

Validation of Moored Vessel Response Simulator with Physical Model Comparisons

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Abstract

The evolution and growth of global maritime trade provides a multitude of new and complex vessel mooring challenges. An increased diversity in ship size and type, mooring infrastructure, berthing facilities and locations necessitates innovative and comprehensive solutions in order to accurately predict moored vessel motion and facilitate accurate mooring system design. This paper will provide a detailed validation of the new MIKE 21 Mooring Analysis (MIKE21 MA) model through comparisons with physical model results.

MIKE21 MA simulates moored vessel motions induced by current, wind and wave forcing in the time domain. MIKE21 MA is directly integrated with the MIKE21 wave and hydrodynamic models enabling the accurate prediction of moored vessel response to spatially varying passing vessel drawdown waves, mixed sea states in the lee of structures as well as dynamic winds and currents.

We demonstrate model performance against four physical model investigations, specifically: 1) an LNG tanker moored to an open berth and forced by long-crested sea states; 2) an LNG tanker moored to a sheltered gravity based structure (GBS) and forced by short-crested sea states; 3) an oil tanker moored to an open berth in a port channel and forced by the drawdown wave of a passing vessel; and 4) two LNG tankers moored in tandem and forced by short-crested sea states. In each physical model the vessel motions, mooring line/chain forces and fender forces were measured and are the bases for this validation. MIKE21 Boussinesq wave and depth-integrated hydrodynamic models were generated in order to replicate the wave conditions from the physical models numerically, for use as input to MIKE21 MA. This paper presents motion spectra, motion time series, peak to peak motion and maximum line and fender force comparisons between the numerical and physical model results. MIKE21 MA accurately reproduces the physical model results in all four of the validation cases. These results give confidence that new challenges in vessel mooring can be met with confidence.

Keywords: Moored vessel response, validation, MIKE 21 MA.

1. Introduction

MIKE21 MA is the result of DHI's latest development efforts in moored vessel response software, and is capable of accurately predicting moored vessel motions and mooring system forces for a wide range of complex scenarios. The model framework is based on the original work of Bingham [1], which has been used on commercial engineering projects and continually improved over more than a decade. Earlier staged releases of the model have had previous names such as WAMSIM and DVRS before being fully integrated into the MIKE software environment.

Following an overview of the scientific model framework, this paper presents four validation cases which cover a wide array of mooring arrangements used extensively in modern Port and Terminal design. For each test case, physical modelling results carried out in DHI model basins in Denmark have been compared to identical configurations tested numerically within MIKE21 MA.

2. Nomenclature

N : Degrees of freedom
 C_{jk} : Restoring matrix
 M_{jk} : Mass matrix of the floating bodies
 A_{jk} : Added mass matrix
 B_{jk} : Radiation damping matrix
 α_{jk} : Added mass matrix of the floating bodies
 x_k : Position, speed and acceleration terms of the floating bodies
 K_{jk} : Impulse response function
 F_{jD} : Exciting force matrix
 F_{jnl} : Non-linear external forces
 K_{jD} : Exciting force impulse response function
 η : Time history of surface elevation
 S_b : Wetted body surface
 n_j : Unit normal of body panel

3. Modelling Methodology

MIKE21 MA is a time-domain modelling software package for calculating moored vessel motions and mooring system forces. The model is an integrated part of MIKE, which allow for a fast and

seamless coupling to established 2D wave and hydrodynamic models.

The underlying equation of motion utilised by MIKE21 MA is presented in Equation 1.

$$\sum_k^N \left[(M_{jk} + \alpha_{jk}) \ddot{x}_k(t) + \int_0^t K_{jk}(t - \tau) \dot{x}_k(\tau) d\tau + C_{jk} \dot{x}_k(t) \right] = F_{jD}(t) + F_{jnl}(t) \quad (1)$$

$j = 1, 2, \dots, N$

MIKE21 MA utilizes the inbuilt frequency radiation-diffraction solver FRC, which is DHI's boundary element code used to solve the linear boundary problem for the free surface flow around a body to calculate first order wave forces and second order wave drift forces on offshore structures in the frequency-domain. FRC is capable of accurately modelling single and multibody scenarios in open water or near reflective structures. FRC uses realistic vessel hull geometry and linear potential theory to calculate the hydrodynamics (M_{jk} and C_{jk}) and frequency response functions ($A_{jk}(\omega)$, $B_{jk}(\omega)$ and $F_{jD}(\omega)$) required by MIKE21 MA. MIKE21 MA calculates the corresponding impulse response functions from Fourier transforms of these frequency response functions using Equation 2 to Equation 4.

$$A_{jk}(\omega) = \alpha_{jk} - \frac{1}{\omega} \int_0^\infty K_{jk}(t) \sin(\omega t) dt \quad (2)$$

$$B_{jk}(\omega) = \int_0^\infty K_{jk}(t) \cos(\omega t) dt \quad (3)$$

$$F_{jD}(\omega) = \int_0^\infty K_{jD}(t) e^{-i\omega t} dt \quad (4)$$

If the wave input for MIKE21 MA is spatially consistent we assume a superposition of long-crested waves and the exciting force $F_{jD}(t)$ is calculated by Equation 5.

$$F_{jD}(t) = \int_0^{2\pi} \int_{-\infty}^\infty K_{jD}(t - \tau) \eta(\tau, \beta) d\tau d\beta \quad (5)$$

For the four validation exercises, the MIKE21 Boussinesq Wave (BW) and Hydrodynamic (HD) models have been executed to generate spatially varying data files representing the wave conditions from the physical models. In this case, MIKE21 MA extracts the incident wave potential ϕ_i and first order dynamic pressure P_i from the wave input, while the first order radiation velocity potential ϕ_j is computed by FRC. The wave exciting force $F_{jD}(t)$

is then calculated from the Haskind relations in Equation 6.

$$F_{jD}(t) = \iint_{S_b} P_i(\vec{x}, t) \cdot n_j(\vec{x}) d\vec{x} + \rho \int_{-\infty}^\infty \left(\iint_{S_b} \phi_j(\vec{x}, t - \tau) \dot{\phi}_{in}(\vec{x}, \tau) d\vec{x} \right) d\tau \quad (6)$$

Non-linear external forces are also included in MIKE21 MA simulations. Second order wave drift forces are calculated using [5]. Wind and current conditions are input to MIKE21 MA as either spatially consistent (0D) or spatially varying (2D) data files and the forces are based on generic (provided by MIKE21 MA) or vessel specific (user defined) drag coefficients. Mooring line and fender forces are calculated based on generic (provided by MIKE21 MA) or specific (user defined) load-displacement curves. Viscous damping can also be added to MIKE21 MA models and is included as a combination of constant friction damping plus linear, quadratic and cubic damping. All of these forces are combined in the term F_{jnl} .

4. Model Validation

4.1 Test #1: Open Water Berth

Open water berths in shallow water are a very common terminal option for bulk carrier and tanker berthing in areas with mild to moderate wave climates. This mooring scenario can be influenced by challenging environmental conditions such as long period wave penetration and non-uniform currents at the berth.

In Test #1 an LNG tanker was moored at a water depth of 15m using 14 synthetic rope lines with 11m tails and 4 SCN2000 E1.5 fenders. The vessel characteristics are given in Table 1.

Table 1 Vessel characteristics for Test #1.

Characteristic	Value
LOA [m]	318.2
Beam [m]	50.6
Draft [m]	12
Displacement [m ³]	133824

The Test #1 physical model is displayed in Figure 1 and the mooring setup is detailed in Figure 2.



Figure 1 Test #1 open water physical model setup.

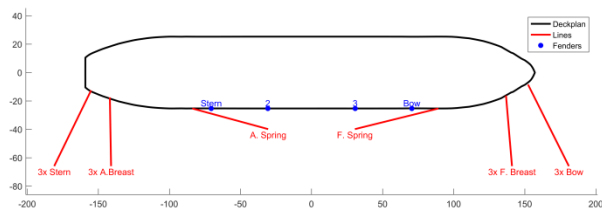


Figure 2 Test #1 open water mooring system definitions.

The wave conditions considered for Test #1 are a significant wave height of 1m and a peak period of 8s. The wave direction is beam-on and into the fenders. A MIKE21 BW model has been used to replicate these wave conditions numerically to serve as the wave forcing input for MIKE21 MA. Figure 3 displays the MIKE21 BW surface elevations with the moored vessel.

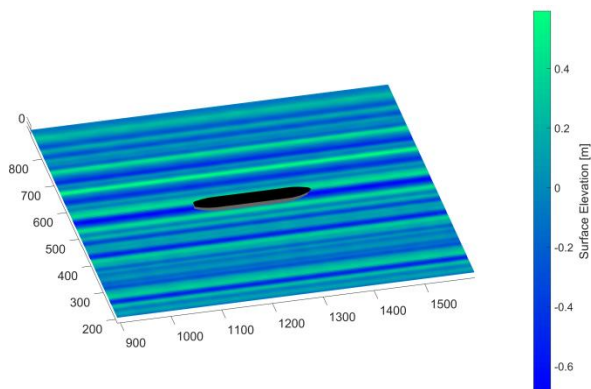


Figure 3 Test #1 MIKE21 BW surface elevation.

Mooring results obtained with MIKE21 MA have been compared to the physical model results. Comparisons of motion spectra and peak to peak motions are presented in Figure 4 and Figure 5. The motion spectra are used to exhibit the distribution of energy along the wave frequencies, while the peak to peak motions are often used to determine moored vessel operability in practice. Comparisons of maximum line and fender forces (only bow and stern fender forces were measured in the physical model) are presented in Figure 6 and Figure 7. All the result comparisons show that MIKE21 MA has very accurately reproduced the

physical model results. Of special interest is the low frequency response observed in particularly sway and roll. The response is replicated well in the numerical model and is caused by a combination of long wave generation and its interaction with the natural resonance frequency of the mooring system.

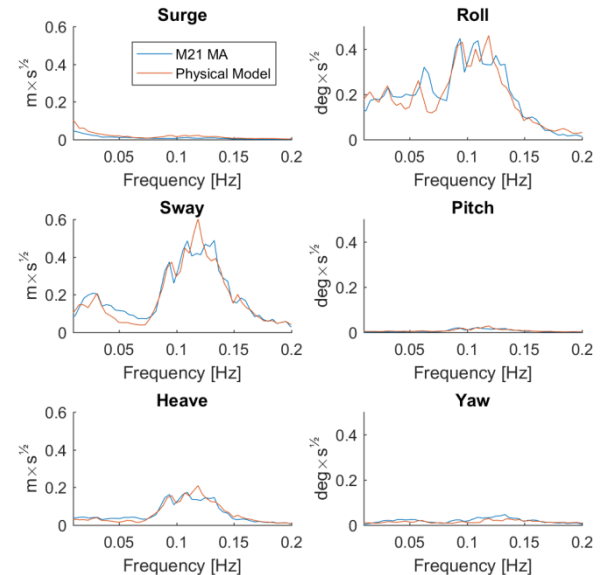


Figure 4 Test #1 motion spectra validation.

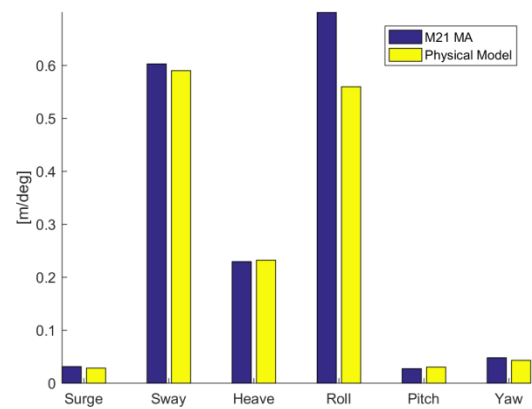


Figure 5 Test #1 peak to peak motion validation.

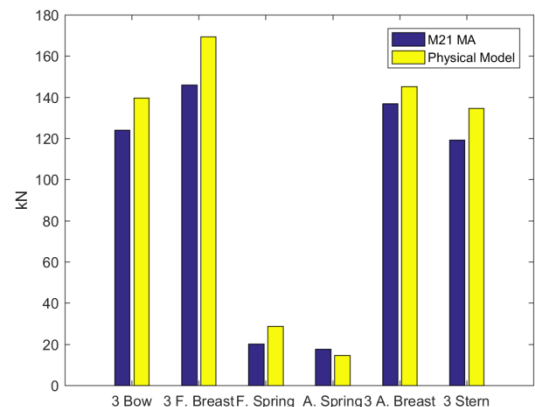


Figure 6 Test #1 maximum line forces.

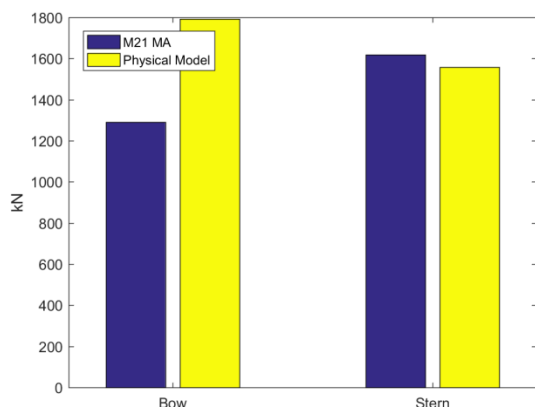


Figure 7 Test #1 maximum fender forces.

In order to demonstrate the effect of the natural resonant frequency of the mooring system a model forced with a spatially consistent timeseries of long-crested waves (no long period wave energy) was executed in MIKE21 MA. It was found that the response of the moored ship was very similar to the full validation, as demonstrated in Figure 8 and Figure 9. The long period response of the ship is thus mostly due to the effect of the natural resonance frequency of the mooring system. Simple steady-state models cannot capture this effect.

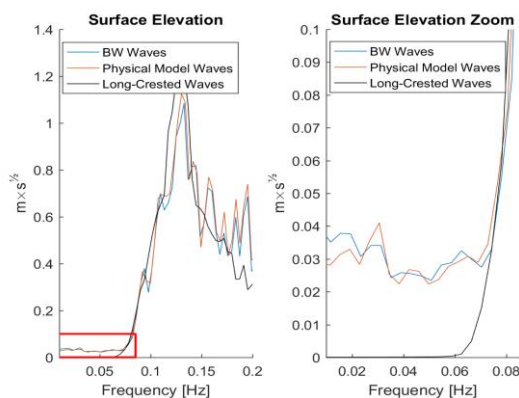


Figure 8 Test #1 surface elevation spectra comparison.

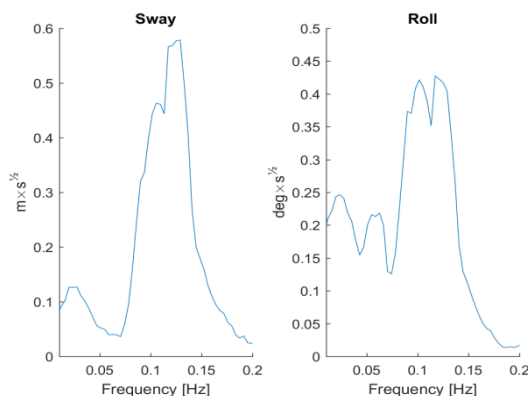


Figure 9 Test #1 MIKE21 MA motion spectra based on forcing of superposition of long-crested waves

4.2 Test #2: Sheltered Berth

Offshore structures, such as gravity based structures (GBS), are used in the petroleum industry as drilling, extraction and storage units for crude oil or natural gas. The interaction between moored vessels and such structures involves complex wave diffraction/sheltering and radiation effects. In order to accurately perform mooring analyses of these scenarios, a coupling of mooring analysis and complex wave modelling is required.

In Test #2 an LNG tanker is positioned 25m away from the GBS at a depth of 15m and the mooring system and vessel characteristics are as described in Section 4.1. The physical model is displayed in Figure 10.

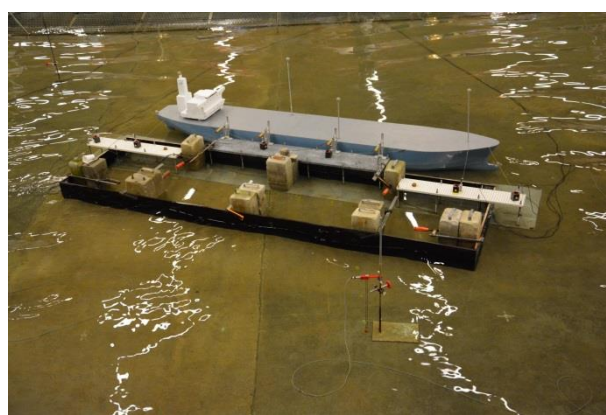


Figure 10 Test #2 sheltered berth physical model setup.

The wave conditions considered for this validation are a significant wave height of 3m and a peak period of 12s. The wave direction is perpendicular to the GBS to maximise its sheltering effects. A MIKE21 BW model was again used to replicate these wave conditions numerically to serve as the wave forcing input for MIKE21 MA.

When moored vessels are in close proximity to fixed structures, such as a GBS, viscous damping effects become complex and significant (especially in shallow water) [2]. M21 MA can account for viscous damping and its effect on vessel motions but requires damping coefficients to be established a priori. Based on physical modelling results a linear roll induced damping coefficient of $4.3E+06 \text{ kNms/rad}$ was established, which was applied to the numerical model setup. Viscous damping in other modes were considered too small to have practical significance.

Test #2 results obtained with the numerical model have been compared to the physical model results. Comparison of motion spectra and peak to peak motions are presented in Figure 11 and Figure 12 and comparisons of maximum line and fender forces are presented in Figure 13 and Figure 14. All the result comparisons show that MIKE21 MA

has very accurately reproduced the physical model results. Again, a long period response of the moored ship has been observed and is mostly due to the effect of the natural resonance frequency of the mooring system.

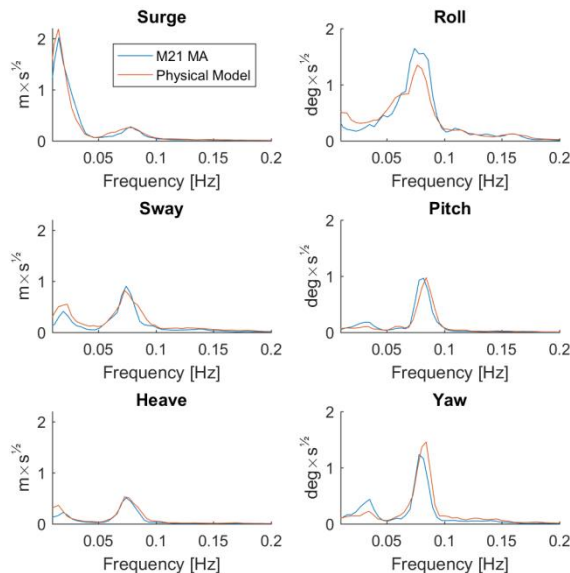


Figure 11 Test #2 motion spectra validation.

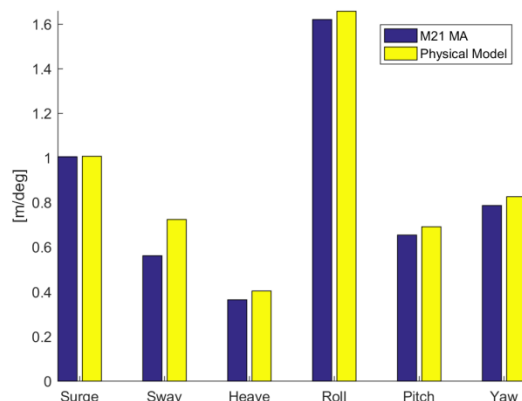


Figure 12 Test #2 peak to peak motion validation.

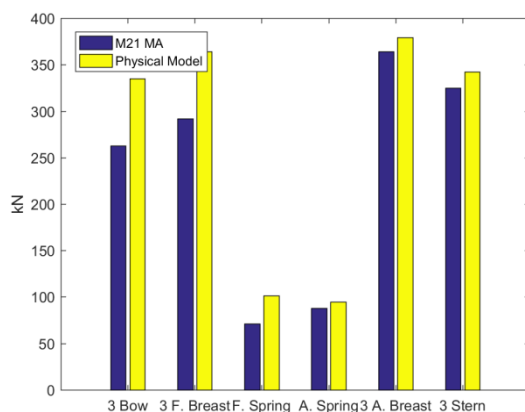


Figure 13 Test #2 maximum line forces.

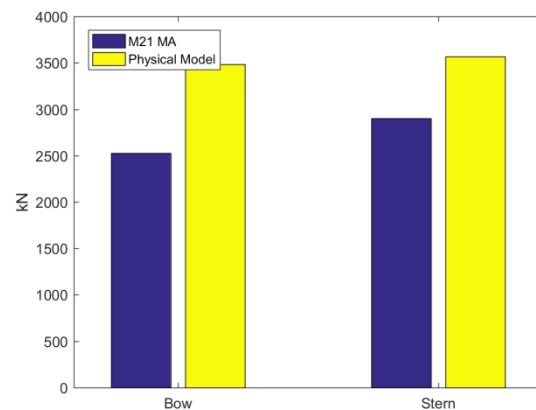


Figure 14 Test #2 maximum fender forces.

4.3 Test #3: Passing Vessel

In transit through shallow/confined waters, vessels generate displacement waves called drawdown which can induce a surge motion to nearby moored vessels of several meters, thereby resulting in hazardous conditions at the berth. The magnitude of this phenomenon is dictated by vessel size, vessel speed, passing distance, channel depth and channel width. Consequently, passing vessel induced moored vessel motion becomes particularly problematic when large vessels are passing in constrained channels. With growing ship sizes and increased port traffic an accurate numerical model is required to provide a cost effective solution to assess this problem. In order to accurately perform mooring analysis of these scenarios, coupling of mooring analysis and complex hydrodynamic modelling is required.

Mortensen et al. 2009 [4] demonstrated this validation using a previous version of the underlying code behind MIKE21 MA. Due to changes/improvements to the code this validation has been updated here. In this paper only the motion validation is presented.

The moored vessel was positioned 130m away from the passing vessel trajectory at a depth of 13.6m. Both the moored and passing vessel have the characteristics shown in Table 2.

Table 2 Test #3 characteristics for both moored and passing vessels.

Characteristic	Value
LOA [m]	200.4
Beam [m]	30.3
Draft [m]	10
Displacement [m ³]	46900

The physical model is displayed in Figure 15 and the mooring setup is detailed in Figure 16.

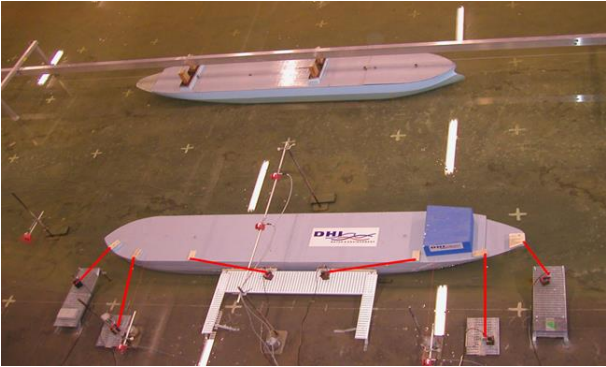


Figure 15 Test #3 passing vessel, physical model setup.

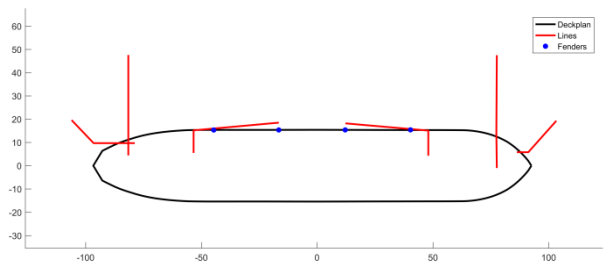


Figure 16 Test #3 passing vessel, mooring system definition.

This drawdown wave is generated in the physical model by towing the passing vessel through the tank along pre-determined tracks at a prototype speed of 8 knots. The wave conditions in the physical model have been replicated numerically by representing the moving vessel as a moving pressure field within the MIKE21 HD model to serve as the wave forcing input for MIKE21 MA.

Results obtained with the numerical model have been compared to the physical model results. Comparison of the motion timeseries' are presented in Figure 17. All the result comparisons show that MIKE21 MA has very accurately reproduced the physical model results.

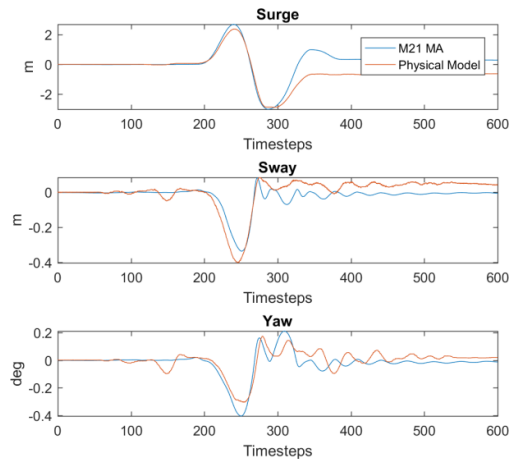


Figure 17 Test #3 motion timeseries validation.

4.4 Test #4: Tandem Moored Vessels

Tandem moored vessel scenarios are often seen in offshore LNG loading and/or offloading systems. This side-by-side moored vessel scenario represents an option for offloading LNG from an intermediate storage tanker with a turret mooring system to a shuttle tanker that will transport the gas to terminals onshore.

Hansen et al. 2009 [3] has demonstrated this validation using a previous version of the underlying code behind MIKE21 MA. Due to changes/improvements to the code this validation has been updated here. In this paper only the motion validation is presented.

The vessels are positioned 4m apart and moored together by 4 lines and 2 fenders. Vessel one is anchored by 4 chains. Both vessels have the characteristics shown in Table 3.

Table 3 Test #4 characteristics for both tandem vessels.

Characteristic	Value
LOA [m]	290
Beam [m]	46
Draft [m]	11.4
Displacement [m ³]	100219

The physical model is displayed in Figure 18 and the mooring setup is detailed in Figure 19.

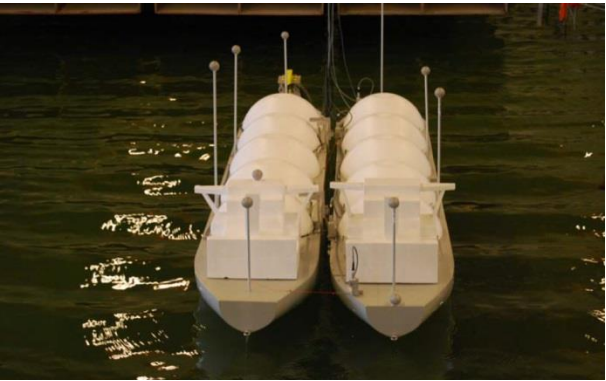


Figure 18 Test #4 tandem vessel mooring physical model setup.

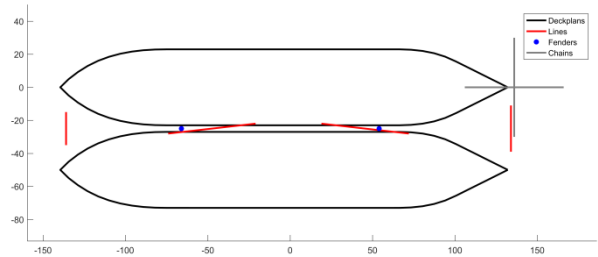


Figure 19 #4 tandem vessel mooring system definition.

The wave conditions considered for Test #4 are presented in Table 4.

Table 4 Test #4 mixed seastate wave conditions.

Swell	Hs [m]	Tp [s]	Direction [deg]
	1.5	16	25
Wind	Hs [m]	Tp [s]	Direction [deg]
	0.5	7.5	0

The wave conditions in the physical model have been replicated numerically by executing a MIKE21 BW model to be used as the wave forcing input for MIKE21 MA.

Results obtained with the numerical model have been compared to the physical model results. Comparison of motion spectra are presented in Figure 20 and Figure 21. All the result comparisons show that MIKE21 MA has very accurately reproduced the physical model results.

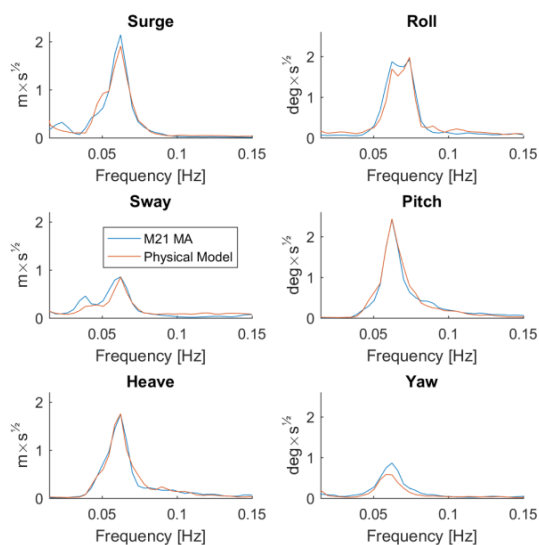


Figure 20 Test #4 motion spectra validation of vessel 1.

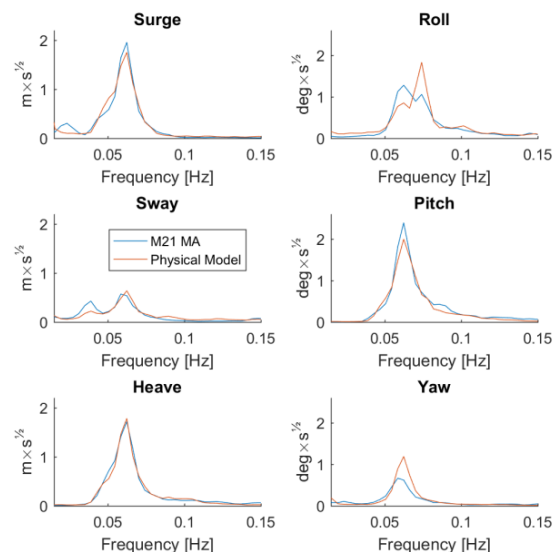


Figure 21 Test #4 motion spectra validation of vessel 2.

5. Summary

The use of a time domain model for predicting moored vessel motions and mooring system forces has been further developed and validated. This paper has shown that DHI's new moored vessel response software MIKE21 MA is capable of very accurately predicting moored vessel motions and mooring forces for a comprehensive range of scenarios. Four test cases have been involved in this analysis including open berth, sheltered berth (moored to a GBS), passing vessel and tandem moored vessels scenarios. The numerical results have been compared to measurements taken during physical modelling examinations and in each case the comparisons show that MIKE21 MA has very accurately reproduced the physical model results.

6. References

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