SHORETENSION AS CARGO HANDLING SYSTEM: CONTROLLING THE RELATIVE HORIZONTAL MOTIONS BETWEEN THE HTV AND THE CARGO DURING OFFSHORE LOADING AND DISCHARGE

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Key words: *Dockwise, Heavy Transport Vessel, Offshore loading and discharge, Relative horizontal motions, Cargo handling system, ShoreTension, Dockwise Vanguard*

ABSTRACT

One of the challenges of offshore loading and discharge are the relative horizontal motions between the HTV and its cargo which must be controlled, to ensure safe and reliable operations. Optimization of the cargo handling system is needed to control the relative horizontal motions. This study investigates whether the mooring device ShoreTension will minimize the relative horizontal motions between a HTV and a cargo, when it is used as the cargo handling system during offshore loading and discharge operations.

A MATLAB function of ShoreTension is developed, which is implemented into AQWA to predict the relative horizontal motions between the HTV and the cargo in time. Multiple simulations have been performed, each with its own cargo handling system. A simplified MATLAB mass-spring-ShoreTension model resembling the HTV and the cargo is set up to determine why and when ShoreTension reduces motions.

A cargo handling system including ShoreTension cannot reduce the high-, wave-frequent relative horizontal motions occurring between the HTV and the cargo, as they are induced by an excitation frequency far beyond the natural frequency of the original system. Furthermore, a cargo handling system including ShoreTension should be able to lower the low-frequent relative horizontal motions, which are the result of resonance; by increasing the stiffness and by adding damping through giving out and heaving in the mooring line. The optimal configuration has not yet been found. It is recommended to further investigate in how ShoreTension should be outfitted as cargo handling system such that the low-frequent relative horizontal motions are minimized.

1. INTRODUCTION

Large and heavy structures, usually utilized in the offshore industry, have to be transported around the world; which is frequently done by self-propelled semi-submersible vessels known as Heavy Transport Vessels (HTVs). Heavy Marine Transport (HMT), the conveyance of these cargos by HTVs, is a widely accepted method of transportation.

Currently HMT is limited to sailing to and from sheltered areas, such as harbours and other inshore locations. Here, the environmental loadings caused by waves, wind and current are low. The Dutch shipping company Dockwise is researching the possibility to extend the HMT market towards offshore loading and discharge: being able to perform loading and discharge operations in a harsher environment at open sea.

The world's demand for energy has increased significantly in the last few years, and it is expected to continue growing. As a result, the offshore industry is expanding and shifting to explorations in deeper and more remote areas. Consequently, the size of offshore structures, which are the possible future cargos for HMT, is growing; reducing the number of inshore loading and discharge locations capable of facilitating these cargos. Furthermore, the remoteness of production fields is driving the need for offshore loading and discharge as well; it is preferred to discharge a cargo directly on its final location. In addition, studies have shown the dry-docking of Floating Production Storage and Offloading units (FPSOs) will be a new market in the HMT industry in the near future [1].

Although the scope of offshore loading and discharge seems promising, there are challenges which have to be overcome before it will be executable. It is essential to be able to accurately and cost-effectively predict the hydrodynamic behaviour of a cargo above a HTV during the loading and discharge operation. It is shown that the inaccuracies in current prediction methods are caused by the narrow gap of water between the cargo and the HTV [2]. Investigations to assess a multi-domain diffraction method are in progress. Moreover, the relative motions between the HTV and its cargo must be controlled to ensure safe and reliable operations. If not, excessive motions may lead to mooring line breaks, collision and/or damage to both vessels. To control the relative horizontal motions between the HTV and the cargo, optimization of the cargo handling system is needed.

This study investigates whether the mooring device ShoreTension will minimize the relative horizontal motions between a HTV and a cargo, when it is used as cargo handling system during offshore loading and discharge operations.

2. SYSTEM DESCRIPTION

The Dockwise Vanguard and a fully integrated semi-submersible are chosen as the system's Heavy Transport Vessel and cargo respectively to perform this study. The same configuration has been analysed in model tests for offshore loading and discharge. The particulars of both vessels are shown in Table 1.

		HTV	Cargo
L_{OA}	[m]	275	110
B	[m]	70	110
T_{op}	[m]	28.65	11.85
D	[m]	15.50	23.65
DWT	[tonne]	117 000	
Displ.	[tonne]		108 000

Table 1: Vessel particulars

The system is investigated in the most critical state of an offshore loading or discharge operation: when the cargo is floating above the HTV with only a small clearance between its keel and the deck of the HTV. This is the state of interest because the cargo handling system is operation in these moments in time; employed to position the cargo on the cribbing on deck. The cribbing are the wooden beams on the deck of the HTV, which transfer the loads from the cargo into the vessel. Cribbing beams have a width of 0.30 m, which directly sets the limit of maximum acceptable relative horizontal motions.

The system is exposed to a JONSWAP wave spectrum representing swell wave conditions in head seas; Table 2 shows its properties. Wind and current loadings are not taken into account.

H_S [m]	T_{PD} [s]	T_Z [s]	α [˚]
1	14.1	11.0	180

Table 2: Wave spectrum properties

The relative horizontal motions are measured in 4 points on the HTV, relative to 4 points on the cargo. When the cargo is located on its final position, the measuring points are exactly on top of each other and the resulting relative motion is zero. The measurement points of the relative motions are situated where the semi-submersible crosses the side of the deck of the Dockwise Vanguard. The measurement point on the bow and port side of the semi-submersible, is chosen as the ultimate reference point. All motions presented throughout this study are measured here.

The system is equipped with different cargo handling systems, with and without ShoreTension, to compare its performances in controlling the relative horizontal motions. A detailed description of the different cargo handling systems investigated is given in the simulation methodology section in 4.1.

3. SHORETENSION

ShoreTension is a hydraulic system developed by the Royal Boatmen Association Eendracht (KRVE), to moor large seagoing vessels along a quay. ShoreTension is designed to absorb the motions of the moored vessel present due to external loads passively, by giving out and heaving in the mooring line connected to ShoreTension.

ShoreTension is placed between two bollards on the quayside along the moored vessel. One end of the system is fixated to one bollard, while the other, moveable end of the system is connected to the vessel with a mooring line, guided via a sheave on the second bollard. In Figure 1 the moveable end of the ShoreTension system is shown on the right side.

Figure 1: ShoreTension [3]

If the tension in the mooring line connected to ShoreTension exceeds a certain limit, the system gives out; providing slack in the line. Consequently the tension remains constant. If the tension in the mooring line decreases sufficiently, the system heaves in, taking up the slack. As long as ShoreTension's piston does not approach the beginning or the end of its stroke, the tension in the line cannot become larger than its maximum value (at which the system gives out) or smaller than its minimum vale (at which the system heaves in); preventing both high snapping loads and slack in the line. Furthermore, as the tension level between the outgoing and ingoing motions of ShoreTension differs, the system does work and thus dissipates energy. Effectively, ShoreTension adds damping to the moored system.

4. METHODOLOGY

The ShoreTension system is thoroughly analysed with a MATLAB SimHydraulics and Simscape model, providing insight in how the system works and which parameters affect its behaviour. Additionally, a MATLAB function of ShoreTension is developed, describing the reaction of ShoreTension combined with the connected mooring line. The stretch of the mooring line is thus incorporated in the results. The MATLAB function of ShoreTension may either be used in the MATLAB environment itself, or it can be compiled and exported as a stand-alone function. The latter is utilized in external programs like AQWA via a Dynamic Link Library (DLL).

The methodology applied in the performed AQWA simulations and the MATLAB mass-spring-ShoreTension model is discussed in detail in the following sections.

4.1 AQWA SIMULATIONS

AQWA is utilized to predict and analyse the relative horizontal motions between the HTV and the cargo during offshore loading and discharge, with and without ShoreTension as cargo handling system (CHS). AQWA solves the multi-body dynamic problem in the time domain. In the AQWA simulations the HTV holds its position due to a global mooring system: four anchored mooring lines. The global mooring system represents an actual mooring system or temporary tug assistance during offshore loading and discharge.

CHS without ShoreTension

The original mooring configuration (OMC) includes 8 mooring lines (Figure 2), which approach the HTV horizontally when the clearance between the HTV and the cargo is 1.5 metres. As the clearance in this study is set at 1 metre, the mooring lines have a small angle. In the OMC the cargo is connected to the HTV by relatively stiff mooring lines made of two materials: polypropylene (15 metres) and steel (remaining length). The elastic capacity of the mooring lines applied is summarized in Table 3.

CHS with ShoreTension

First, a CHS is tested containing only ShoreTension; no other mooring lines are applied. ShoreTension is positioned on the accommodation and the casings of the HTV; with the corresponding sheaves located on the same locations as the winches in the OMC. This CHS is illustrated in Figure 3. The lines connected to ShoreTension are developed by Dyneema, which are as strong as steel (Table 3) but weigh much less.

Secondly, ShoreTension is installed alongside the OMC. It is assumed that both the mooring lines and ShoreTension are capable to work on exactly the same location, presented in Figure 4.

	Polypr.	Steel	Dyneema
EA [kN]	18240	79360	75000

Table 3: Material properties

4.2 MATLAB MASS-SPRING-SHORETENSION MODEL

A MATLAB mass-spring-ShoreTension model is set up to investigate why and when ShoreTension reduces motions. It resembles the system simulated in AQWA, but it is significantly simplified.

The reference case is investigated in the MATLAB mass-spring model, representing the CHS without ShoreTension. The HTV is modelled as a fixed reference point and the cargo is modelled as a point mass with one degree of freedom. The OMC is replaced by a spring with a stiffness equal to the stiffness of all mooring lines in the surge direction. An external force excites the mass, following a sine-signal with a specified amplitude and frequency (Eq. 1). A schematic illustration and the equation of motion is presented in Figure 5.

$$F_{ext} = F_0 \sin(\omega t) \qquad \text{(Eq. 1)}$$

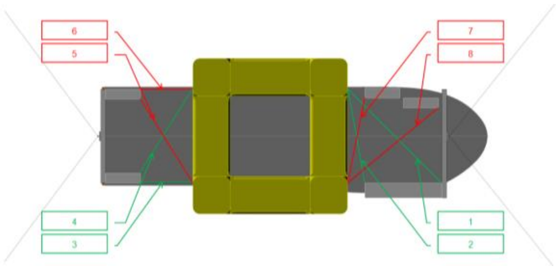


Figure 2: Mooring line configuration without ST

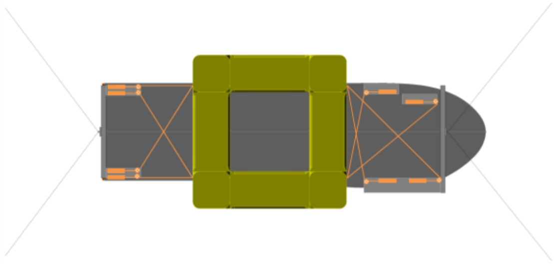


Figure 3: Location of ST on HTV (not on scale)

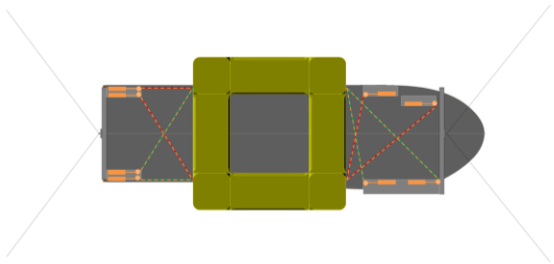
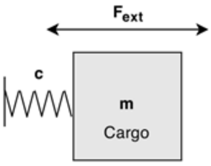


Figure 4: Location of ST on HTV simultaneously as OMC (not on scale)

The MATLAB mass-spring model is expanded with ShoreTension in the MATLAB mass-spring-ShoreTension model. ShoreTension is positioned on both sides of the cargo and it is assumed to be correctly modelled with the MATLAB function of ShoreTension. The number of ShoreTension cylinders on each side of the mass is determined by the factor NST. Figure 6 shows the model and its equation of motion.

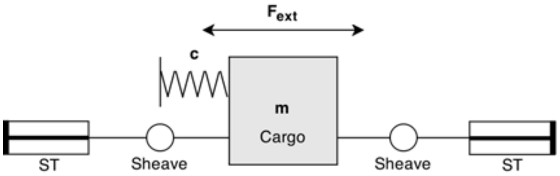
To visualize the working principles of ShoreTension, the MATLAB mass-spring-ShoreTension model is simplified even further: the spring and the ShoreTension systems are replaced by a spring and viscous damper; both linear. The stiffness of the spring is equal to the equivalent mean stiffness of the MATLAB mass-spring-ShoreTension model, so it is defined by both the OMC and ShoreTension. The damping coefficient is determined by the dissipated energy in the MATLAB mass-spring-ShoreTension system, which results in an equivalent value for a viscous damper.

The MATLAB mass-spring-ShoreTension model is solved several times with varying parameters. The mass, stiffness and the ShoreTension properties are kept constant, while the external force frequency, amplitude and the number of ShoreTension systems applied on each side are varied. Moreover, the interaction of ShoreTension with an irregular external force is investigated.



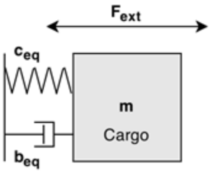
$$m\ddot{x} + cx = F_{ext}$$

Figure 5: MATLAB mass-spring model



$$m\ddot{x} + cx + NST \cdot F_{ST}(x, \dot{x}) = F_{ext}$$

Figure 6: MATLAB mass-spring-ShoreTension model



$$m\ddot{x} + b_{eq}\dot{x} + c_{eq}x = F_{ext}$$

Figure 7: MATLAB mass-spring-damper model

The irregular force is a summation of two sine-signals with different amplitudes and frequencies, as shown in (Eq. *2*).

$$F_{ext} = F_1 \sin(\omega_1 t) + F_2 \sin(\omega_2 t) \qquad \text{(Eq. 2)}$$

5. SIMULATION RESULTS

5.1 AQWA SIMULATION RESULTS

Three AQWA simulations are discussed: one describing the cargo handling system without ShoreTension (OMC); the other two focussing on the systems with ShoreTension (ST only and ST + OMC).

CHS without ShoreTension

The relative horizontal motions between the HTV and the cargo, when equipped with the OMC as cargo handling system are 2 m in surge direction and 1.3 m in sway direction; which is much larger than the set acceptable horizontal motions of 0.30 m. The motions are plotted against each other, thus independent of time, in Figure 8. In addition, the energy spectra of the relative surge and sway motions are presented in Figure 9 and Figure 10. The relative surge motion contains energy in both the low- and high frequency regions, while the relative sway motion is primarily low-frequent. The peaks in the energy density functions of relative surge and sway, located at low frequencies, are defined by the natural frequencies of this coupled multi-body system.

CHS with ShoreTension

Installing only ShoreTension as CHS results in unwanted drifting behaviour of the cargo relative to the HTV. The cargo finds a new equilibrium position around -1.7 m relative surge, illustrated in Figure 11. ShoreTension behaves unlike a spring, as the system does not directly force the cargo to return to its initial position. The cylinders at the bow side do not heave back in, while the cylinders at the stern cannot give out, because the cargo is constantly pushed in the negative surge direction. The forces working on ShoreTension are balanced before the ingoing or outgoing motions of the pistons are realized. With every loading of waves, the cargo drifts off, until the pistons reach either the end or the beginning of the cylinder's stroke. ShoreTension will stop interacting and further movements are counteracted by the mooring lines. This option is rejected.

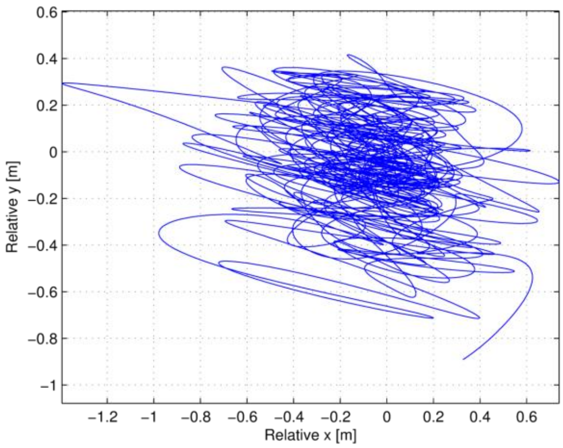


Figure 8: Relative surge vs. relative sway (OMC)

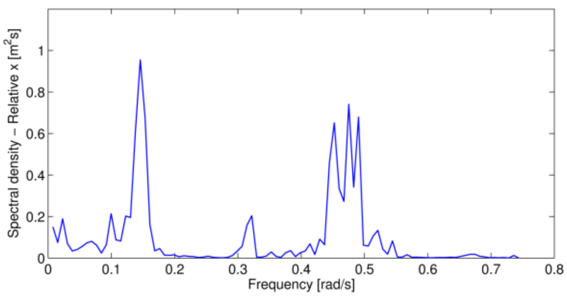


Figure 9: Spectral density of relative surge (OMC)

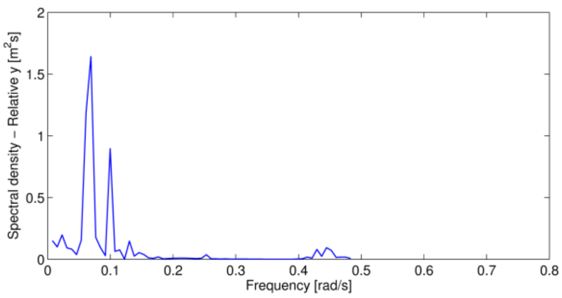


Figure 10: Spectral density of relative sway (OMC)

The relative horizontal motions between the HTV and the cargo are not sufficiently reduced when the CHS including both the OMC and ShoreTension is applied, shown in Figure 12. The relative surge and sway motions have discrepancy values of about 1.5 and 1.1 m respectively. Equipping the cargo handling system with ShoreTension and the OMC distinctly lowers the energy in the relative surge and sway motions present in low frequency range. In contrast, the energy level at higher frequencies is increased. Effectively, no big difference in energy and the corresponding significant motion amplitudes exists between the OMC and ST + OMC (Table 4). The significant motion amplitude is the mean value of the highest one-third of amplitudes, determined from the energy density spectrum.

	$x_{ra\,1/3}$ [m]	$y_{ra\,1/3}$ [m]
OMC	0.53	0.42
ST + OMC	0.49	0.38

Table 4: Significant relative surge and sway amplitudes

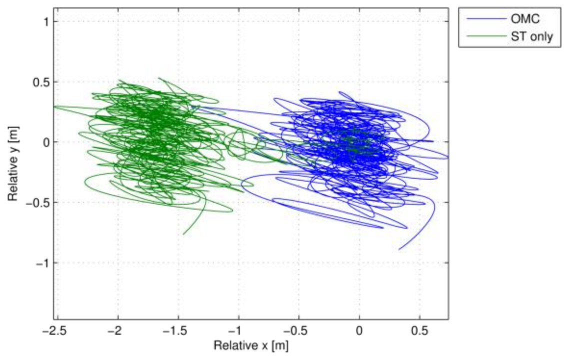


Figure 11: Relative surge vs. relative sway (OMC & ST only)

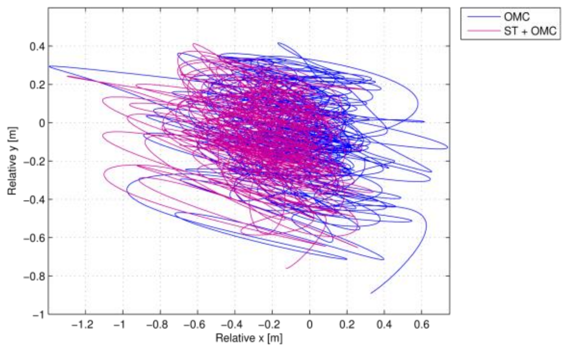


Figure 12: Relative surge vs. relative sway (OMC, ST + OMC)

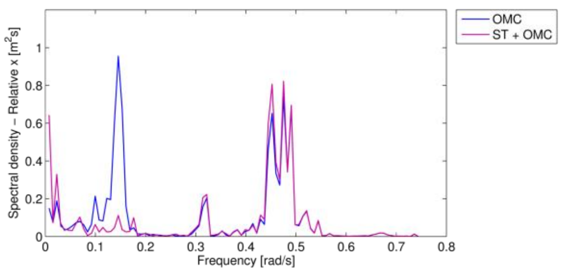


Figure 13: Spectral density of relative surge (OMC & ST + OMC)

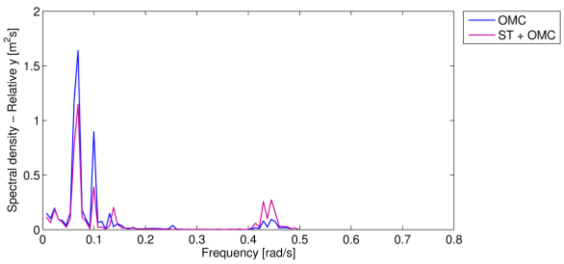


Figure 14: Spectral density of relative sway (OMC & ST + OMC)

5.2 MATLAB MASS-SPRING-SHORETENSION MODEL RESULTS

Many variations are simulated with the MATLAB mass-spring-ShoreTension model; the most interesting case studies are discussed here. The results of the MATLAB mass-spring-ShoreTension model are compared to the reference case: the MATLAB mass-spring model, which natural frequency counts 0.17 rad/s. Case study 1 and 2 describe a system in which the excitation frequency of the external force is almost equal to the natural frequency of the OMC. Case study 3 focusses on a system in which the excitation frequency is much larger compared to the natural frequency of the OMC. Case study 4 and 5 discuss the effects of an irregular external force.

Case study 1

This case study investigates the system in which ω = 0.15 rad/s, F_0 = 500 kN and NST = 1. The excitation frequency is close to the natural frequency of the OMC; consequently the response motion is large and shows the beating effect, plotted in Figure 15. The response motion of the corresponding MATLAB mass-spring-ShoreTension model has significantly reduced (98%) and the beats have disappeared.

Figure 16 plots the reaction force of the total cargo handling system against the resulting motion of the cargo. For the reference case, this includes just the spring force. Consequently, the steepness of the line 'without ShoreTension' in Figure 16, is equal to the stiffness of the spring. However, when ShoreTension is added, the total force includes the spring force and the reaction force of the ShoreTension systems. Adding ShoreTension to the OMC, increases the stiffness significantly. A change in stiffness directly results in a change in the natural frequency. Now, the excitation frequency is small compared to the new natural frequency, and does not excite large excessive motions any more.

The increase in stiffness and its effect on the response of the system is visualized in Figure 17, in which the response amplitude function for each CHS is plotted. The point where the response function crosses the excitation frequency, gives the corresponding motion amplitude. The response amplitude is distinctly smaller when ShoreTension is installed. ShoreTension does not interact much in this simulation, as the systems do not move out or in. This case study shows the first principle why ShoreTension reduces motions; it increases the stiffness by adding stiff Dyneema lines to the CHS.

Case study 2

In case study 2 the system in which ω = 0.15 rad/s, F_0 = 1000 kN and NST = 1 is examined; the force amplitude has doubled compared to CS1. Again, the response motion of the MATLAB mass-spring model displays beats, as the excitation frequency is close to its natural frequency; illustrated in Figure 18. The response motion of the MATLAB mass-spring-ShoreTension model is given in Figure 18 as well, which has reduced with 63% compared to the system without ShoreTension. Figure 19 presents the reaction force of the total mooring system against the displacement, which is fundamentally different to the system in CS1; as in this case an area is enclosed and ShoreTension moves out and heaves back in. Effectively, ShoreTension does work, dissipates energy and thus adds damping to the system. The addition of damping is the second principle of ShoreTension.

To visualize the response amplitude over the excitation frequency, this case study is simplified to the MATLAB mass-spring-damper model. The assumed equivalent stiffness is shown in Figure 20 (dotted line), next to the work done by the ShoreTension system in one period (dashed-dotted line). The equivalent damping coefficient in the MATLAB mass-spring-damper model is chosen such that the work done by the viscous damper equals the work as shown in Figure 20.

Again, ShoreTension increases the stiffness of the total system, as the natural frequencies have moved to higher values. Moreover, the response peak has been decreased significantly, as a result of the damping added to the system by ShoreTension. Comparing the response amplitude functions shown in Figure 21 with the functions of CS1 in Figure 7-33, the shift in natural frequencies in CS2 is not as large as seen in CS1. This phenomenon is due to the fact that damping is added to the system, for which the out- and ingoing motions of the system are required. The motions induce a lower equivalent stiffness, decreasing the natural frequencies. However, still both principles are effective in reducing the motions.

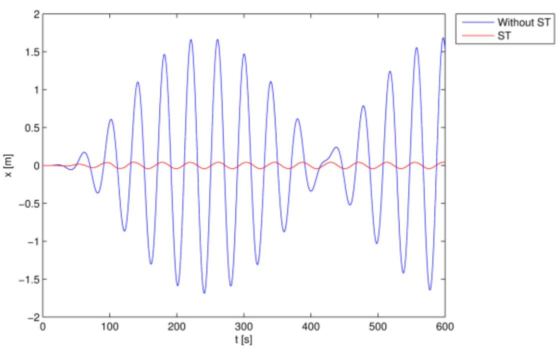


Figure 15: CS1 - Response motion vs. time

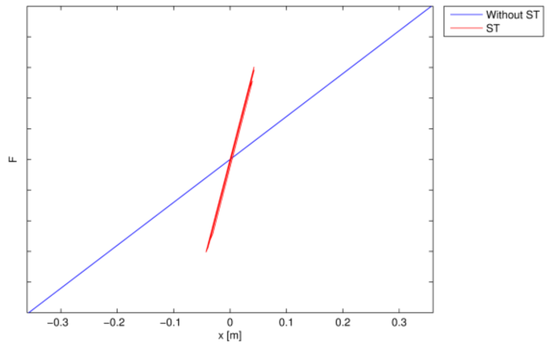


Figure 16: CS1 – Total reaction force vs. displacement

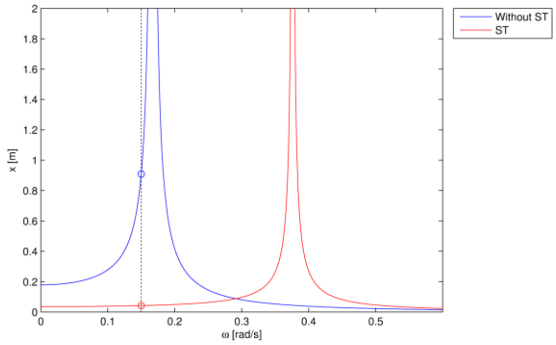


Figure 17: CS1 – Response amplitude vs. frequency

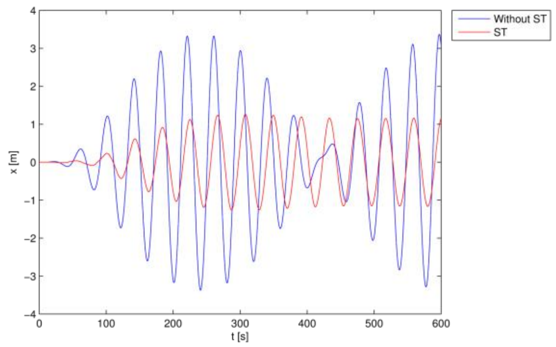


Figure 18: CS2 - Response motion vs. time

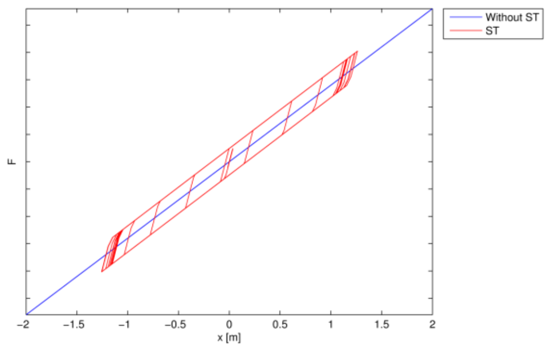


Figure 19: CS2 – Total reaction force vs. displacement

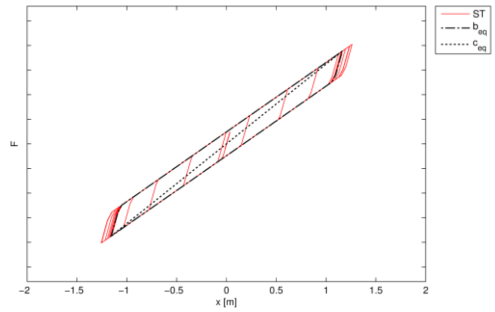


Figure 20: CS2 – Equivalent stiffness and damping

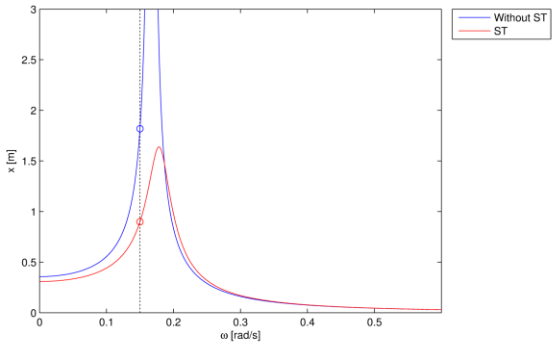


Figure 21: CS2 – Response amplitude vs. frequency

Case study 3

To investigate the effects of ShoreTension on a system which is excited by a force similar to the actual waves, the peak frequency of the wave spectrum is applied as excitation frequency. This frequency of 0.45 rad/s lies far beyond the natural frequency of the original mass-spring configuration. A very large force amplitude is required to induce the motions in the same order of magnitude as the resulting motions found in the AQWA simulations. Therefore, this case study involves the MATLAB mass-spring-ShoreTension model with an excitation frequency of 0.45 rad/s, a force amplitude of 10 000 kN and 10 ShoreTension cylinders on each side of the mass.

The response motion of the MATLAB mass-spring model and combined with ShoreTension are presented in Figure 22. Applying ShoreTension increases the motions with 3%; it has a negative impact. Figure 23 presents the total reaction force of the cargo handling systems against the displacement. The bandwidth of the area enclosed by ShoreTension, thus the total capacity, evidently increased, proportional to the amount of cylinders installed. As a result, the equivalent stiffness and equivalent damping have grown significantly.

The response amplitude functions of the different cargo handling systems are plotted in Figure 24. The resonance peak in the natural frequency region of the system including ShoreTension almost disappeared as a result of the vast amount of damping. However, the growth in stiffness induces a shift in the natural frequency of this system towards the excitation frequency, resulting in an undesired larger motion amplitude.

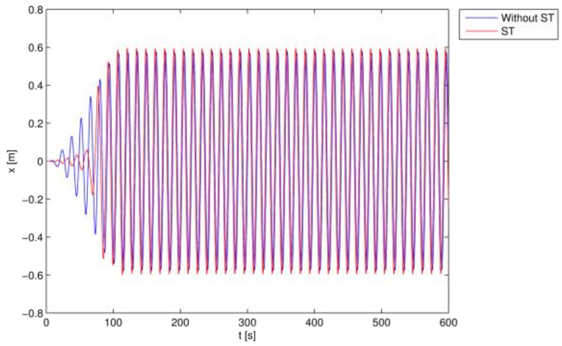


Figure 22: CS3 - Response motion vs. time

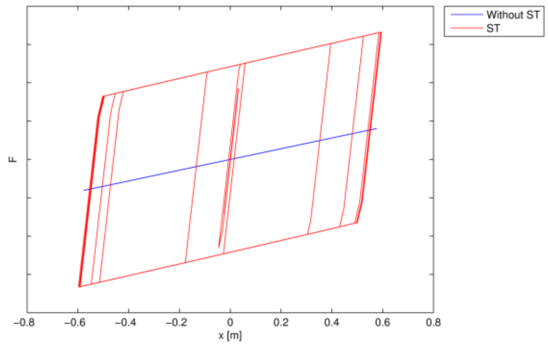


Figure 23: CS3 – Total reaction force vs. displacement

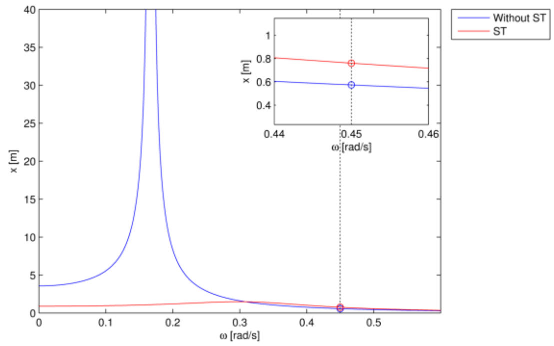


Figure 24: CS3 – Response amplitude vs. frequency

The damping hardly affects the amplitude in the higher frequency range were the excitation frequency is located. The response amplitude function crosses the excitation frequency above the function of the original mooring configuration, as shown in the zoomed view in Figure 24.

Case study 4

The irregular force exciting the MATLAB mass-spring and the MATLAB mass-spring-ShoreTension model is the summation of two regular sine-waves, each with its own amplitude and frequency. The first sine-wave represents the high frequent wave forces: the amplitude and frequency equal 10 000 kN and 0.45 rad/s respectively. The second sine-wave is described by a low-frequency force signal, with an amplitude of 500 kN and a frequency of 0.15 rad/s. The irregular force is illustrated in Figure 25. One ShoreTension cylinder is positioned on each side of the mass (NST = 1). Figure 26 shows the motion response of the reference case excited by the irregular wave force. Both excitation frequencies are clearly present in the response; but the beating effect is governing. The beats are the result of the fact that one of the excitation frequencies, 0.15 rad/s, exists in the natural frequency region belonging to this system. Installing ShoreTension alongside reduces the responses with 30% as plotted in Figure 26. Because the irregular force is dominated by the high-frequent signal with its extreme force amplitude, ShoreTension interacts continuously, running through all of its phases. Similar to previous case studies, it increases the stiffness of the total system and adds damping to dissipate energy. Although the increase in stiffness of the total cargo handling system causes larger response motions resulting from the high frequent force signal, the added damping affects the amplitudes caused by resonance such that the response motions resulting from the low frequent signal significantly decrease. As a result, the total response motions effectively decrease as well.

In short, ShoreTension reduces the low frequent, by resonance driven motions induced by an irregular external force.

Case study 5

Similar to CS4, the irregular force is defined by a high and a low frequent component. The frequency of the first signal, 0.45 rad/s, is much bigger than the natural frequency of the reference case, while the frequency of the second force signal, 0.10 rad/s, is lower than the described natural frequency. Consequently, the motions induced by this system are not driven by resonance, as both frequencies are located far from the natural frequency. The irregular force signal is very alike to the one shown in Figure 25, as only the frequency of the low frequent force is altered. Again, the first force component, described with a large amplitude, governs the signal. Figure 27 presents the response motion of the original system without ShoreTension over time, together with the response of the system including ShoreTension. The response motions are very similar and both the high and low frequencies of the irregular force are easily detected. ShoreTension increases the motions with a small amount, and thus it has a negative influence.

The motions resulting from this case study are not excited in the natural frequency region of the original system. Consequently, both the high and low frequent motions remain unaffected by the damping added by ShoreTension. Moreover, the increase in stiffness of the total cargo handling system caused by ShoreTension, shifts the natural frequency of the system towards the high excitation frequency, enlarging the motion amplitudes.

5.3 DISCUSSION

The AQWA simulations showed that ShoreTension reduces the low frequent part of the relative horizontal motions, when it is applied alongside an existing mooring configuration. However, the high frequent part of the motions continues to exist and is eventually increased.

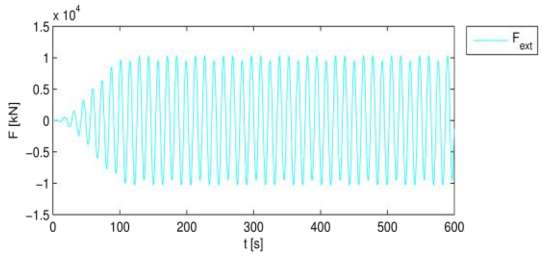


Figure 25: CS3 – Irregular force signal

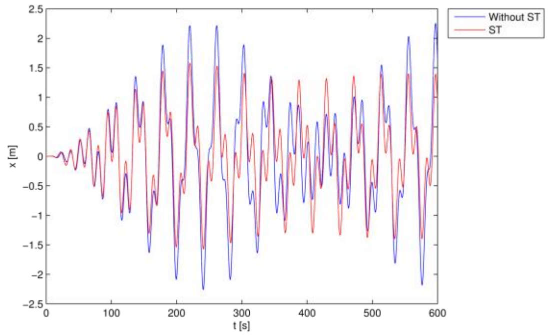


Figure 26: CS4 – Response motion vs. time

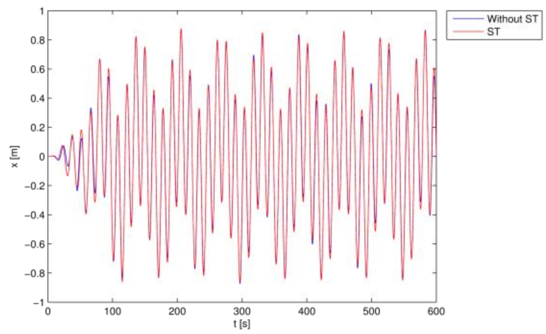


Figure 27: CS5 – Response motion vs. time

This phenomenon is confirmed by the MATLAB mass-spring-ShoreTension model excited by an irregular external force signal. The MATLAB mass-spring-ShoreTension model showed a reduction in the low frequent, by resonance driven motions, induced by the irregular force; while the high frequent motions remained.

6. CONCLUSIONS & RECOMMENDATIONS

Carefully examining the obtained simulation results, conclusions are drawn and recommendations for future work are initiated:

6.1 CONCLUSIONS

The following conclusions apply to ShoreTension in general:

- ShoreTension is capable of reducing motions which are excited in the natural frequency region of the original system. Two principles are followed to reduce the motions:

1. ShoreTension increases the stiffness of the system, such that the natural frequency of the system including ShoreTension shifts away from the excitation frequency, into higher frequency ranges. Consequently, the motion amplitude reduces.
2. ShoreTension adds damping to the system in case the tension in the lines exceeds a certain set limit. Accordingly, ShoreTension gives its mooring line out and heaves it back in. The damping significantly lowers the motion amplitude.

- ShoreTension is incapable of reducing motions which are induced by frequencies beyond the natural frequency of the original system. These motions are not caused by resonance.

Recalling the problem statement of this study:

- ShoreTension is unable to reduce the high-, wave-frequent relative horizontal motions occurring between the HTV and the cargo, as they are induced by frequencies beyond the natural frequency of the original system.
- ShoreTension should be able to reduce the low frequent relative horizontal motions between the HTV and the cargo, as these are determined by the natural frequencies of the original mooring configuration. ShoreTension should in particular be capable of lowering the relative sway motion, as neither of the vessels are excited in this direction. Only hydrodynamic and mechanical coupling loads provoke the relative sway motion. However, the optimal configuration of a cargo handling system including ShoreTension is not yet found. Further research is required.

6.2 RECOMMENDATIONS

As it is expected that ShoreTension is able to minimize the low-frequent relative horizontal motions; it is advised to continue the investigation:

- Extend the MATLAB mass-spring-ShoreTension model, to gain more insight in how the optimal configuration of a cargo handling system including ShoreTension should be outfitted. The following activities are recommended:
  1. Investigate the influence of the direction in which the ShoreTension systems work
  2. Investigate the influence of a more irregular force on a vessel equipped with ShoreTension.
  3. Incorporate two degrees of freedom, such that both the relative surge and relative sway can be resembled in the model.
- Find other cargo handling systems, which possess the ability to reduce the high-, wave-frequent motions.
- Investigate whether the acceptable relative motions can be increased, for example by using wider cribbing beams as support. Increasing the acceptable relative horizontal motions will ease the process of obtaining a capable cargo handling system.

NOMENCLATURE

CHS	Cargo Handling System
CS	Case study
DLL	Dynamic Link Library
FPSO	Floating Production Storage and Offloading unit
HMT	Heavy Marine Transport
HTV	Heavy Transport Vessel
KRVE	Royal Boatmen Association Eendracht/ Koninklijke Roeiers Vereniging Eendracht
OMC	Original mooring configuration
ST	ShoreTension

A	[m^2]	Area
B	[m]	Breadth
b_{eq}	[Ns/m]	Equivalent damping
c	[N/m]	Stiffness
c_{eq}	[N/m]	Equivalent stiffness
Displ.	[tonne]	Displacement
DWT	[tonne]	Deadweight
E	[N/m^2]	Elastic modulus
F_0, F_1, F_2	[N]	External force amplitude
F_{ext}	[N]	External force
F_{ST}	[N]	ShoreTension force
H_S	[m]	Significant wave height
L_{OA}	[m]	Length over all
m	[kg]	Mass
NST	[-]	Number of ShoreTension cylinders, each side of mass
t	[s]	Time
T_{op}	[m]	Draft; moment of operation
T_{PD}	[s]	Spectral peak period
T_Z	[s]	Zero crossing period
α	[°]	Wave direction
ω, ω_1, ω_2	[rad/s]	External force frequency
$\ddot{x}$	[m/s^2]	Acceleration
$\dot{x}$	[m/s]	Velocity
x	[m]	Displacement
$x_{ra\ 1/3}$	[m]	Significant relative surge amplitude
$y_{ra\ 1/3}$	[m]	Significant relative sway amplitude

REFERENCES

[1] T. Terpstra, E. A. Hellinga and H. C. Leerdam, “Offshore dry-docking of FPSOs; a response to industry needs,” in *Offshore Technology Conference (OTC)*, Rio de Janeiro, 2013.

[2] O. A. J. Peters, R. H. M. Huijsmans and M. Seij, “Hydrodynamic behavior during offshore loading and discharge,” in *Offshore Technology Conference (OTC)*, Houston, 2012.

[3] ShoreTension Holding B.V., ShoreTension® Safer mooring, efficient and sustainable operations, Rotterdam.