CPU time required to perform a vessel motion analysis in SIMO, a slender structure analysis in RIFLEX and a fully coupled analysis in SIMA are shown in the table. The numbers are from Case 1 when wind is included.

Program	CPU time
Uncoupled RIFLEX analysis	510.4 s (=8.5 min)
Uncoupled SIMO analysis	103.9 s (=1.73 min)
Coupled SIMA analysis	632.7 s (=10.5 min)

Table 8.1 - CPU time required to perform the analyses

The vessel motion analysis in SIMO requires least CPU time. This indicates that the detailed FE model of the slender structures allowed in RIFLEX and SIMA is the factor contributing most to long computation time.

The small difference in required CPU time in an uncoupled RIFLEX analysis and a coupled SIMA analysis should also be noted. The computation time required to perform a fully coupled analysis is significantly shorter now compared to a few years back [Ormberg et al., 1997]. A coupled approach is therefore highly relevant to use in design analysis of new concepts. On the other hand, the analyses performed in this study have a relatively short simulation time. How the required CPU time for a fully coupled analysis changes with increased simulation time is not covered in this project.

A more detailed overview of the CPU time required in the different stages of the analyses is given in Appendix D.

Chapter 9

Experiences with the Analysis Programs

It has been a lot of problems with the analyses, both regarding warning and error messages and to obtain reliable results. Especially the uncoupled SIMO and RIFLEX analyses were troublesome, and several months are spent on troubleshooting before realistic results were obtained. Using three different software programs also make it more difficult to ask for help. People are often specialized in one of the programs, and are therefore only able to answer questions related to 'their program'.

SIMA is a new software developed especially to perform coupled analyses. SIMA was released in September 2012 which means that the program has been through a 'testing period' during the work with the thesis. Consequently, bugs in the software have sometimes made it difficult to run the analyses. The lack of manuals and publications about the program has also made it challenging to learn how the different tools available in SIMA work. However, SIMA has been working very well the last couple of months. SIMA makes it easier to model and analyze slender structures and marine operations compared to SIMO and RIFLEX alone. It is no problem editing the input files when they are imported in SIMA, and the program gives instantaneously feedback and assistance if something in the input file is wrong. The post-processing tool in SIMA is also very helpful, and it gives you a lot of opportunities when analyzing the results.

Chapter 10

Conclusion

The methodology for both uncoupled and coupled analyses has been outlined and applied on a turret-moored FPSO operating in deep water. The FPSO experienced three different significant wave heights: 9m, 12.19m and 15m.

The motion time series and spectra showed that the surge motion is governed by the LF motion. The use of an uncoupled separate analysis approach overestimates the LF motion, and the overestimation increases with increasing wave height. Thus, it can be concluded that coupling effects are pronounced in at water depth of 913.5m and must to be included in the calculations in an accurate manner. In deep water, a coupled analysis approach is therefore strongly preferred.

The heave motion of a ship-shaped floater is dominated by the HF motion. The HF motion is not significantly affected by the coupling effects, and uncoupled and coupled analyses give similar results of the heave motion.

The uncoupled analyses overpredict the mooring line forces. This is a consequence of the large surge motions. The forces in the risers are not affected by the overpredicted motions, and the uncoupled RIFLEX analysis and coupled SIMA analysis give similar results.

A fully coupled analysis has earlier been too time-consuming to be used in design analyses. However, the computer and hardware development has come so far that the difference in required CPU time in an uncoupled and a coupled analysis is small.

Chapter 11

Future Work

The need to include the LF damping and current forces from the mooring lines and risers in an accurate manner is demonstrated by a set of analyses on a floating production unit. Further works could look at production units operating in more shallow water than 900 metre, and try to find a criterion for when uncoupled models can give accurate results and when coupled analyses must be applied.

A study on how the choice of material and configuration of the mooring system and risers affect the coupling effects could also be performed. This is particularly important nowadays when the oil industry moves its activities into deeper and deeper water, and new design for deep water concepts are needed.

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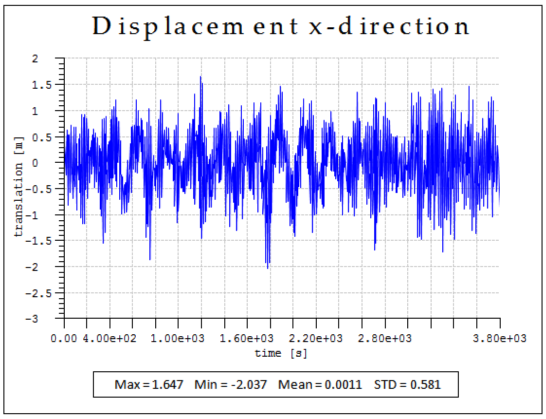
SIMO User Manual, MARINTEK Report 516412.00.04, Appendix A, [2012]

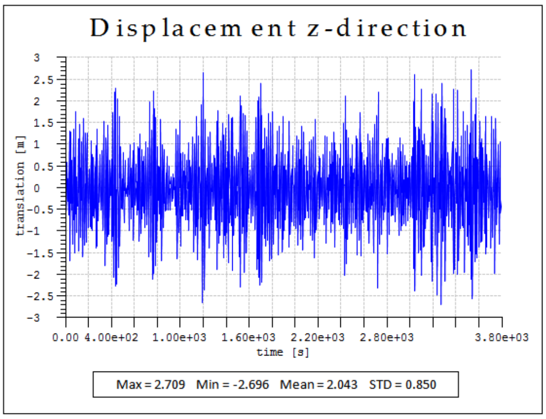
Appendix

Appendix A

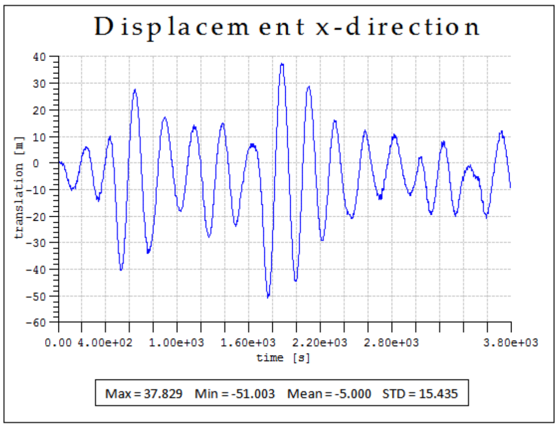
Motion time series Hs = 12.19m

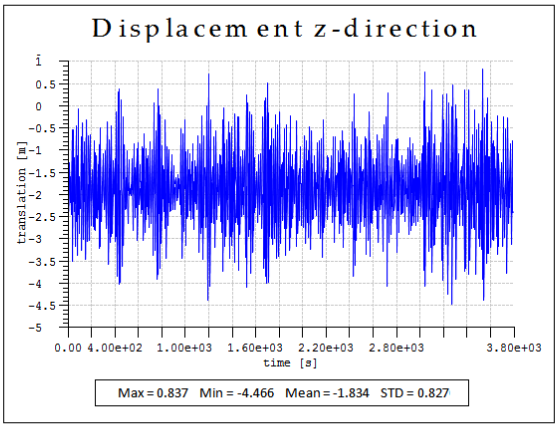
HF motion – SIMO



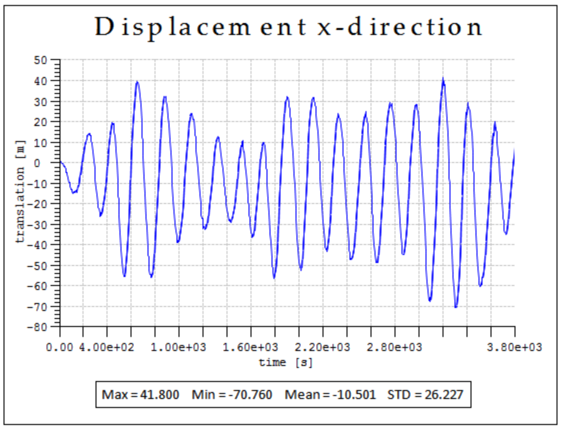


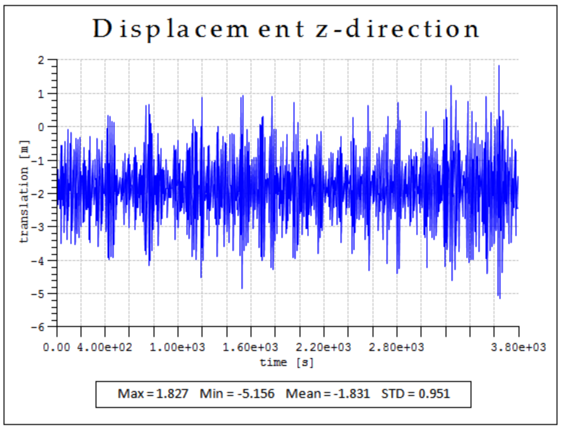
HF+LF motion





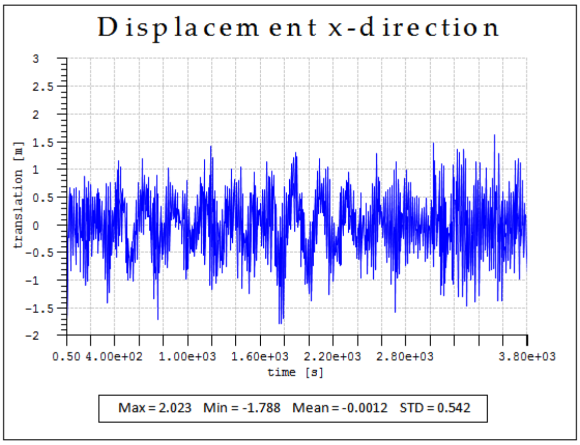
HF+LF motion with wind

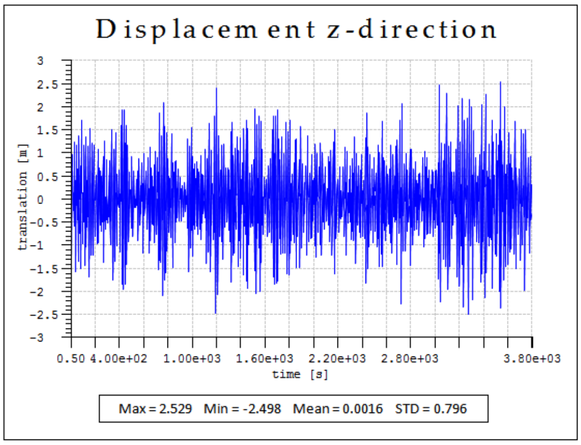




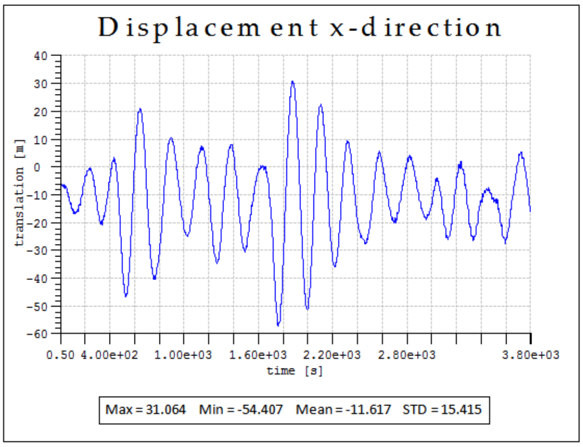
RIFLEX

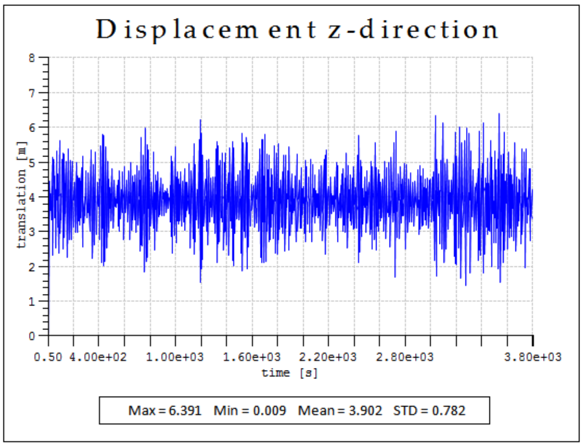
HF motion



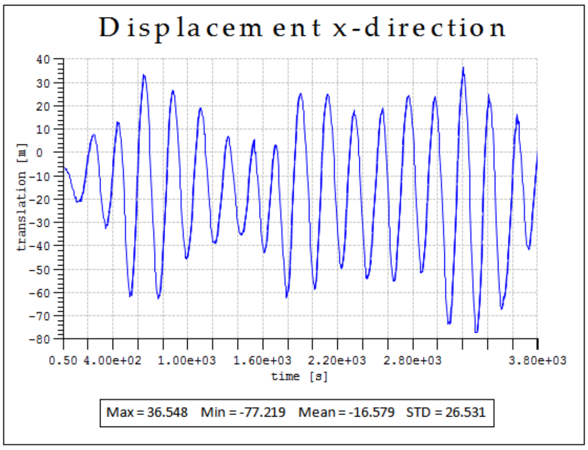


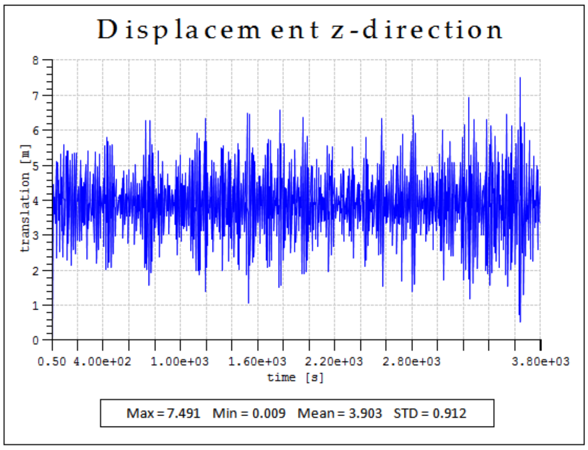
HF+LF motion





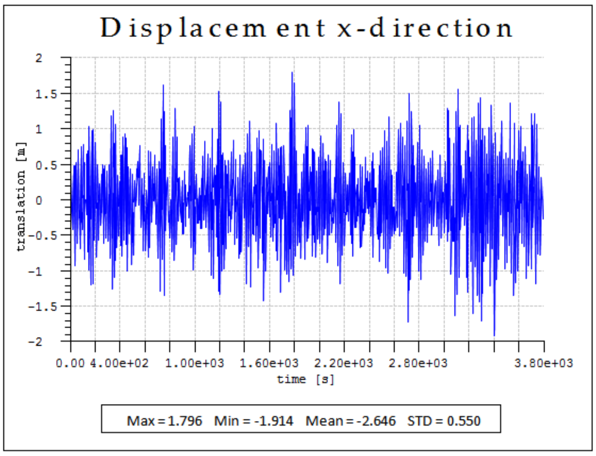
HF+LF motion with wind

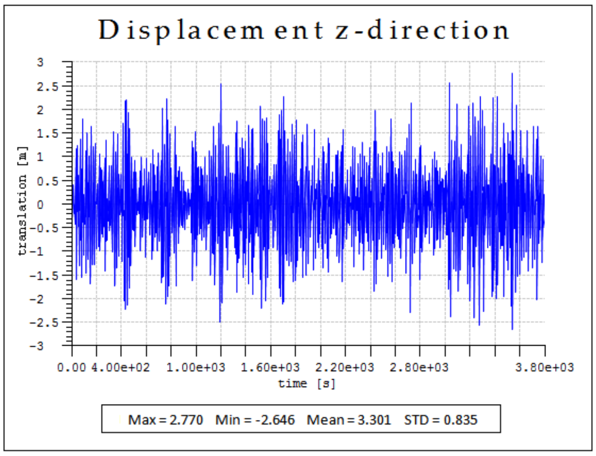




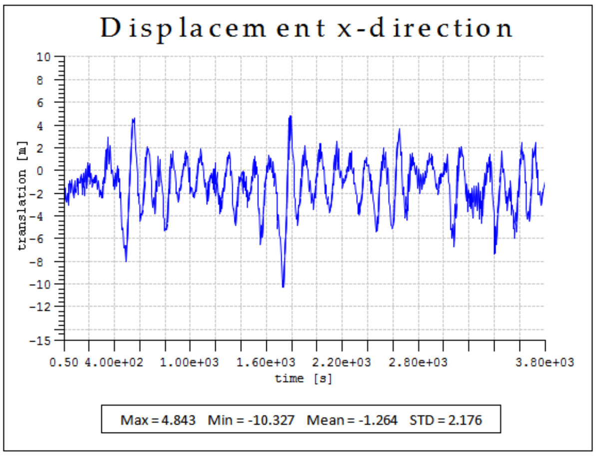
SIMA

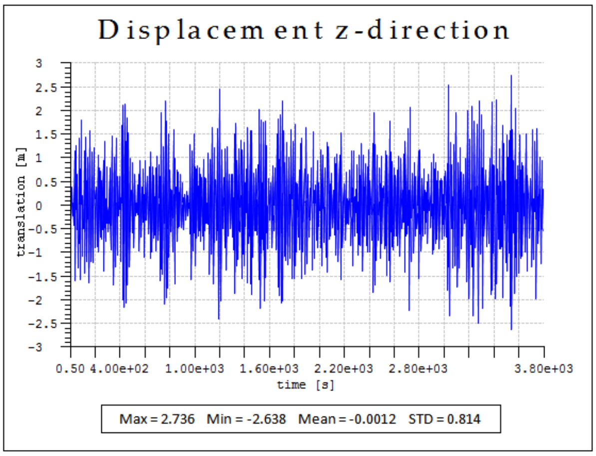
HF motion



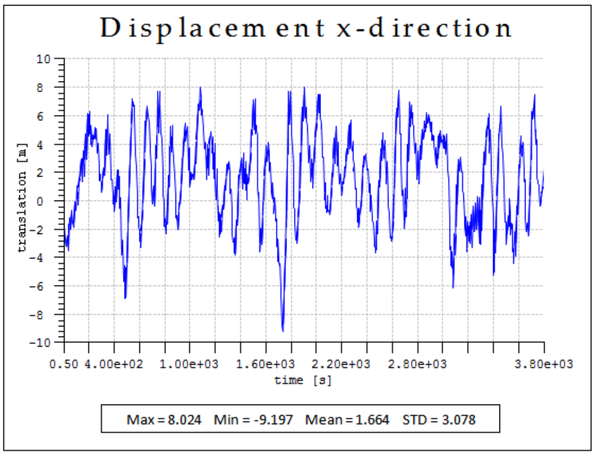


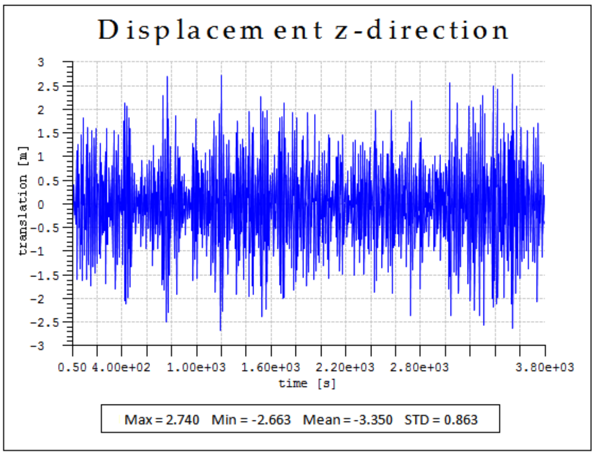
HF+LF motion





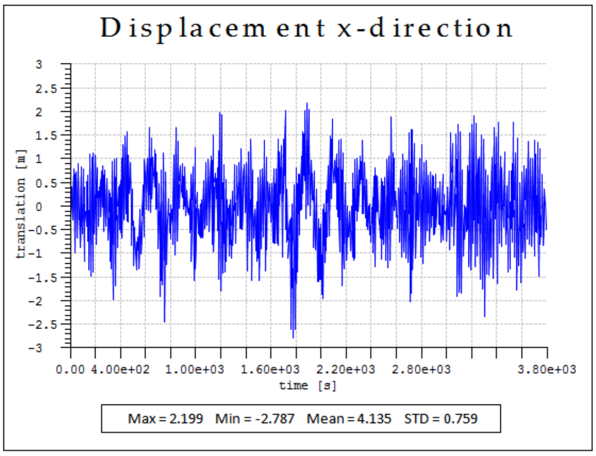
HF+LF motion with wind

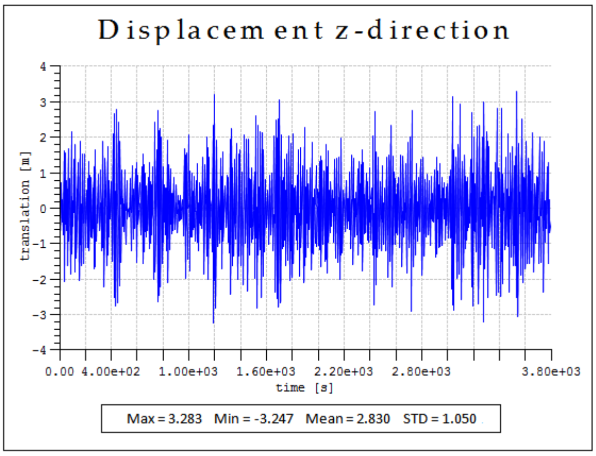




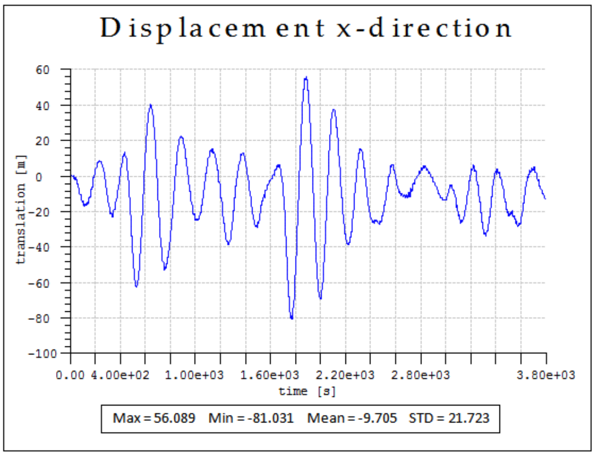
Motion time series Hs = 15m

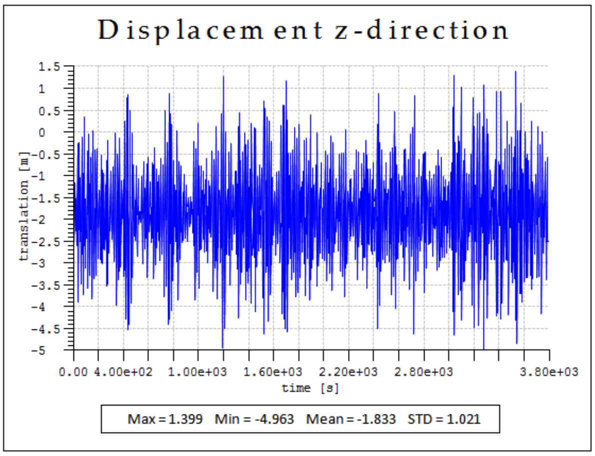
HF motion – SIMO



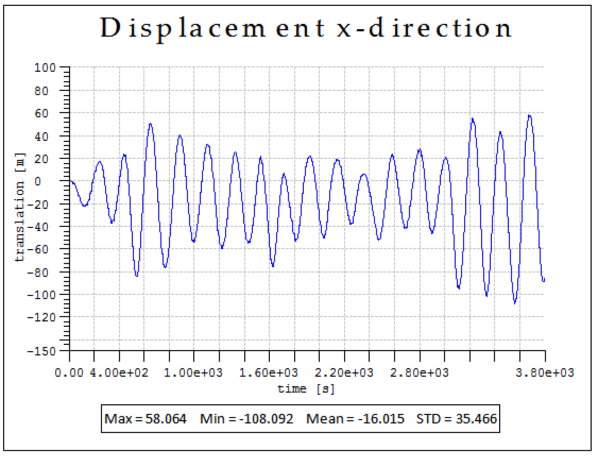


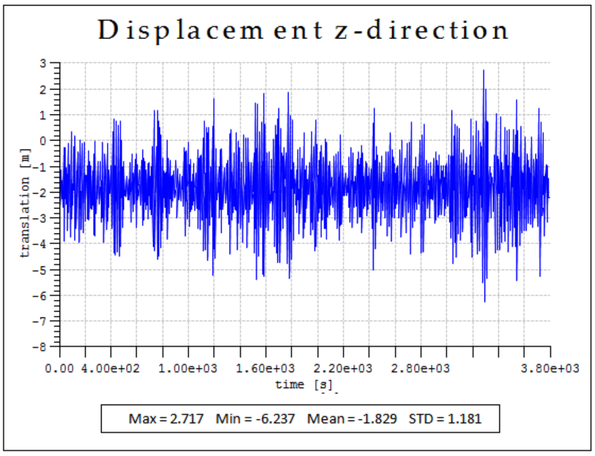
HF+LF motion





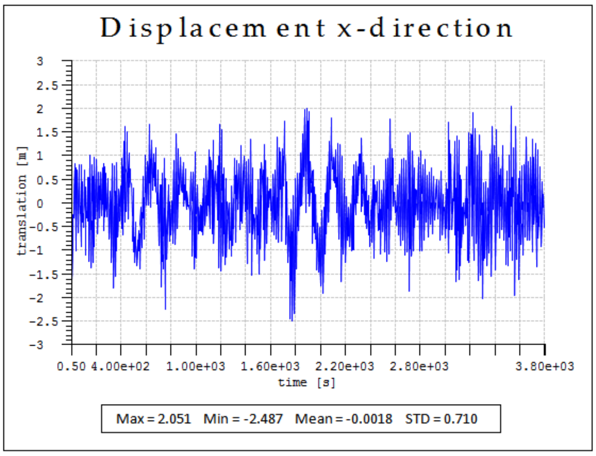
HF+LF motion with wind

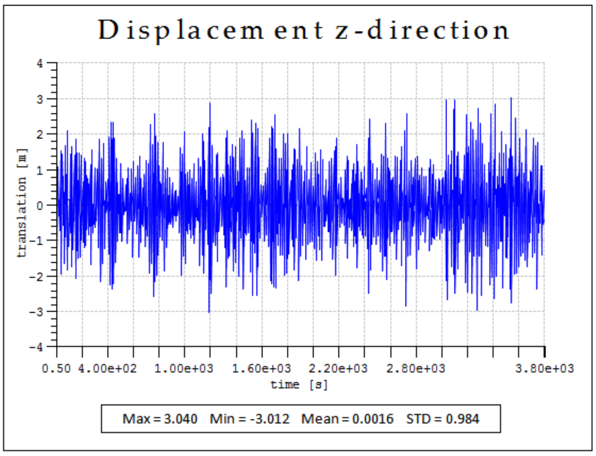




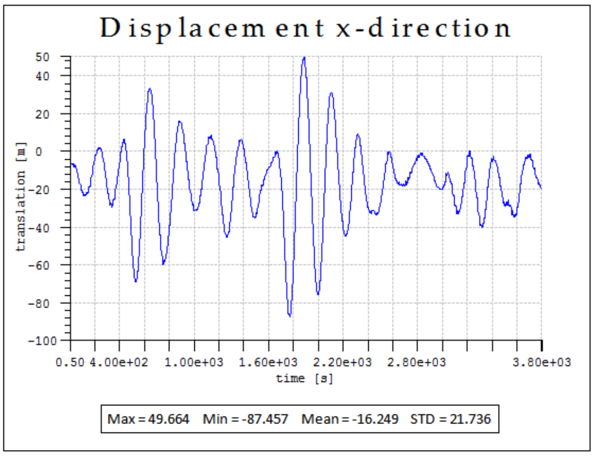
RIFLEX

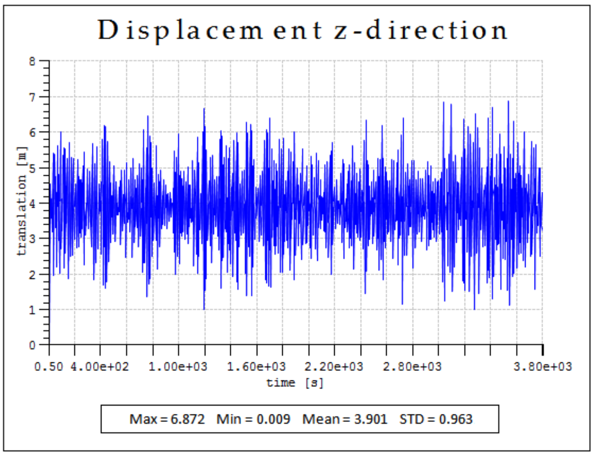
HF motion



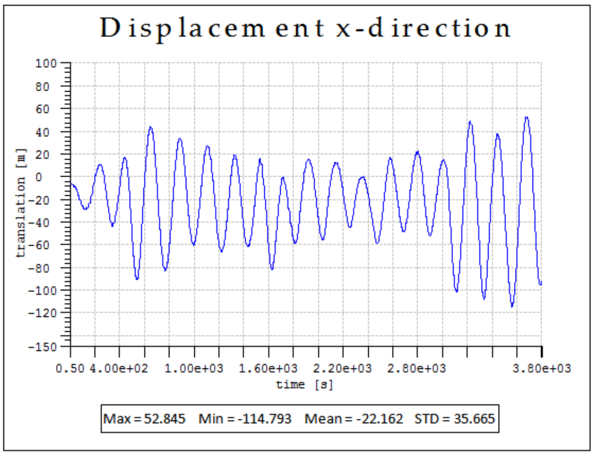


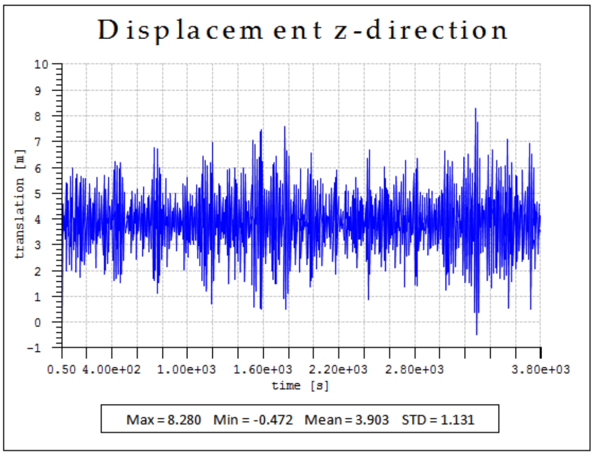
HF+LF motion





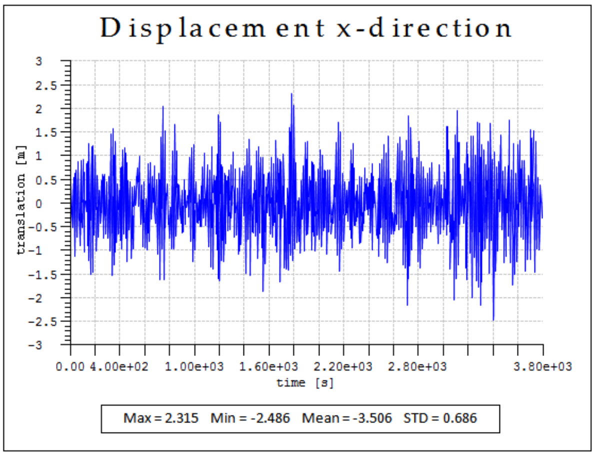
HF+LF motion with wind

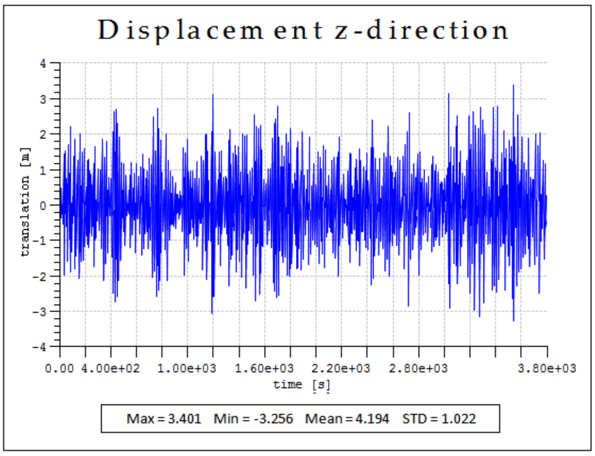




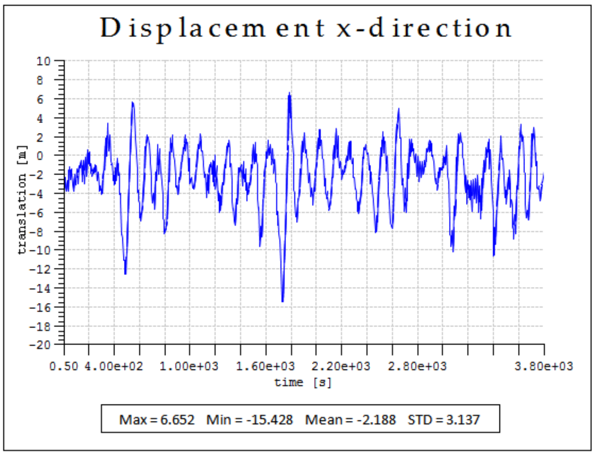
SIMA

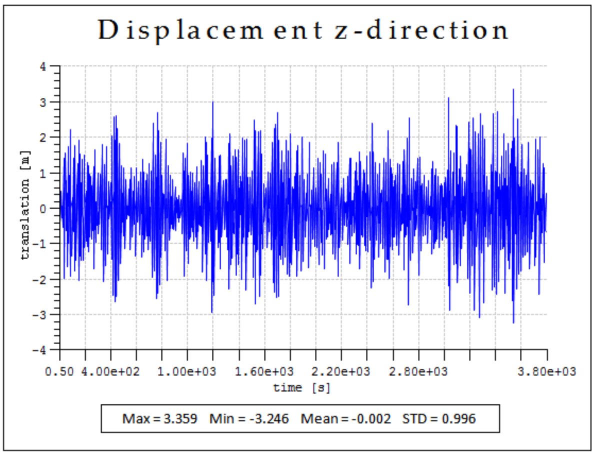
HF motion



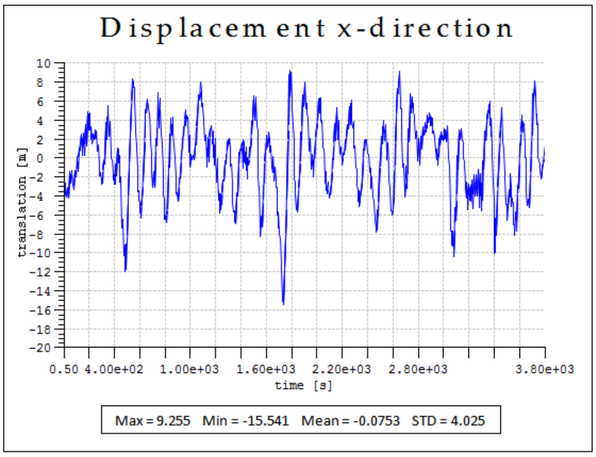


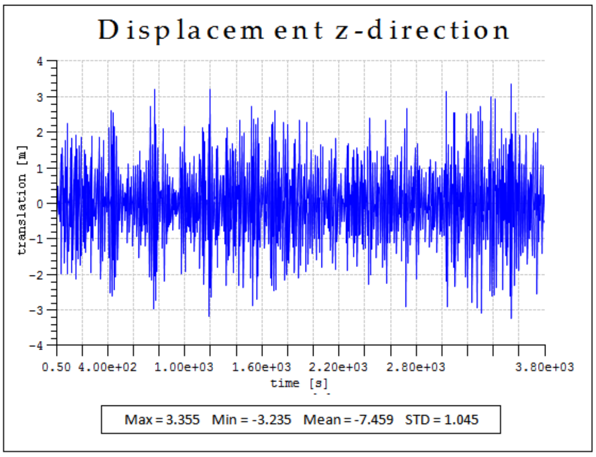
HF+LF motion





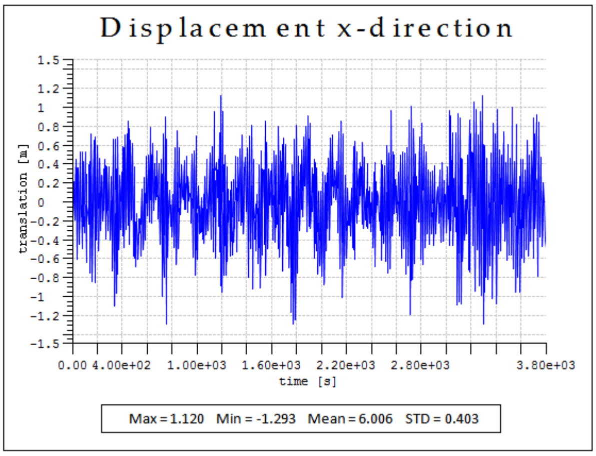
HF+LF motion with wind

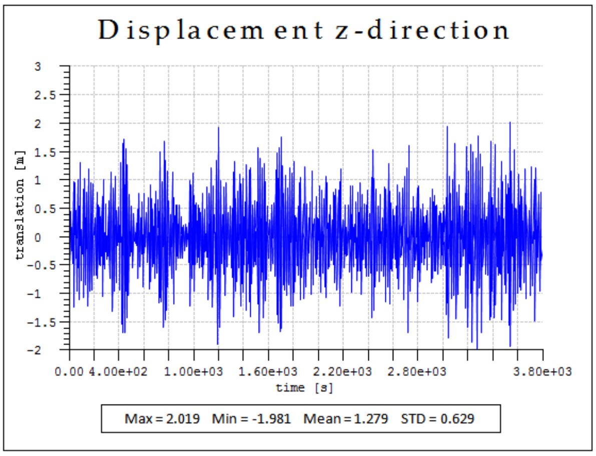




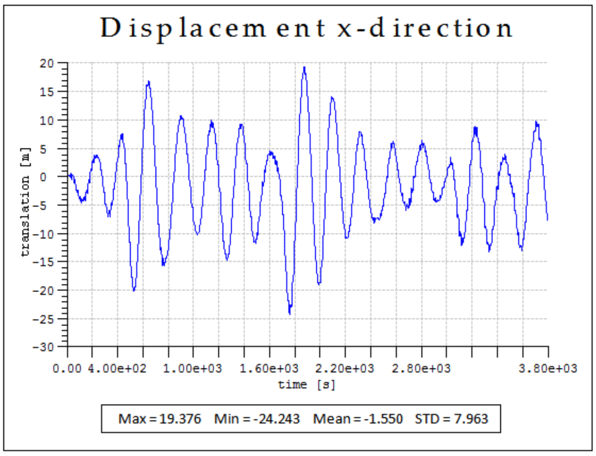
Motion time series Hs = 9m

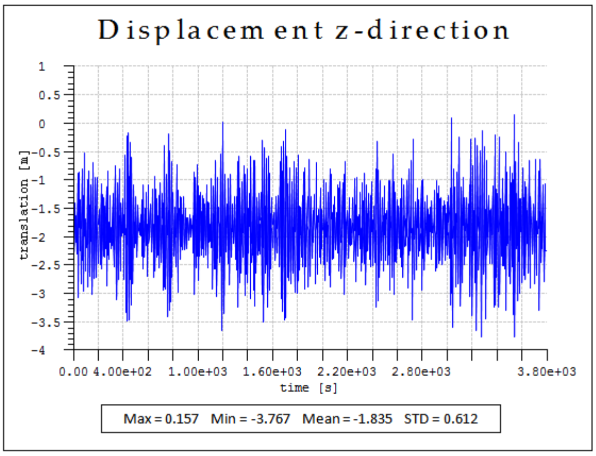
HF motion – SIMO



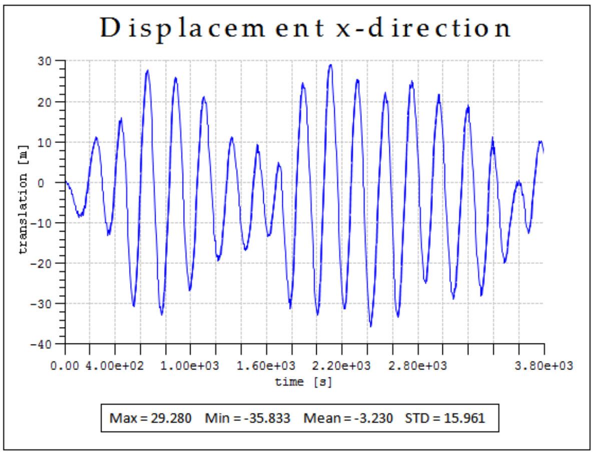


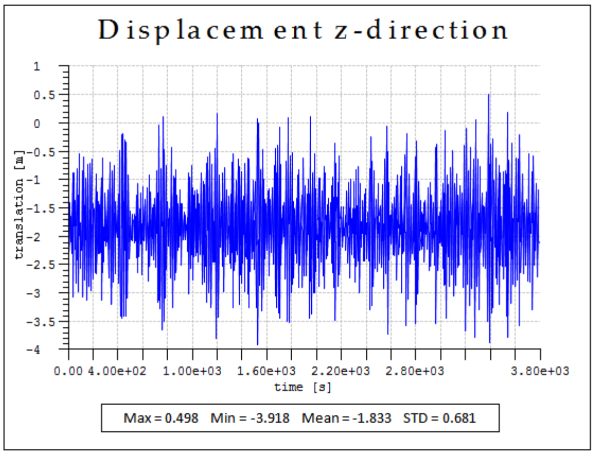
HF+LF motion





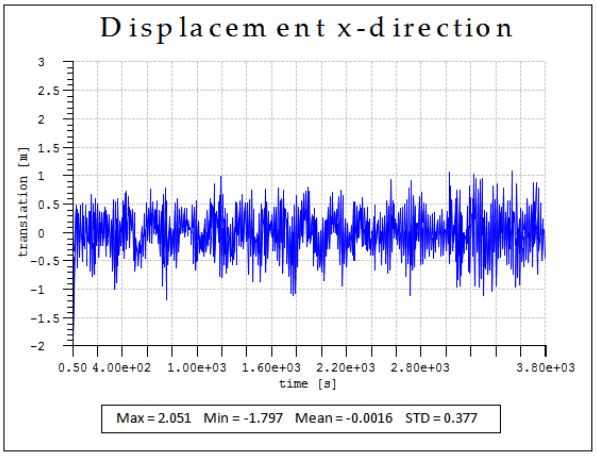
HF+LF motion with wind

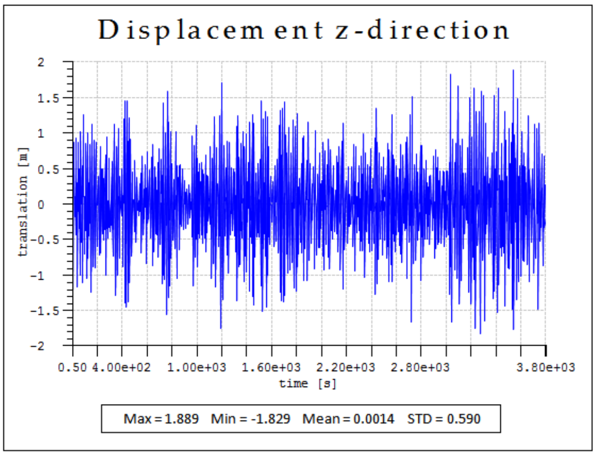




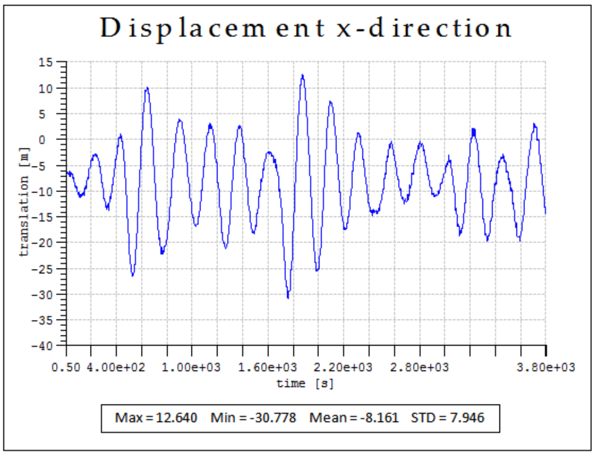
RIFLEX

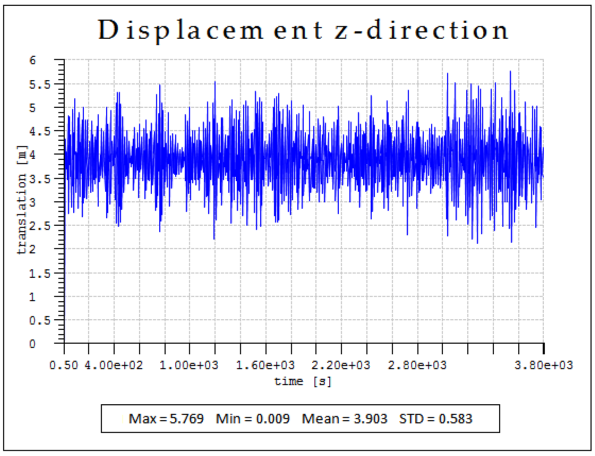
HF motion



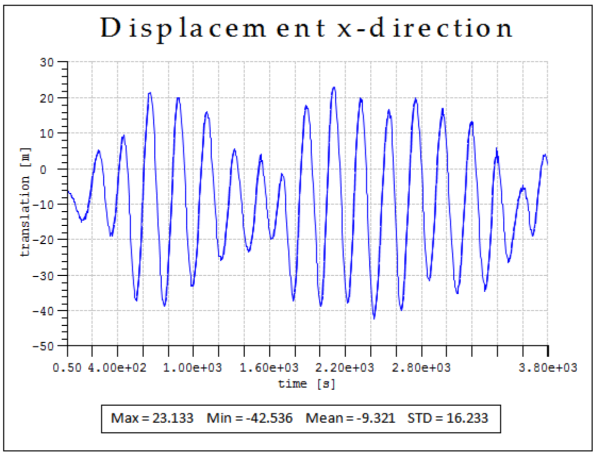


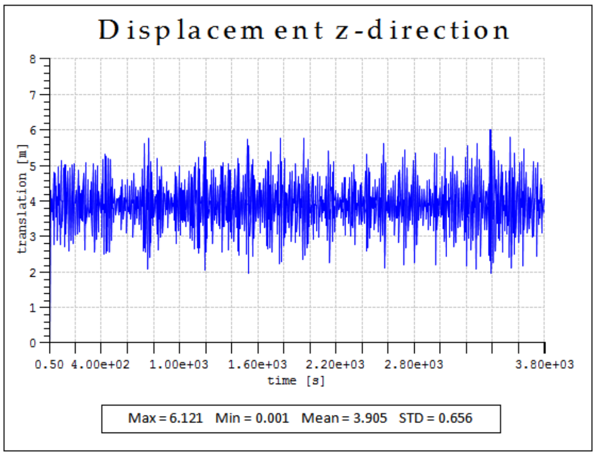
HF+LF motion





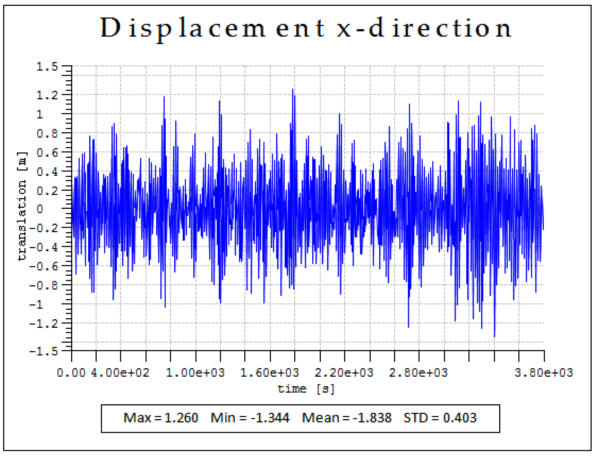
HF+LF motion with wind

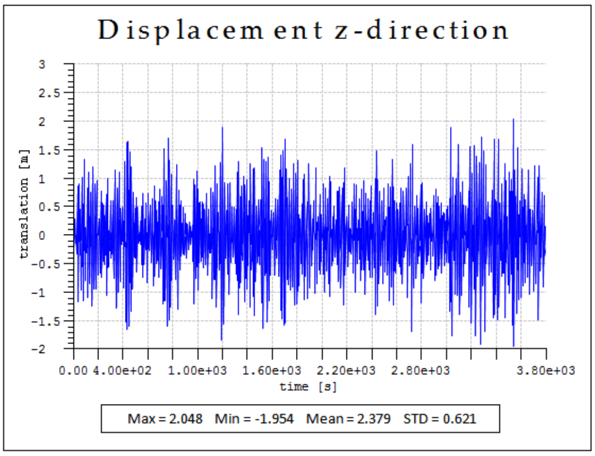




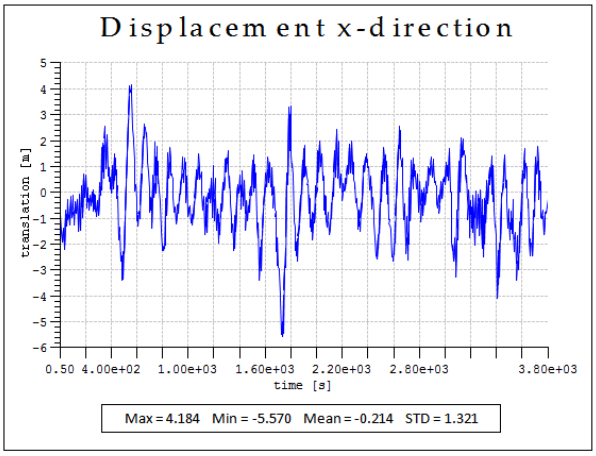
SIMA

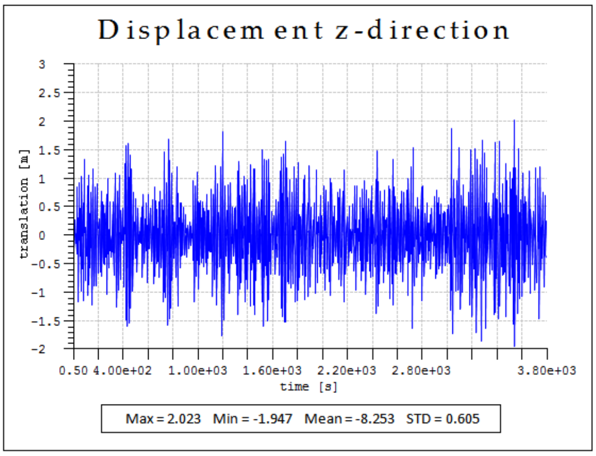
HF motion



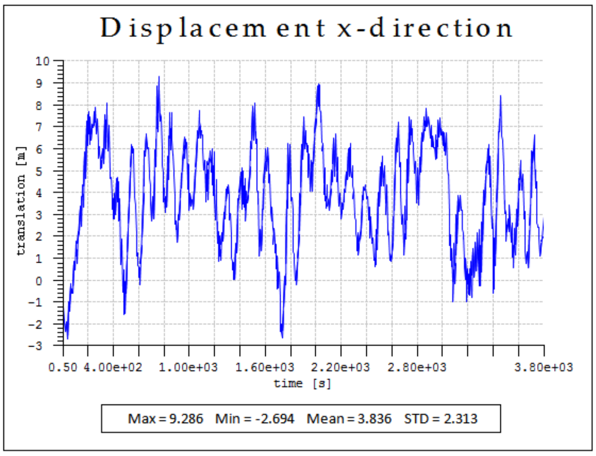


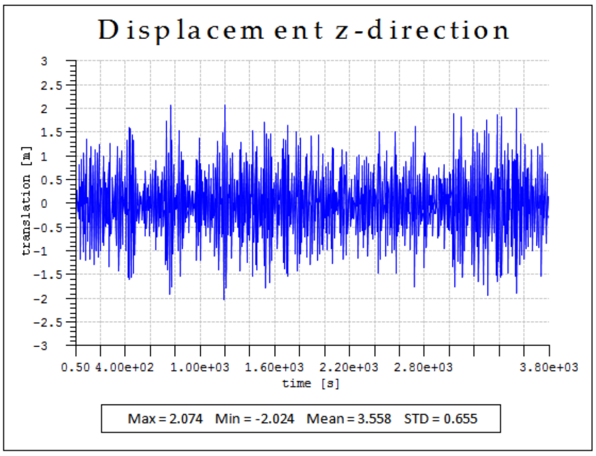
HF+LF motion





HF+LF motion with wind





Appendix B

Case 2 - Hs = 15 m

Motion time series - SIMO

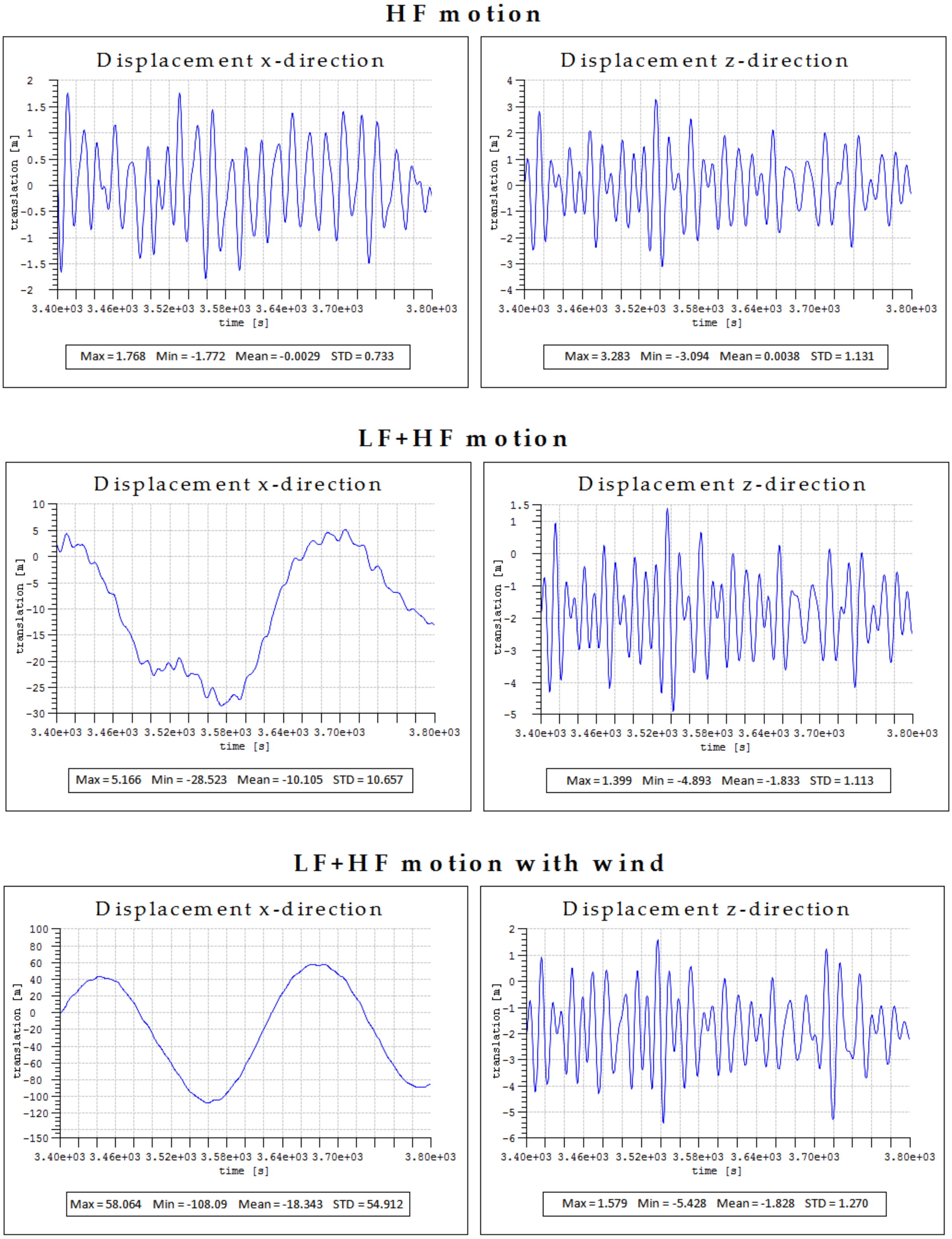


Figure B.1 - The surge and heave motion from SIMO, Hs = 15m

RIFLEX

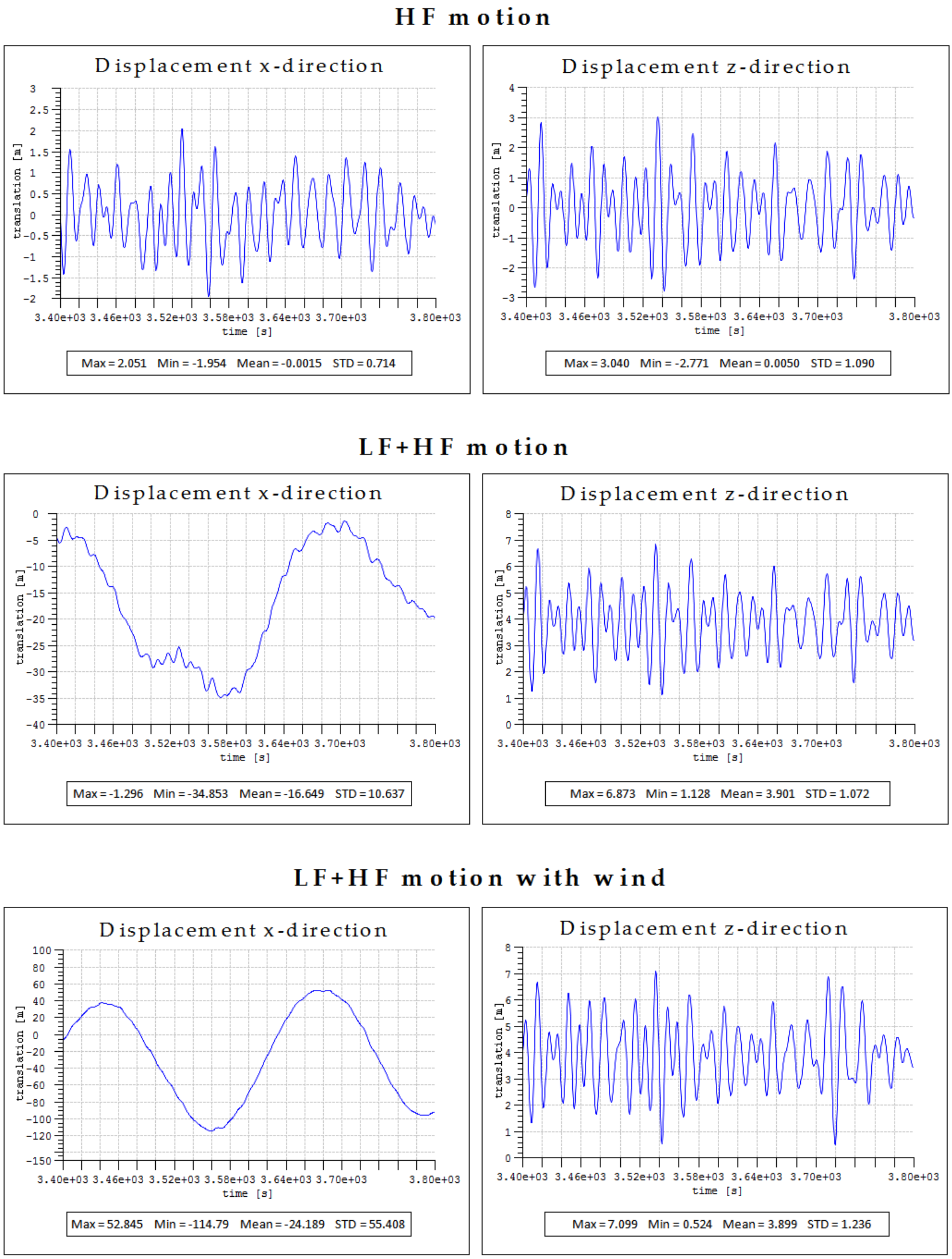
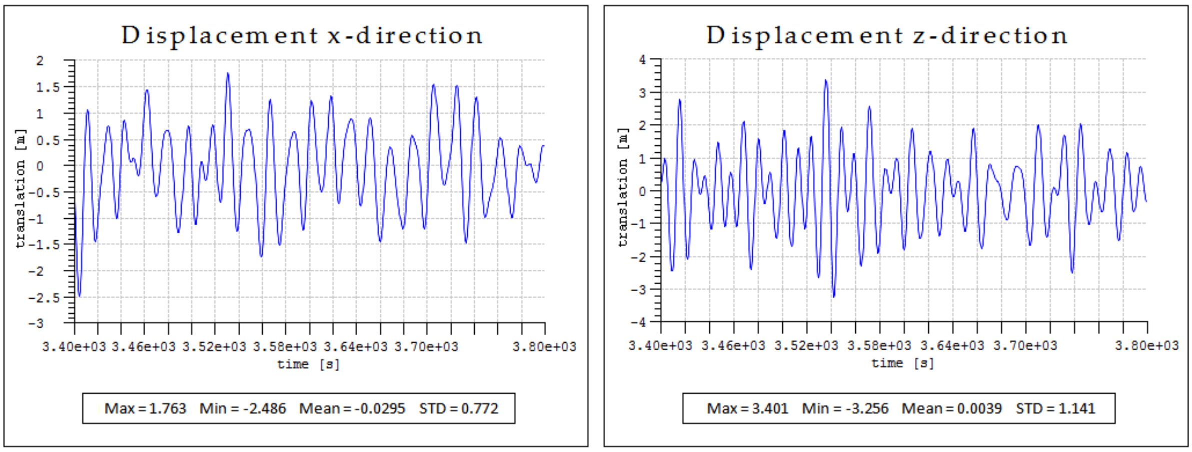


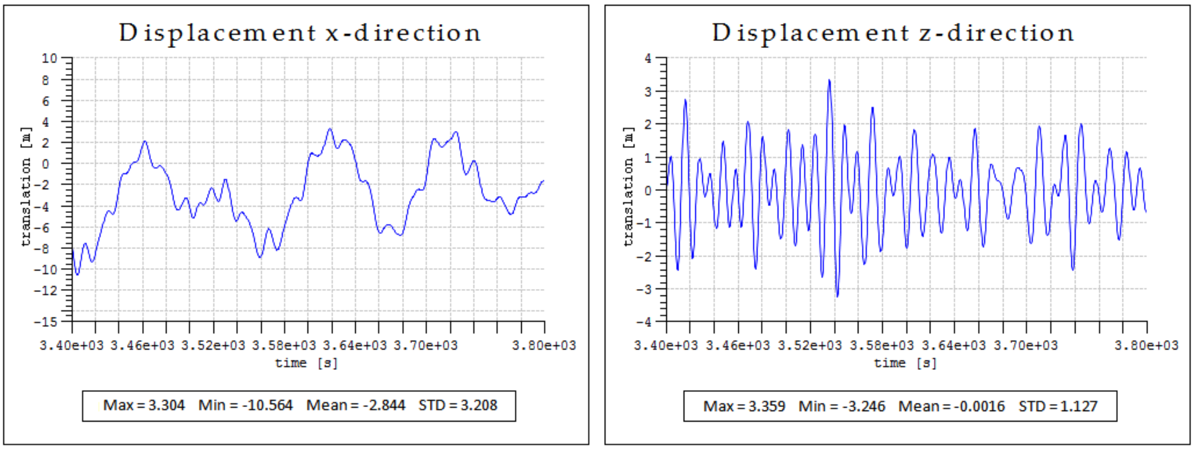
Figure B.2 - The surge and heave motion from RIFLEX, Hs = 15m

SIMA

HF motion



LF+HF motion



LF+HF motion with wind

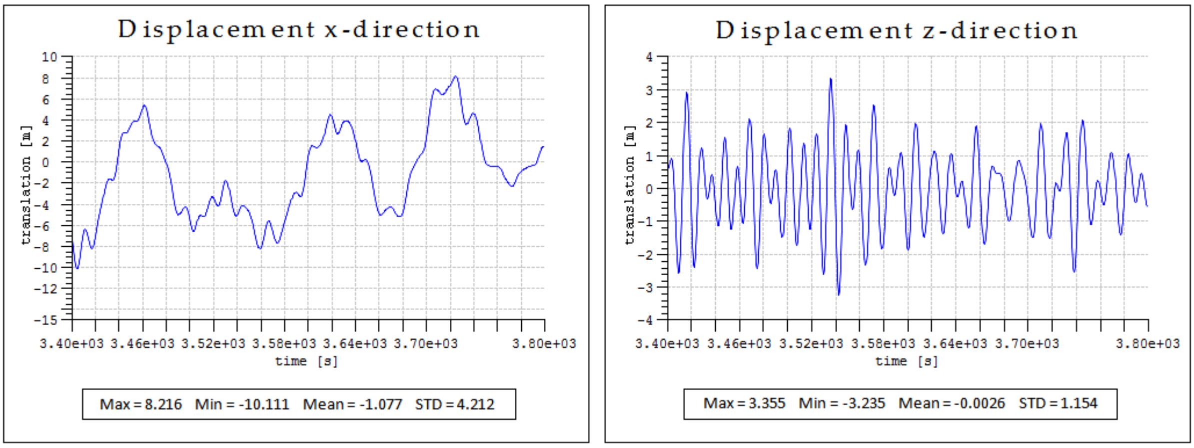


Figure B.3 - The surge and heave motion from SIMA, Hs = 15m

Motion spectra

SIMO

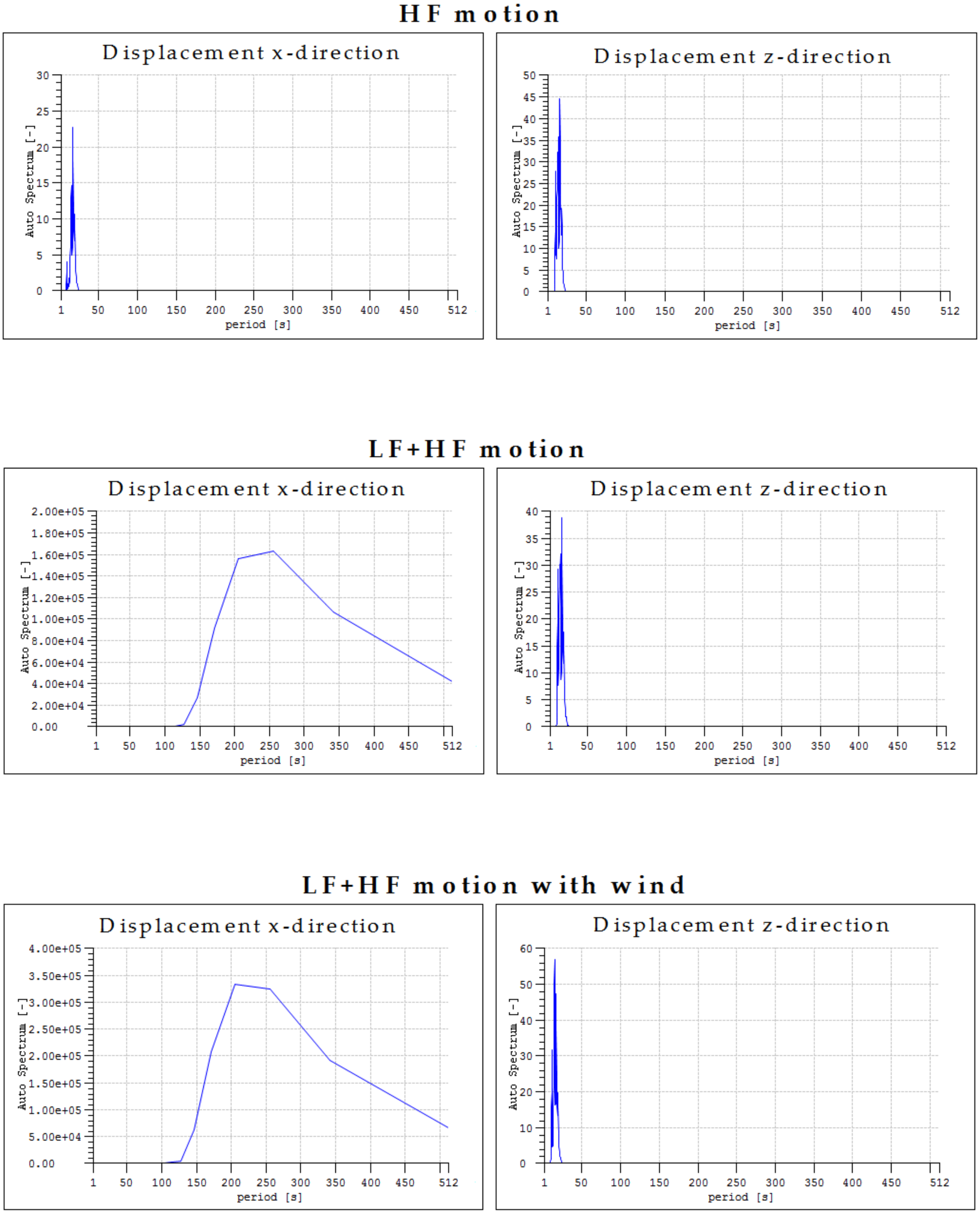


Figure B.4 - Motion spectra from SIMO, H_S = 15m

RIFLEX

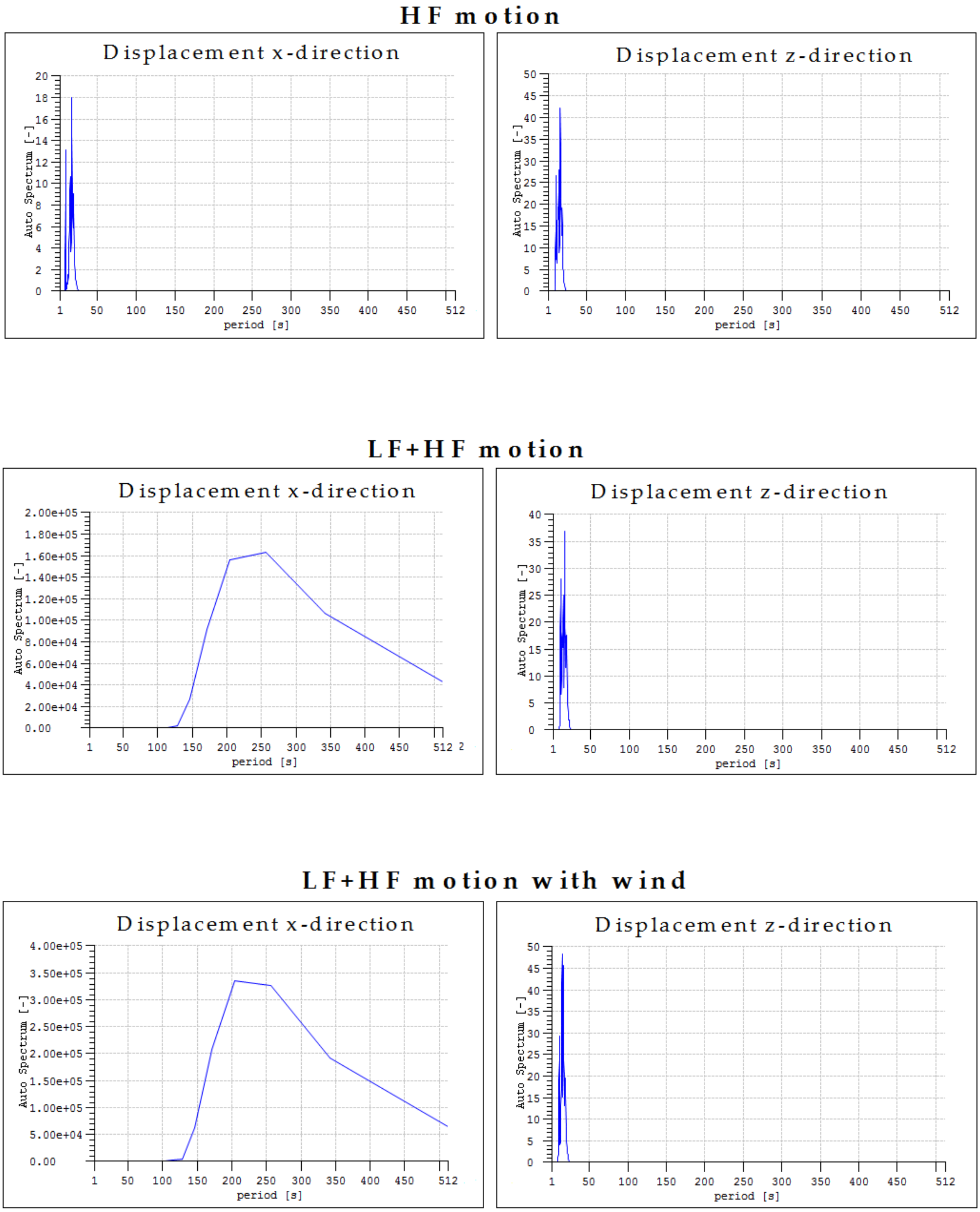


Figure B.5 - Motion spectra from RIFLEX, H_S = 15m

SIMA

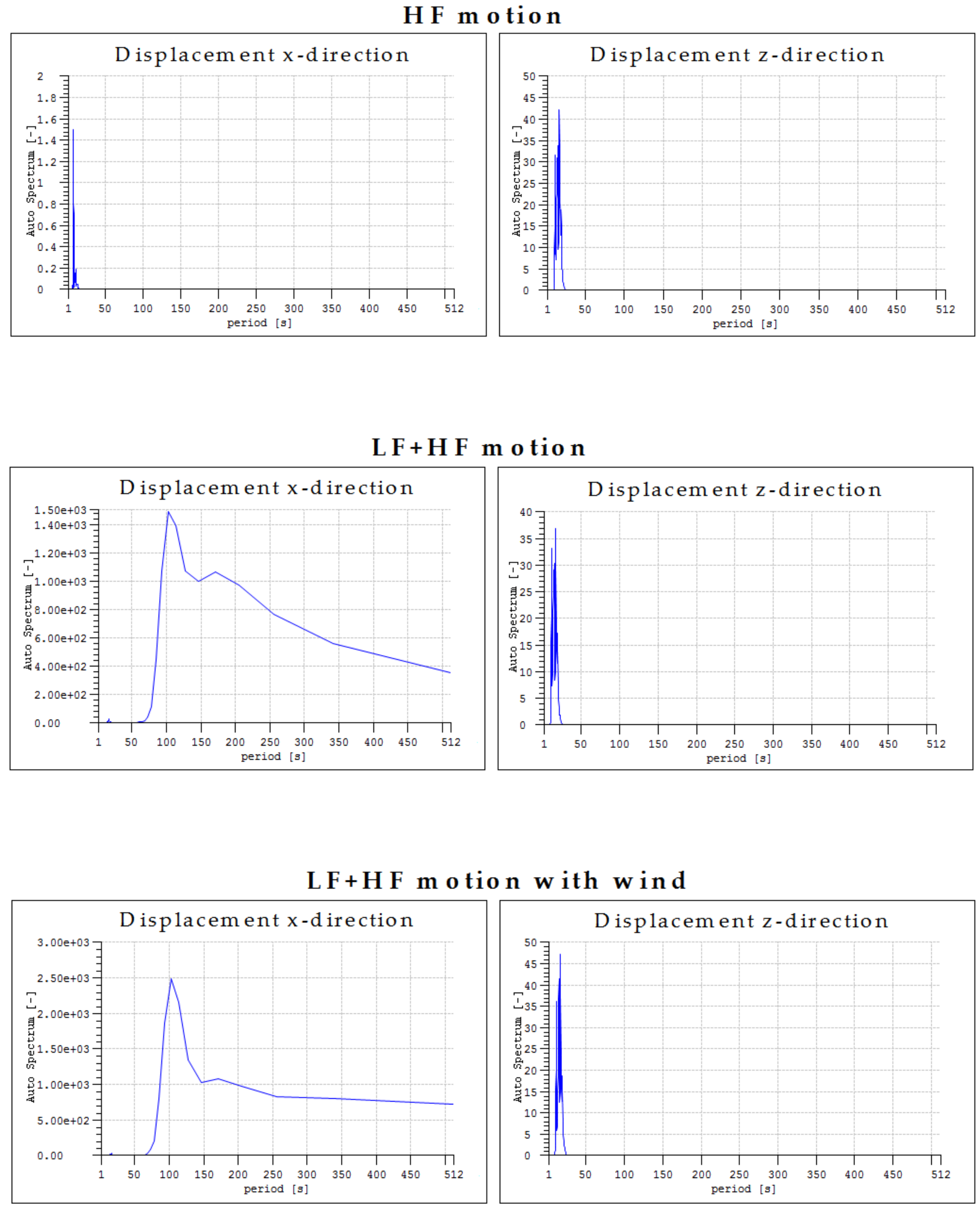


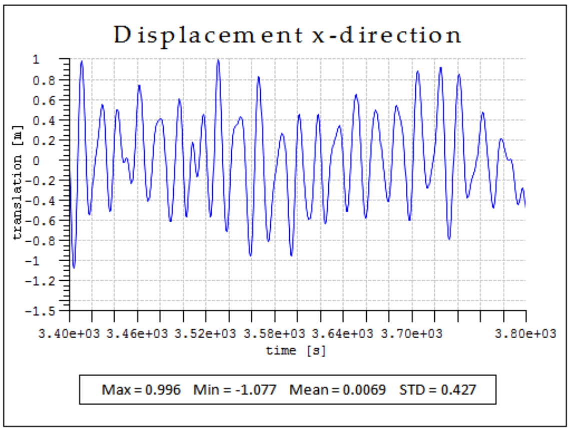
Figure B.6 - Motion spectra from SIMA, Hs = 15m

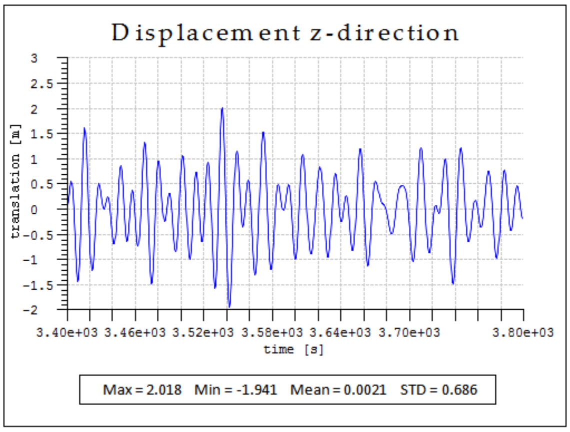
Appendix C

Case 3 - Hs = 9 m

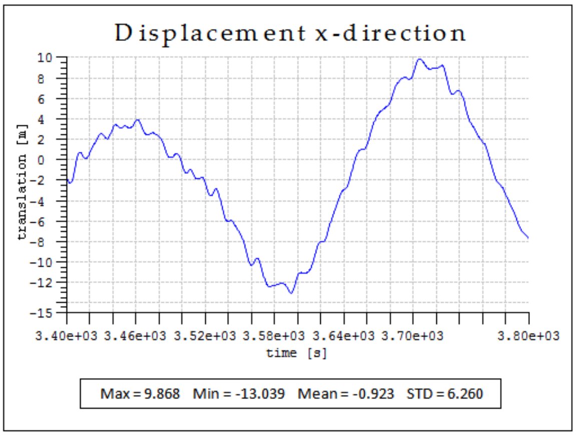
Motion time series - SIMO

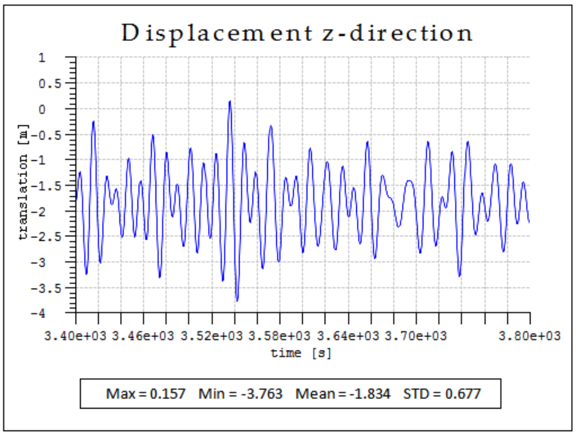
HF motion



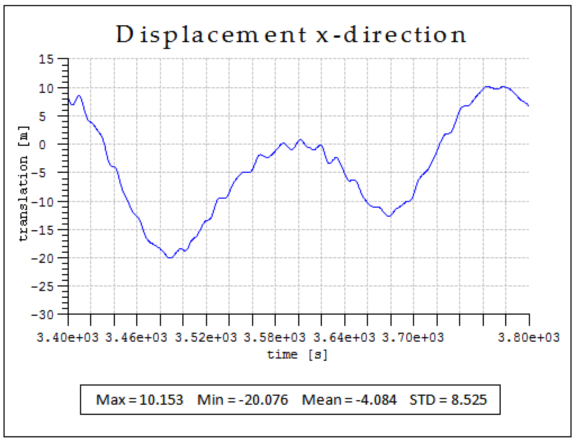


LF+HF motion





LF+HF motion with wind



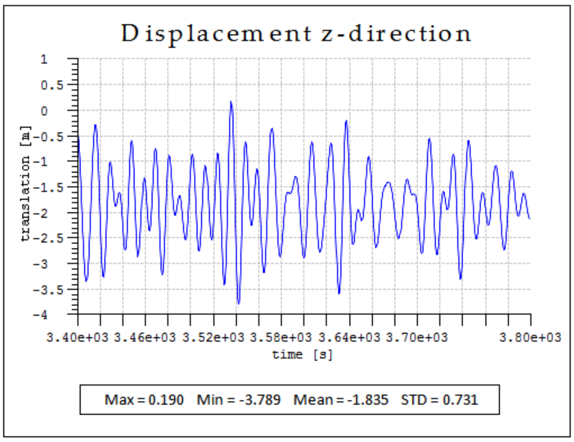
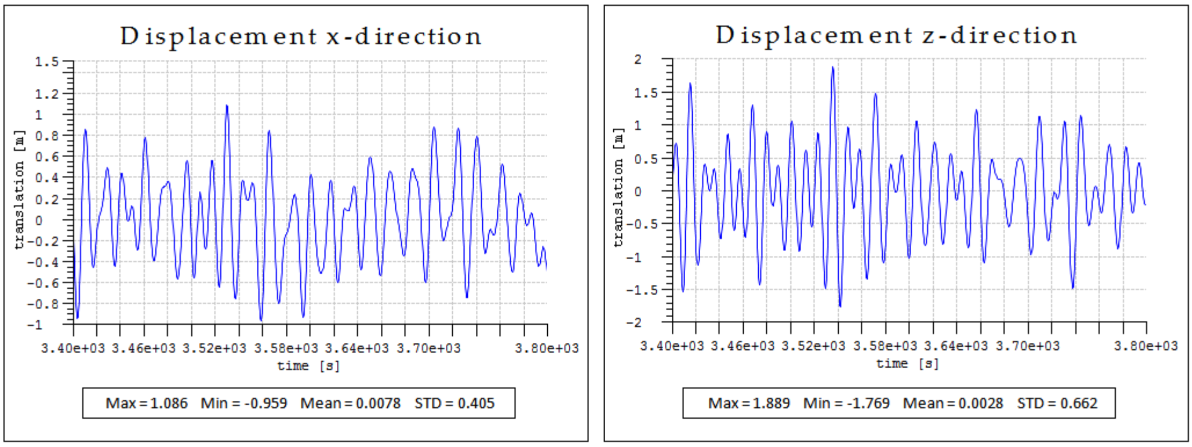


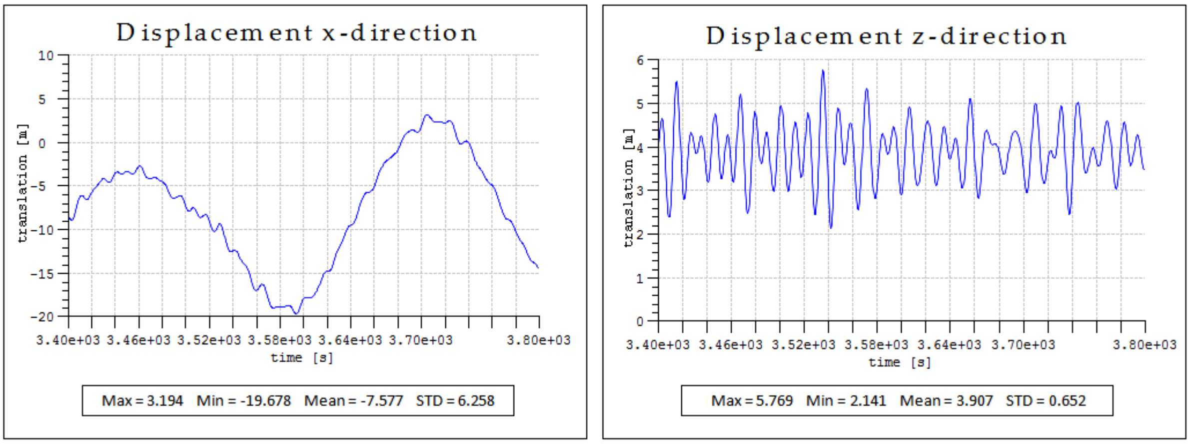
Figure C.1 - The surge and heave motion from SIMO, Hs = 9m

RIFLEX

HF motion



LF+HF motion



LF+HF motion with wind

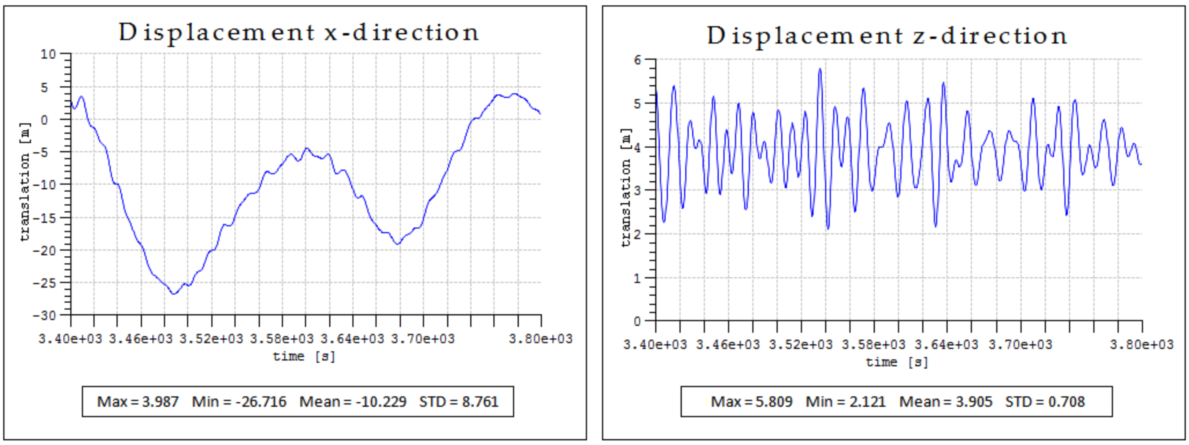


Figure C.2 - The surge and heave motion from RIFLEX, H_S = 9m

SIMA

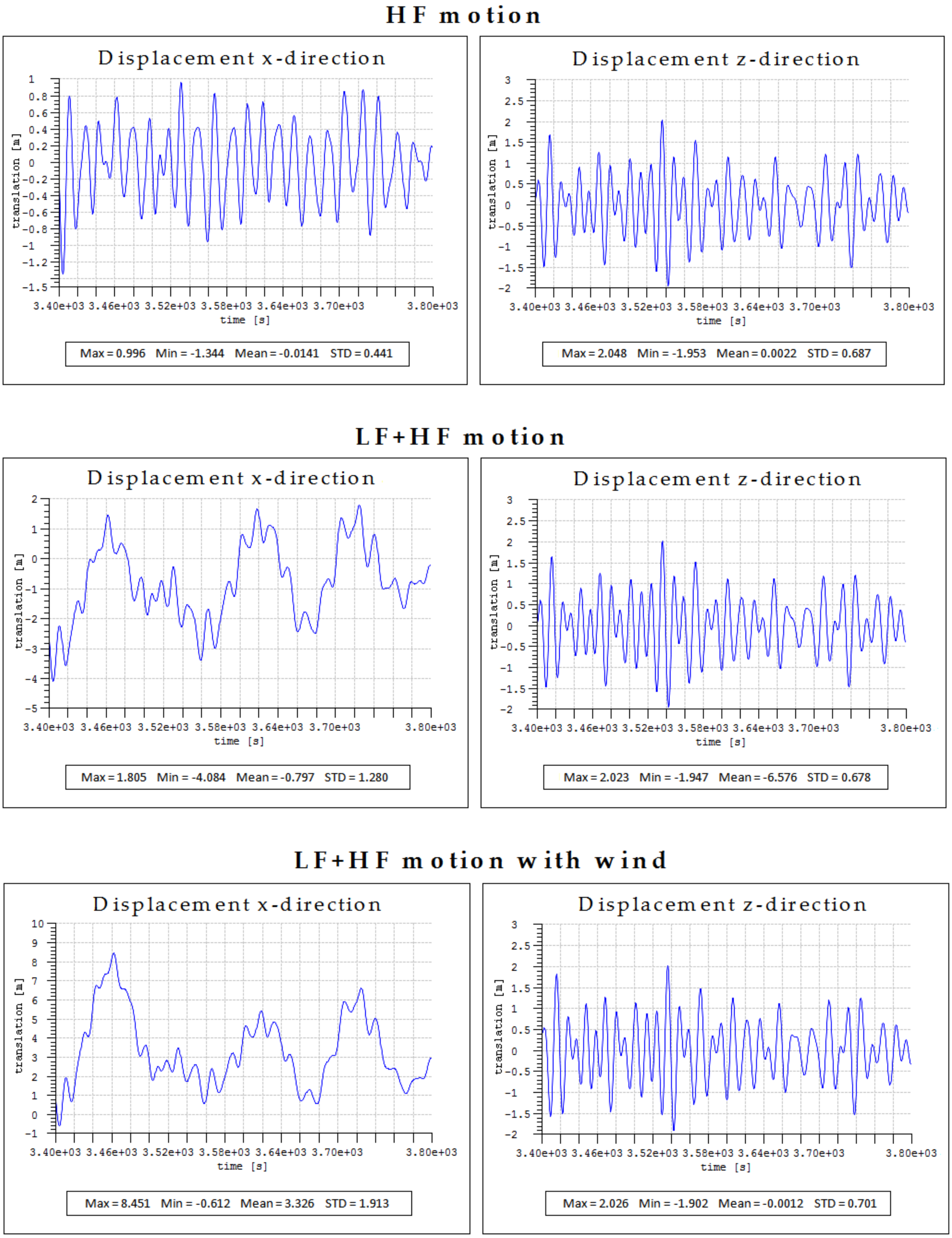


Figure C.3 - The surge and heave motion from SIMA, H_S = 9m

Motion spectra

SIMO

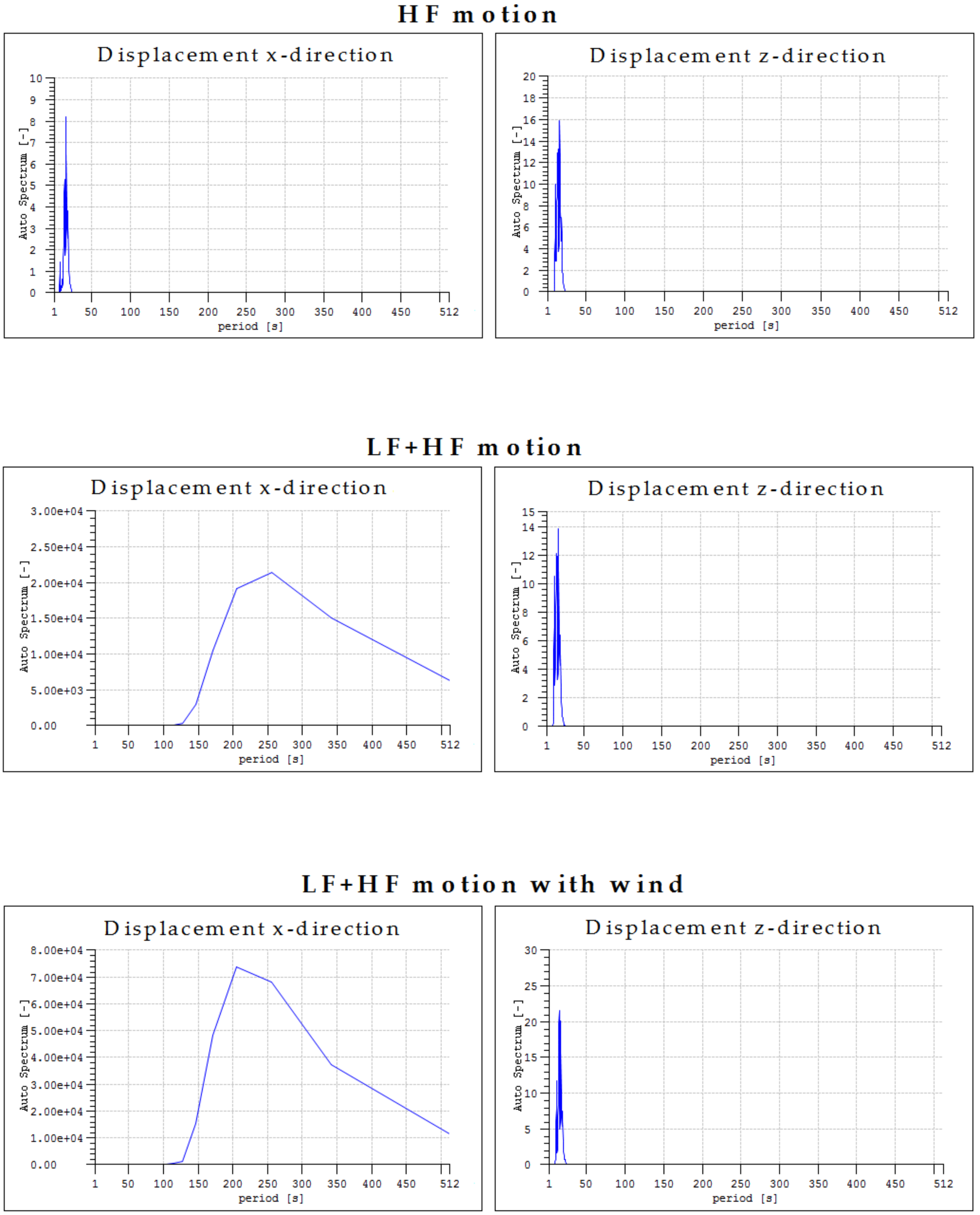


Figure C.4 - Motion spectra from SIMO, H_S = 9m

RIFLEX

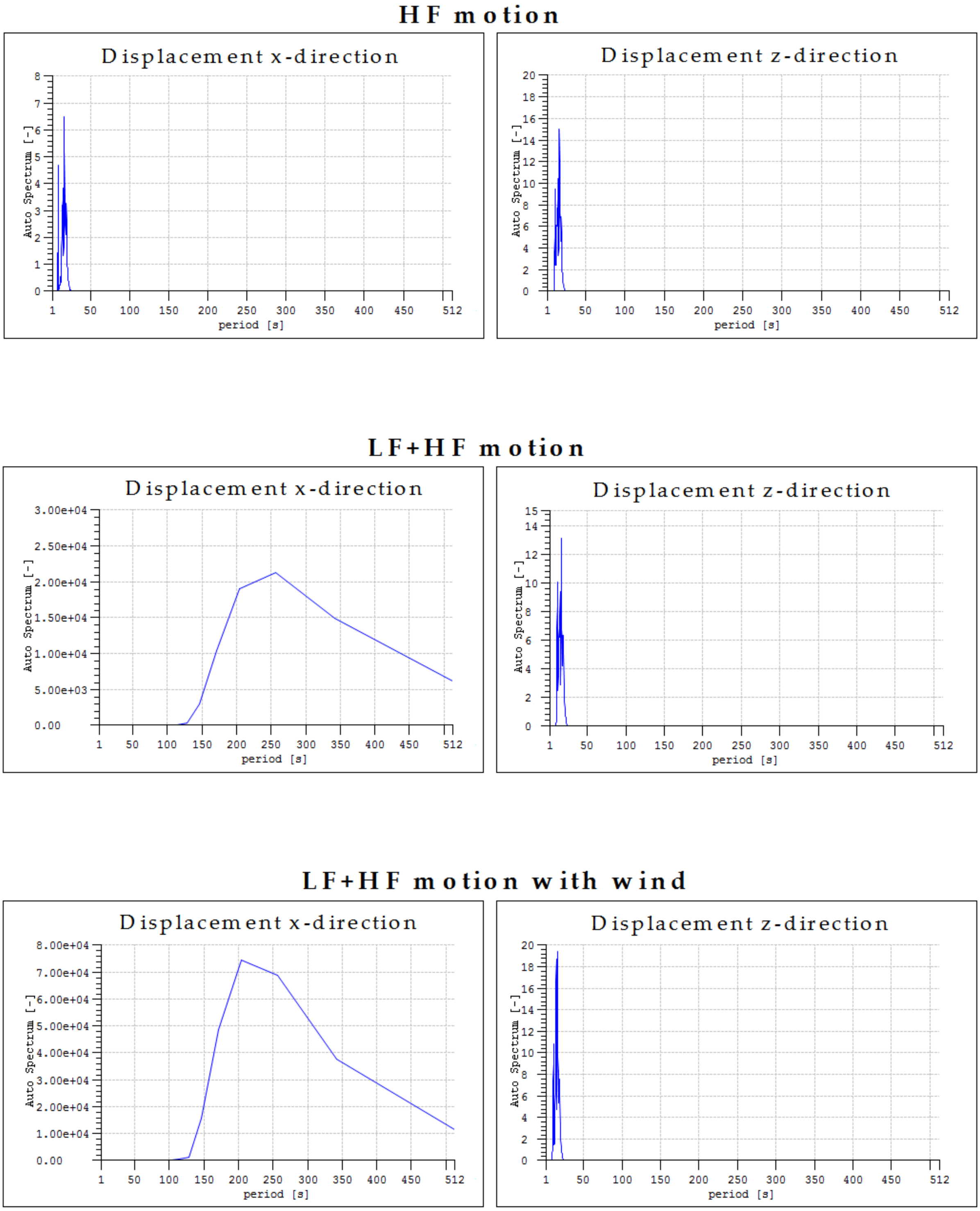
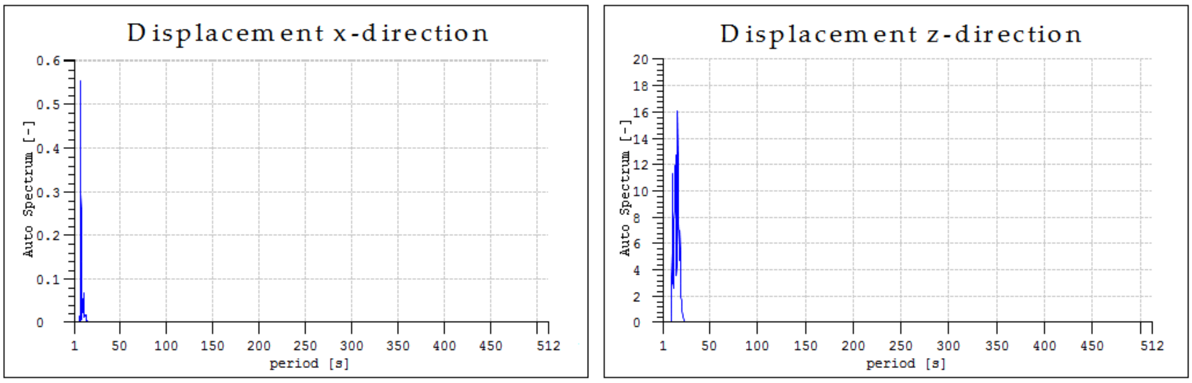


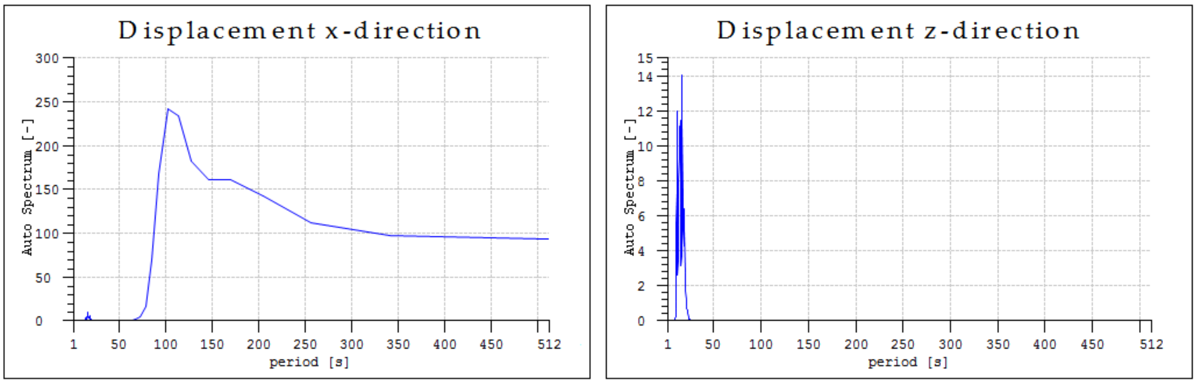
Figure C.5 - Motion spectra from RIFLEX, Hs = 9m

SIMA

HF motion



LF+HF motion



LF+HF motion with wind

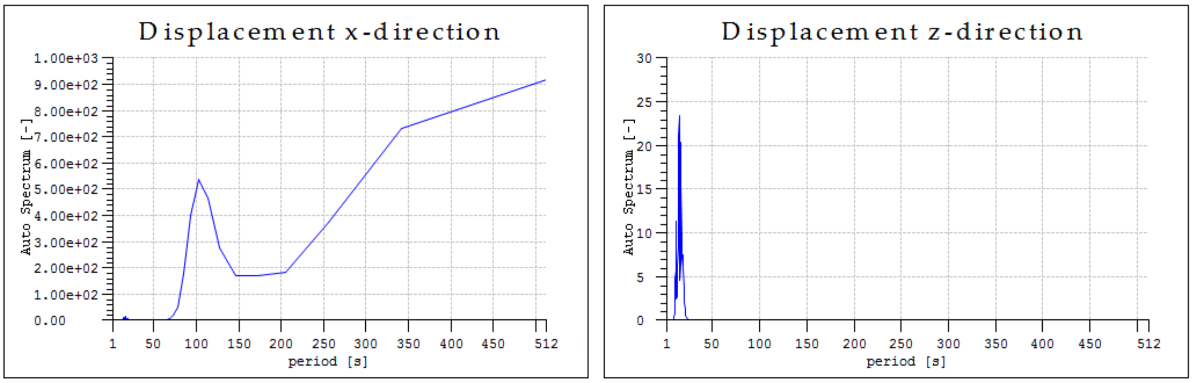


Figure C.6 - Motion spectra from SIMA, H_S = 9m

Appendix D

CPU time for Case 1 when wind is included

SIMO

```
CPU  TIME  LOG  SECONDS      S T A M O D
----------------------------------------
Read system description file      56.504
Read initial condition file        0.000
Modify system description          0.000
Print static condition             0.000
Equilibrium calculation            0.000
Eigen value calculation            0.000
Mooring system optimization        0.000
Write initial condition file       0.000
Write visualization file           0.172
Miscellaneous                      0.016
----------------------------------------
Total                             56.691
========================================
```

```
CPU  TIME  LOG  SECONDS      S T A M O D
----------------------------------------
Read system description file      42.276
Read initial condition file        0.000
Modify system description          0.000
Print static condition             0.000
Equilibrium calculation            0.078
Eigen value calculation            0.000
Mooring system optimization        0.000
Write initial condition file       0.016
Write visualization file           0.140
Miscellaneous                      0.016
----------------------------------------
Total                             42.526
========================================
```

```
CPU  TIME  LOG  SECONDS      D Y N M O D
---------------------------------------------
READ INITIAL CONDITION FILE               0.0
DEFINE PARAMETERS IN DYNAMIC ANALYSIS     0.0
INITIALIZE FOR TIME DOMAIN SIMULATION     0.9
TIME DOMAIN SIMULATION                    3.8
MISCELLANEOUS                             0.0
---------------------------------------------
TOTAL                                     4.7
=============================================
```

Figure D.1 - Required CPU time in SIMO analysis, H_S = 12.19m with wind

RIFLEX

```
CPU TIME LOG SECONDS     I N P M O D
--------------------------------------
READ CONTROL INFORMATION ........ 0.031
READ COUPLED RISER SYSTEM ....... 0.000
READ SINGLE RISER SYSTEM ........ 0.000
READ COMPONENT DATA ............. 0.016
READ ENVIRONMENTAL DATA ......... 0.000
READ SUPPORT VESSEL DATA ........ 0.218
READ FATIGUE CAPACITY DATA ...... 0.000
MISCELLANEOUS ................... 0.031
--------------------------------------
TOTAL SOLUTION TIME ............. 0.296
======================================
```

```
CPU TIME LOG SECONDS     - S T A M O D -
------------------------------------------------
SAM/DMS INITIALIZATION ...................  0.02
DIRECT INPUT FROM USER....................  0.00
DATA GENERATION FOR RISER SYSTEM..........  0.05
STATIC ANALYSIS ..........................  4.74
MISCELLANEOUS ............................  0.00
------------------------------------------------
TOTAL SOLUTION TIME ......................  4.80
================================================
```

```
CPU TIME LOG SECONDS   - D Y N M O D -
---------------------------------------------
SAM/DMS INITIALIZATION .........         0.02
ORGANIZING INPUT DATA ..........         0.05
EIGENVALUE ANALYSIS ............         0.00
PRE-STOCHASTIC ANALYSIS ........         3.85
LINEAR TIME INTEGRATION ........         0.00
NONLINEAR TIME INTEGRATION .....       501.37
MISCELLANEOUS ..................         0.00
---------------------------------------------
TOTAL SOLUTION TIME ............       505.29
=============================================
```

Figure D.2 - Required CPU time in RIFLEX analysis, H_S = 12.19m with wind

SIMA

```
CPU TIME LOG SECONDS     I N P M O D
--------------------------------------
READ CONTROL INFORMATION ........ 0.031
READ COUPLED RISER SYSTEM ....... 0.000
READ SINGLE RISER SYSTEM ........ 0.000
READ COMPONENT DATA ............. 0.000
READ ENVIRONMENTAL DATA ......... 0.000
READ SUPPORT VESSEL DATA ........ 0.000
READ FATIGUE CAPACITY DATA ...... 0.000
MISCELLANEOUS ................... 0.016
--------------------------------------
TOTAL SOLUTION TIME ............. 0.047
======================================
```

```
CPU TIME LOG SECONDS     - S T A M O D -
------------------------------------------------
SAM/DMS INITIALIZATION ...................  0.02
DIRECT INPUT FROM USER....................  0.00
DATA GENERATION FOR RISER SYSTEM..........  0.34
STATIC ANALYSIS .......................... 14.93
MISCELLANEOUS ............................  0.00
------------------------------------------------
TOTAL SOLUTION TIME ...................... 15.29
================================================
```

```
CPU TIME LOG SECONDS   - D Y N M O D -
---------------------------------------------
SAM/DMS INITIALIZATION .........         0.02
ORGANIZING INPUT DATA ..........         0.06
EIGENVALUE ANALYSIS ............         0.00
PRE-STOCHASTIC ANALYSIS ........         0.02
LINEAR TIME INTEGRATION ........         0.00
NONLINEAR TIME INTEGRATION .....       616.11
MISCELLANEOUS ..................         0.00
---------------------------------------------
TOTAL SOLUTION TIME ............       616.20
=============================================
```

```
CPU  TIME  LOG  SECONDS      S T A M O D
----------------------------------------
Read system description file       0.047
Read initial condition file        0.000
Modify system description          0.000
Print static condition             0.000
Equilibrium calculation            0.000
Eigen value calculation            0.000
Mooring system optimization        0.000
Write initial condition file       0.000
Write visualization file           0.156
Miscellaneous                      0.016
----------------------------------------
Total                              0.218
========================================
```

```
CPU  TIME  LOG  SECONDS      S T A M O D
----------------------------------------
Read system description file       0.000
Read initial condition file        0.016
Modify system description          0.000
Print static condition             0.000
Equilibrium calculation            0.000
Eigen value calculation            0.000
Mooring system optimization        0.000
Write initial condition file       0.000
Write visualization file           0.000
Miscellaneous                      0.016
----------------------------------------
Total                              0.031
========================================
```

```
CPU  TIME  LOG  SECONDS      D Y N M O D
---------------------------------------------
READ INITIAL CONDITION FILE               0.0
DEFINE PARAMETERS IN DYNAMIC ANALYSIS     0.0
INITIALIZE FOR TIME DOMAIN SIMULATION     0.9
TIME DOMAIN SIMULATION                    0.0
MISCELLANEOUS                             0.0
---------------------------------------------
TOTAL                                     0.9
=============================================
```

Figure D.3 - Required CPU time in SIMA analysis, H_S = 12.19m with wind