PIANC-World Congress Panama City, Panama 2018

TRUCK EMERGENCY-BRAKING IMPULSE EFFECT MOORED FERRY

by

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ABSTRACT

Heavy trucks may exert significant impulse loads on the moored ferry due to sudden braking when trucks move from linkspan to ferry deck. Its effect on motions of the moored ferry is studied in this paper to examine the ferry operations during loading and unloading processes involving the safety of vehicles and passengers.

The ferry crossing Thames river is moored by intelligent Docklocking System® (iDL), which is an innovative automated mooring system replacing the use of ferry thrusters. The feasibility and potential of this iDL system to minimize the horizontal movements of the moored ferry are presented in this paper based on numerical simulations of dynamic mooring analysis (DMA) in time domain.

The truck impulse model is linked with a multi-body system including numerical models of the ferry and the jetties. Wind, current and wash wave are also considered, together with the impulse load of the truck to represent a combination of possible loads. This paper first gives a systematic procedure to evaluate truck impulse effect on a moored ferry and then presents motion responses of the ferry when moored by the iDL system.

INTRODUCTION

Ferry mooring

Ferries are conventionally moored along berths using thrusters or mooring ropes. To minimize fuel consumption or to increase safety of personnel involving in moorings and reduce mooring time, the *intelligent* Docklocking System® (iDL) can effectively replace thrusters or mooring ropes for mooring purposes. Thus, to meet London's Low Emission Zone standards and to minimize safety risks, the iDL system will be delivered in 2018 for the mooring of Woolwich Ferries in London, where existing Woolwich ferries (**Figure 1**) will be replaced with hybrid diesel-electric ferries (**Figure 2**) and Woolwich terminals are also replaced with floating pontoons anchored by fixed piles[1].

The safety involving the mooring of the ferries has two noticeable aspects:

- The holding capacity of the mooring system shall be greater than the design environmental loads.
- The movements of the moored ferry shall be within the allowable limits of linkspan.

Truck emergency braking

Heavy-weighted trucks or trailers, when loading on/off the ferry, should be checked carefully in terms of speed limit and maximum weight. A critical scenario is the emergency braking of the truck, which has not been fully studied in terms of its influence on ferry movements, though LR *Rules and Regulations for the Classification of Linkspans, June 2016* has dictated as following:

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To allow for the possibility of emergency braking or skidding incidents, a horizontal load of 0,2 × vehicle weight is to be considered in conjunction with the vertical vehicle loadings.

This statement indicates a deceleration rate of 0.2g during emergency braking. Beyond that, two aspects related to emergency braking are also worth noting: 1) the influence of truck emergency braking on the ferry's motion is not known quantitively; 2) the potential damage is also unclear if the horizontal load exceeds the specified value in the LR rules above.

Although the vehicle speed limit is often marked on the ground of the linkspan before any vehicle drives onto the ferry, to what extent this speed limit is observed is hard to measure as the human factor is involved. Even with strictly observed speed limit, the emergency braking of the truck with exceedingly heavy weight might still be hazardous.

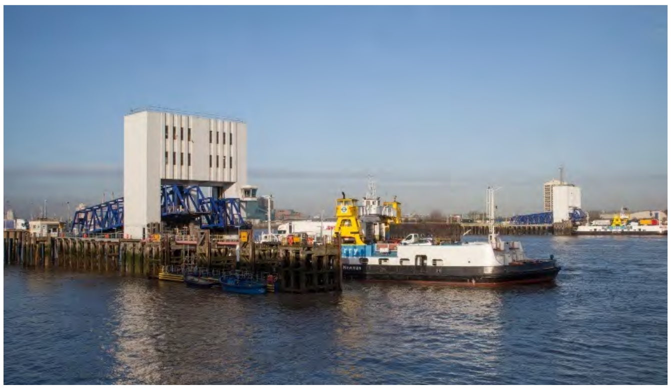

Figure 1: Existing Woolwich Ferry Terminal

Figure 2: New Woolwich Ferry

This paper gives a quantitative study of the ferry movement due to the emergency braking of heavy trucks when the ferry is moored with an automated mooring system (iDL) during realistic environmental conditions (wind, current and wave etc.).

First, the focus is to establish a numerical model of the physical mechanism of the truck emergency braking. For the floating ferry and pontoon jetties, a multibody model is built for hydrodynamic analysis in frequency domain to obtain the required hydrodynamic coefficients. Mooring systems, including iDLs and fenders, are also included in the time domain analysis, taking into account the non-linearities of the mooring systems.

With a complete numerical model as described above, a parametric study is carried out to investigate the influence of varied impulse loads on the ferry movements due to emergency braking. Next, the relationship between ferry oscillatory movements and fender damping is found. This enhances the understanding the effect of truck braking and some preliminary conclusions are drawn regarding the safety of roll-on/off operations.

NUMERICAL MODEL

The objective of a numerical model is to simulate the physical behavior of the complete system involving the ferry, mooring equipment (iDL) and the truck under environmental conditions. The overview of the numerical model is shown in **Figure 3**.

Two inputs for the numerical model are environment conditions and truck impulse. For the environment conditions, they are in line with the site conditions at Woolwich. The truck impulse model is the critical part of the whole simulation to determine the motion response of the ferry.

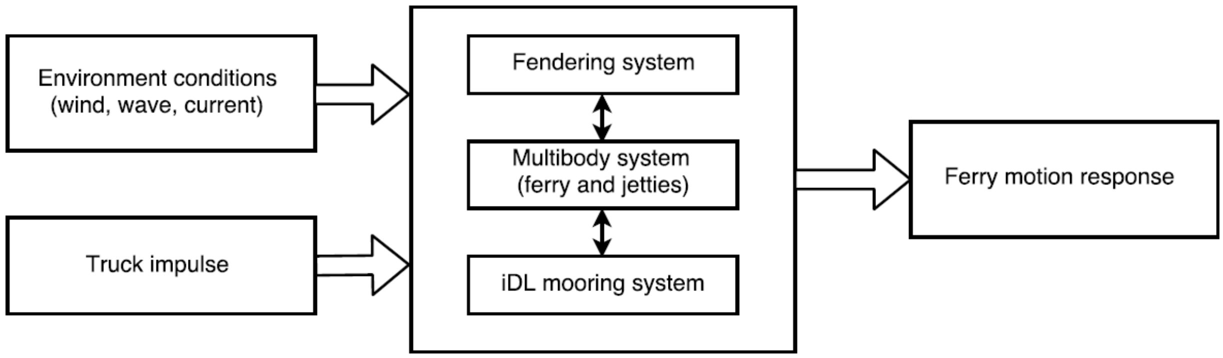

Figure 3: Overview of the numerical model

Environment conditions

The Woolwich berths are located along the inland river, Thames River. Water depth at berthing locations are taken as 10.5 meters corresponding to the highest tide. The wind wave and swell are considered negligible compared to the wash wave generated by passing vessels. Wash wave is assumed to be a regular wave with the height of **0.4 meters** and the period is **3 seconds**. Other input environmental conditions include wind and current. Wind speed is **20 knots** based on 30 seconds gust in transverse direction of the ferry. Current speed is **3 knots** in longitudinal direction.

Multi-floating body

The numerical model includes three floating bodies: two pontoon jetties and the ferry(**Figure 4** and **Figure 5**). The floating pontoons are relatively fixed by piles driven into the riverbed, which allows for free heave movement but very limited horizontal movements for the pontoons. The ferry is a 6-DOF floating body which is moored only by iDLs and fenders.

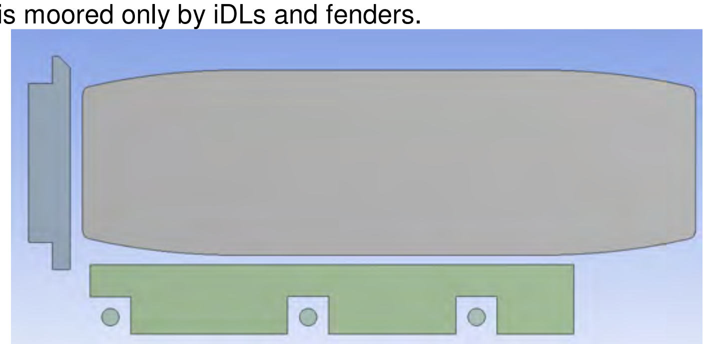

Figure 4: Multi-floating Body (top view)

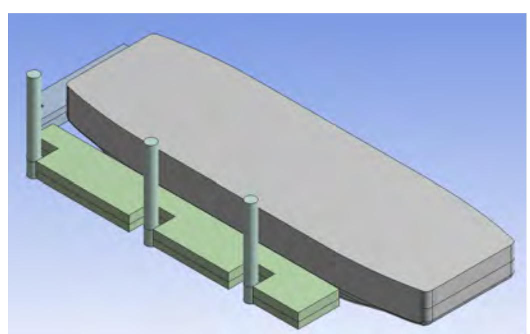

Figure 5: Multi-floating Body (iso view)

External lids are added between pontoons and ferry to suppress the unrealistic standing waves in the gap. Internal lids are also added to remove the irregular frequencies.

In the diffraction model, the pontoons and piles are assumed motionless; this means the diffraction or the shielding effects of the pontoons are considered but the radiation force caused by pontoons is neglected.

Truck impulse model

Despite no directly available element in AQWA to model truck braking process, it can be simulated as the external impulse force connected to AQWA. This impulse force signal is estimated based on the braking deceleration, initial speed, duration of brake etc.

The maximum truck speed before braking is adopted as **10 mph** in this paper based on the speed limit currently marked on the connecting bridge to linkspan of Woolwich ferry berths.

To generate an impulse force signal, three values should first be determined for the signal: shape, magnitude and duration. For the shape of the signal, the rectangle function is assumed to simplify the analysis. Physically, this means braking force will be constant over the course of braking. The magnitude of the signal is the value of the braking force calculated by truck weight multiplying deceleration rate. The duration of the impulse signal is determined based on initial speed and deceleration rate.

Fendering system

The fenders installed on the bow pontoon and the side pontoon are specified as TTV 800 and TTV 600 type respectively. The fender locations on the pontoons are shown in **Figure 8**. To model the load deformation curve of the fenders, a fifth order polynomial function is used:

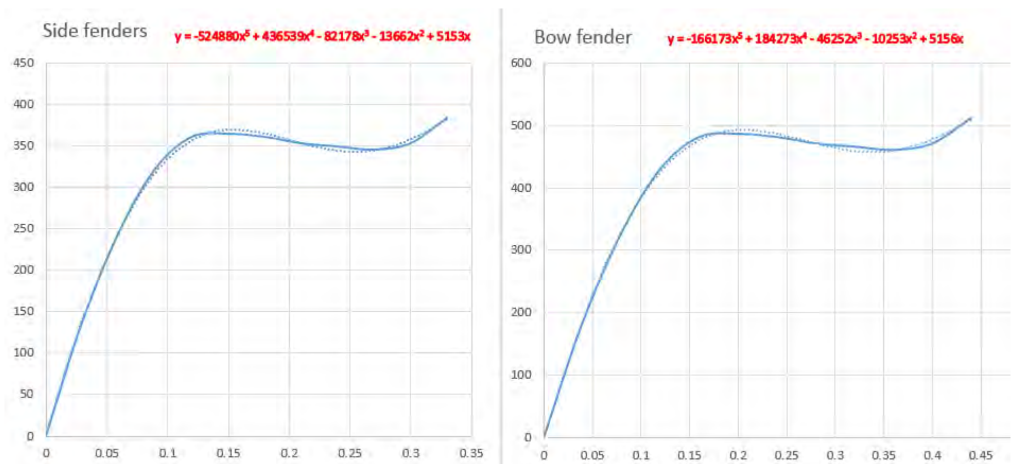

Figure 6: Load Deformation Curve for Bow and Side Fenders

The solid blue curve is the fender compression curve from the manufacturer and the blue dotted curve is the fitted curve by fifth order polynomial. Fender friction coefficient in the DMA analysis is taken as 0.1 in a conservative manner for the selected case, as the manufacturer has specified a value of 0.2; fender damping is not specified and this topic will be discussed later in the results section.

Automated mooring system (iDL)

The iDL is an automated mooring system based on magnets translated by hydraulic cylinders. It is a complicated system that restricts surge and sway movements, but allows for the heave, roll and pitch movements of the vessel. This movement of the vessel needs to be restricted to keep linkspans on the vessel and allow for a safe passage of vehicles.

Two iDL units are placed on the side pontoon symmetrically w.r.t the CoG of the vessel (**Figure 7** and **Figure 8**). iDL units are integrated into the numerical model based on its force and displacement characteristics as well as its control system. Due to confidentiality, the exact details cannot be disclosed in this paper.

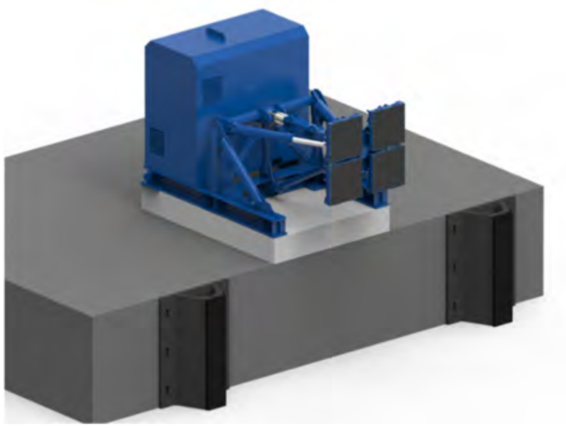

Figure 7: intelligent Docklocking System® (iDL)

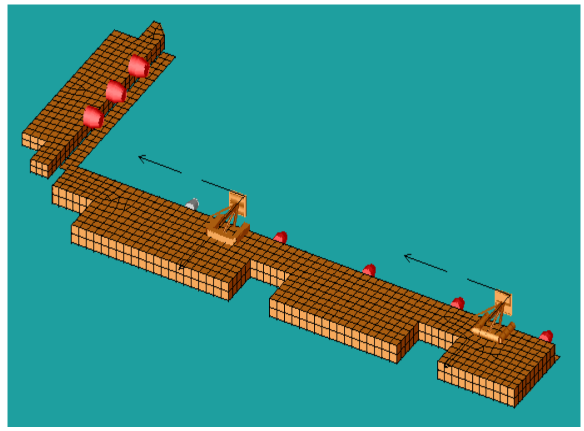

Figure 8: Two iDLs Mounted on the Side Pontoon With Fenders Installed (red).

THEORY

With all the elements defined in the numerical model, the 6-DOF movements of the ferry subjected to truck impulse loads as well as environmental factors will be evaluated in time domain. The motions in time domain are solved in AQWA based on Cummins[2] EoM (Equation of Motions):

$$(m + A_\infty)\ddot{X} + c\dot{X} + kX + \int_0^t R(t-\tau)\dot{X}(\tau)d\tau = F(t) \qquad (1)$$

where external $\boldsymbol{m}$ is the ferry mass matrix and $\boldsymbol{A_\infty}$ is the added mass at infinite frequency, $\boldsymbol{c}$ is the linear damping matrix due to radiation and $\boldsymbol{k}$ is the total stiffness matrix; $\boldsymbol{R}$ is the impulse response function which can be integrated to represent 'memory' effect. Also noted that $\boldsymbol{F(t)}$ is the time-varying external force including Froude-Krylov force, diffraction force, drift force, viscous damping force and other user-defined external force etc. Hence, the truck impulse force is input into AQWA as the user-defined external force which is a rectangular pulse function of duration $\boldsymbol{T}$ based on the Dirac Delta function:

$$\delta_T(t) = \begin{cases} 0 & for\ t \le \boldsymbol{T_1} \\ \dfrac{\boldsymbol{a}}{(\boldsymbol{T_2} - \boldsymbol{T_1})} & for\ \boldsymbol{T_1} < t \le \boldsymbol{T_2} \\ 0 & for\ t > \boldsymbol{T_2} \end{cases}$$

where $\boldsymbol{a}$ is the magnitude of impulse momentum.

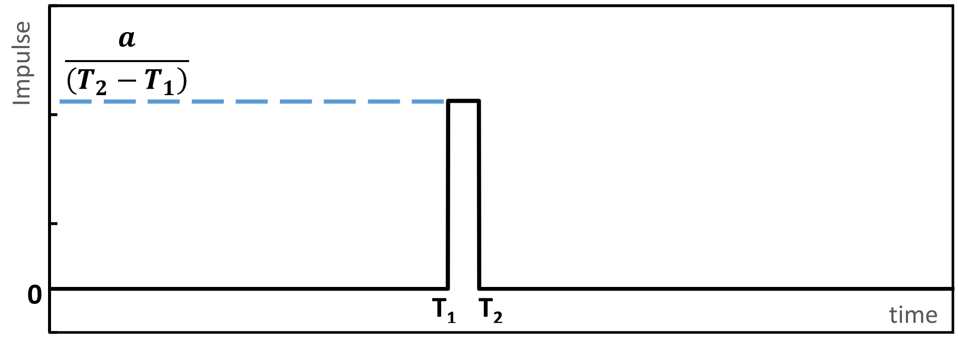

Figure 9: Rectangular Pulse Function

By solving time domain equations, the velocity of the ferry can be obtained such that the energy balance equation is established between the truck impulse-kinetic energy, the ferry kinematic energy and other damping dissipated energy:

$$E_{truck} = E_{fender} + E_{damping} \tag{2}$$

where the truck kinetic energy E_{truck} due to impulse is defined as:

$$E_{truck} = \frac{1}{2} m_{truck} v_{initial}^2 \tag{3}$$

Here the dissipated damping energy is only vaguely defined as the sources of the damping force can be varied: linear radiation damping, viscous damping and material damping etc.

RESULTS & ANALYSIS

Base case

The base case is presented here to give an overview of the response of the entire system subject to environmental conditions and truck impulse load. Input environmental conditions are based on the table **1**.

The truck impulse deceleration is taken as 0.2g m/s^2 in the longitudinal direction(surge) based on LR rules. The input truck weight is 44 tons, giving an impulse load of 86.3 kN. The impulse starts from 101s and ends at 103.3s, within the total 200 seconds of time series record.

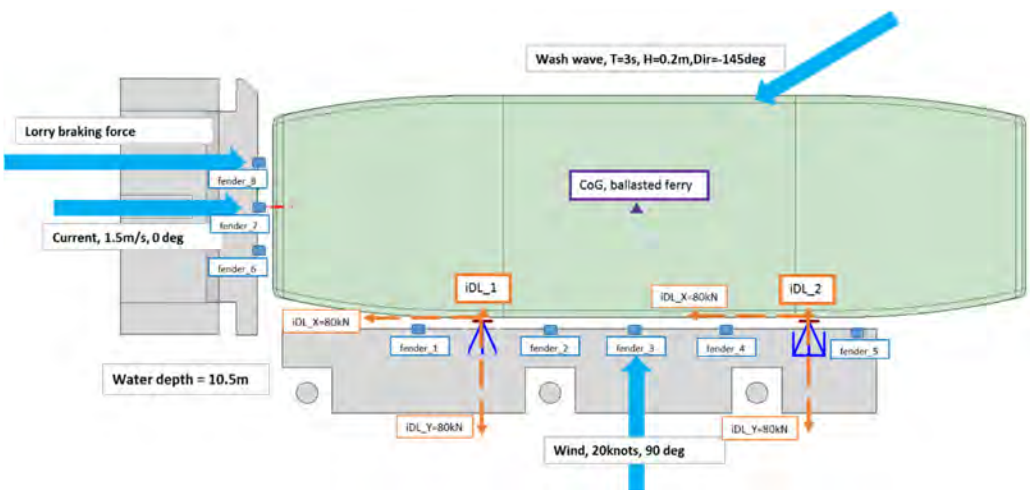

Figure 10: Directions of Environmental and Truck Braking Loads

As shown in **Figure 11**, iDLs could effectively keep the ferry in position with minimized ferry responses. The ferry dynamic surge movement due to wash wave is within ±5 mm range. When subjected to impulse load due to truck (**Figure 12**), the surge movement spikes to [+15mm, -10mm] range, but still within a very acceptable limit for safe ferry operations for vehicles and passengers.

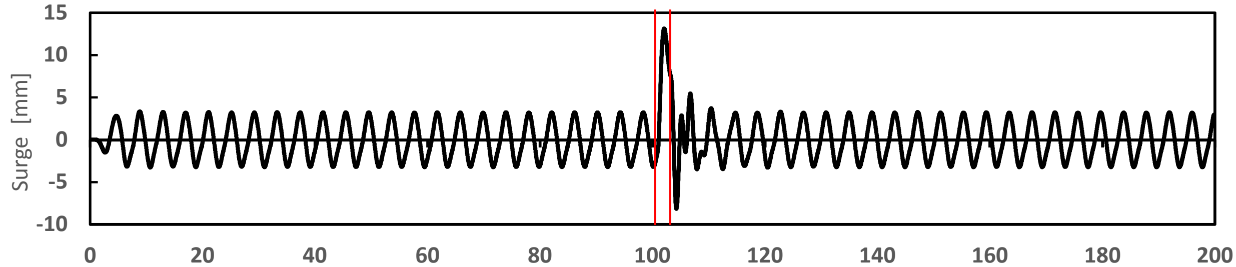

Figure 11: surge movement of the ferry

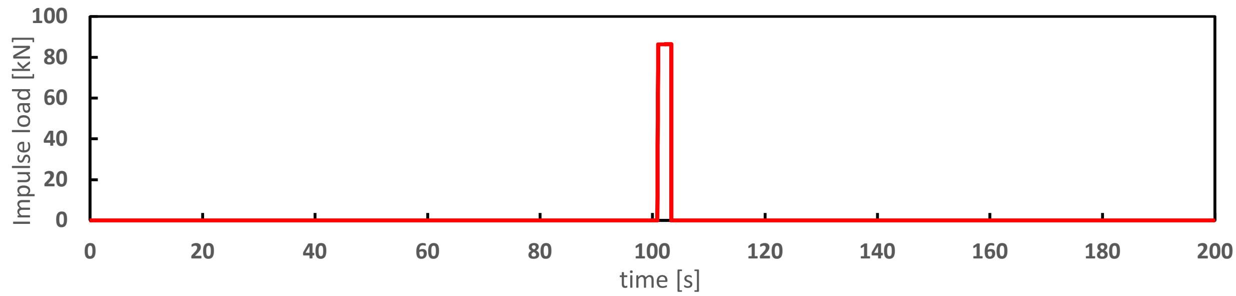

Figure 12: impulse signal due to truck emergent brake

Varying truck impulse

The influence on ferry surge motions due to varying decelerations of truck brake impulse from 0.1g to 0.4g is studied here based on equation of motions in time domain. In line with base case, for each deceleration, the impulse starts from 101 second and the impulse load is constant over the impulse duration. The impulse duration is determined by the initial truck kinetic energy and deceleration rate.

The impulse signals are illustrated in **Figure 13**, where the area under each truck impulse signal from 0.1g to 0.4g has the same value, as the area represents the total impulse kinetic energy, which is constant as the initial speed of the truck is defined as 10 mph for all cases.

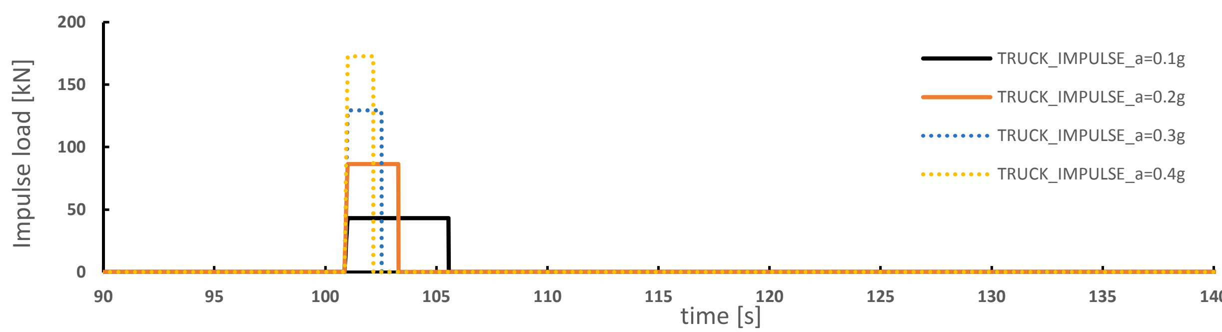

Figure 13: Varied Truck Impulse Rates

The influence of varying truck impulse on ferry surge motions is illustrated in **Figure 14**. Two patterns can be distinguished from it: the dotted lines show large oscillatory surge movements pattern lasting more than 10 seconds, whereas solid lines last only 5 seconds with surge movements less than 10 mm.

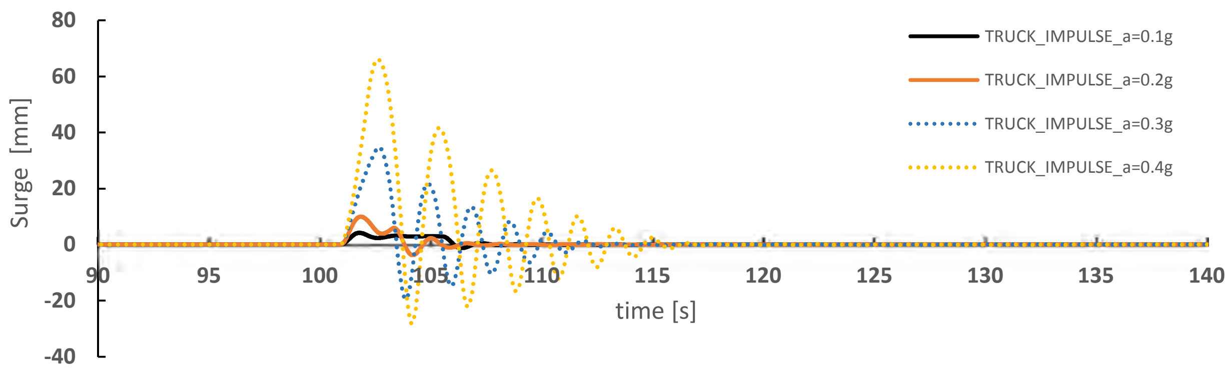

Figure 14: Surge Movement of the Ferry with Varied Truck Impulse Rates

To analyze the behaviour of the ferry under sharp impulse load in details, with the case for truck impulse of 0.4g, this large oscillatory surge movement pattern can be further divided into 3 stages based on kinematics as shown in **Table 1** and **Figure 15**.

Stage	**Stage 1, S1**	**Stage 2, S2**	**Stage 3, S3**
Duration	Equal to impulse duration	Dependent on iDL force	Dependent on damping
Characteristics	Impulse load due to truck	iDL holding vessel back	iDL and fender force exerted
Ferry movement	Started to move	Movement reaching peak	Oscillatory movement
Ferry velocity	Increased from zero to peak	Decreased from peak to zero	Oscillatory velocity
Ferry acceleration	Accelerated	Decelerated	Accelerated and decelerated

Table 1: Three Stages of Ferry Responses due to Truck Impulse

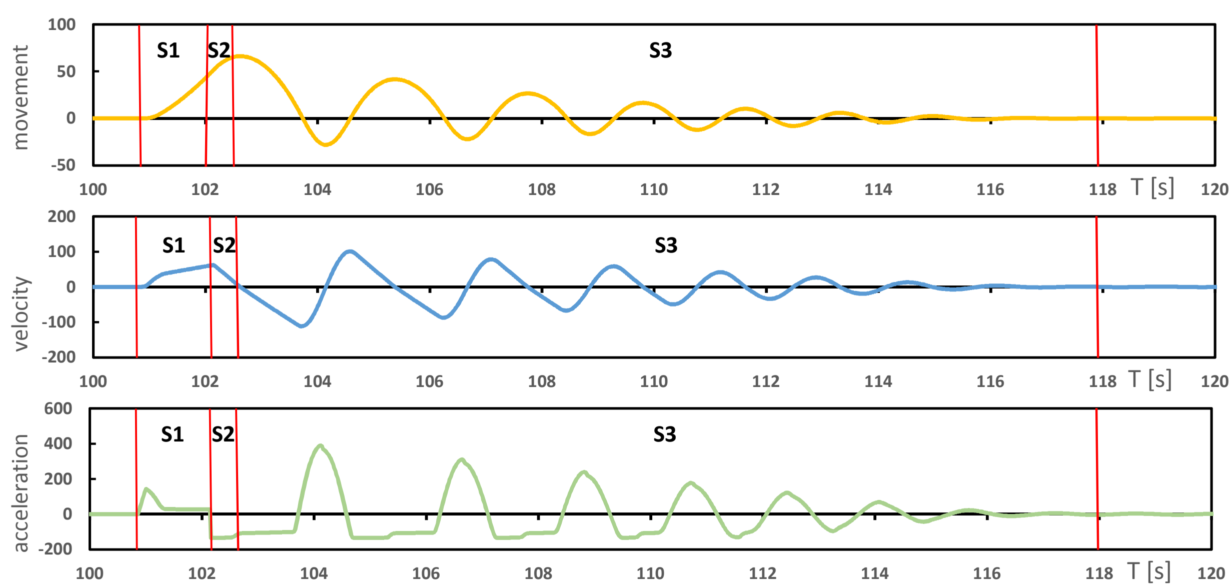

Figure 15: Movement [mm], Velocity[mm/s] and Acceleration[mm/s^2] of Ferry due to Truck Impulse of 0.4g

Varying fender damping

Stage 3 is the oscillatory stage where damping plays a pivotal role in ferry response. In previous sections where the fender damping is assumed zero, the decay rates of oscillatory ferry movements are determined by hydrodynamic damping, whose values have been widely studied elsewhere.

Therefore, the focus here is on fender damping due to hysteresis[3], despite it being ignored in most motion analysis (**Figure 16**). The fender hysteresis is the phenomenon that over a full cycle of compression and decompression, part of the absorbed energy is dissipated in the recoil cycle (**Figure 17**).

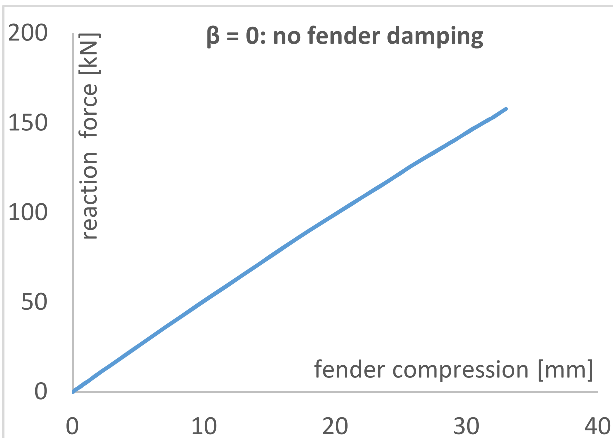

Figure 16: Fender load-deformation curve

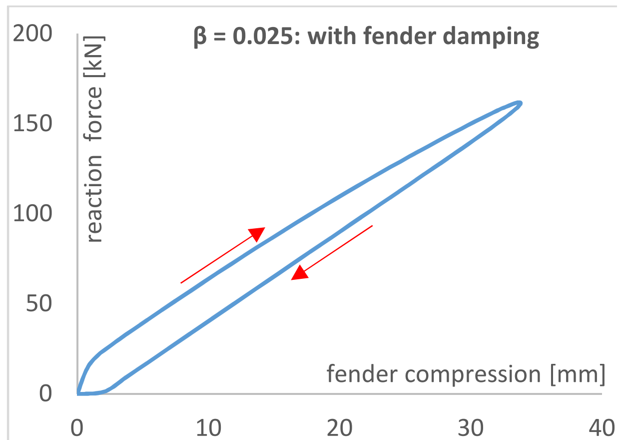

Figure 17: Fender load-deformation curve

By varying fender damping coefficient, its influence on ferry movement is investigated. As shown in **Figure 18**, with increased fender damping, both the amplitudes and cycles of oscillation of ferry surge response are reduced. Furthermore, the first peak is not so much influenced by fender damping coefficients as the subsequent peaks.

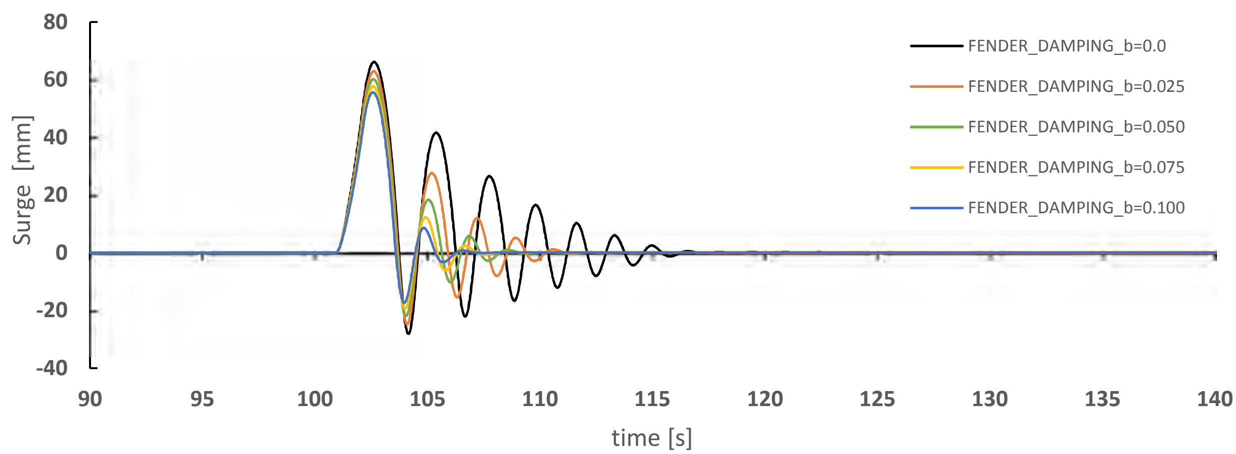

Figure 18: Influence of Fender Damping on Surge Movement of Ferry due to Truck Impulse of 0.4g

CONCLUSION

This paper describes a systematic numerical model encompassing the key elements to simulate the process of truck emergency braking. The focus was to investigate the influence of truck impulse on the motions of the ferry moored by iDL and fenders. Summarizing the results, several conclusions are made:

1. The automated mooring system, iDL, can effectively keep the ferry in position safely under the truck impulse force and environmental conditions specified in this paper.

2. The response of the ferry under pure truck impulse can be divided into 3 stages; the first stage reaches the highest velocity of the ferry, second stage with the peak movement and third stage with oscillatory decay response lasting much longer than the duration of impulse load.

3. By varying truck brake impulse from 0.1g to 0.4g and keeping the same amount of input kinetic energy, it is found that with sharp impulse (e.g., 0.4g), the response of the ferry will be much increased compared to mild impulse. Moreover, the duration of the decaying oscillation due to sharp impulse is also longer than that of mild impulse.

4. For the third stage with long oscillatory decay response due to sharp impulse, the significance of fender damping caused by hysteresis is reflected on the reduced amplitudes and cycles of the ferry movements. Thus, the fender damping will help reduce the oscillatory movement of the ferry.

Based on the numerical model established in this paper, further work should be continued. Field measurements are necessary to verify and fine-tune the numerical model. Obtaining practical fender hysteresis damping coefficient is an often-overlooked effort but worth doing as it could effectively dampen ferry movement due to impact. Also, the practical kinetic energy of the ferry due to truck impulse will be further reduced based on eccentricity factor, softness factor and berth configuration factor.

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