A mooring arrangement optimisation study

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ABSTRACT

Ports want to ensure safe and reliable loading operations for all ships. Increase in ship sizes, especially container ships, potentially cause unsafe mooring situations. For ships moored at quay walls, there is also a lack of international guidelines for mooring arrangements. This paper presents a case study for a moored containership being passed by a vessel of identical dimensions. The behaviour of the moored ship is simulated using UGent's time-domain mooring software Vlugmoor. Starting from a well-balanced arrangement used in daily operation, three optimisation steps are presented, aiming at lowering the ship motions, which are critical. The first step explores the impact of changing line positioning to reduce line length disparity and improve efficiency in critical force directions. The second step considers a lower fore mooring deck to reduce line steepness, as well as additional winches below the bridge and funnel. The third step proposes replacing medium stiff lines with a very stiff HMPE line, combined with an elastic tail. The effect of these optimisation steps on the ship motions are presented and compared with predictions based on efficiency parameters, expressing the capacity of the configuration to deal with positive and negative surge forces. It is shown that applying these optimisation steps can significantly improve the safety of a moored container ship during a ship passage.

NOMENCLATURE

A_f	[m²]	frontal wind surface	MBL	[ton]	minimum Breaking Load
A_l	[m²]	lateral wind surface	n	[ ]	number of lines
$A_{l,s}$	[m²]	A_l, including quay shielding	$O_{-x,y,z}$	[ ]	earth fixed coordinate system
A	[varies]	added mass	$O'_{-x',y',z'}$	[ ]	local bollard coordinate system
B	[m]	beam	X	[varies]	general motion vector
B	[varies]	damping	T_d	[m]	design draft
C_B	[ ]	block coefficient	T_s	[m]	scantling draft
C	[varies]	restoring term	ukc	[%]	under keel clearance
D	[m]	depth	x	[m]	surge motion moored ship
e_{Xp}	[ ]	positive longitudinal efficiency	x_{neg}	[m]	negative surge motion amplitude
e_{Xn}	[ ]	negative longitudinal efficiency	x_p	[m]	position of passing ship in $O_{-x,y,z}$
e_{Xp}'	[ ]	e_{Xp}, including line elasticity factor	x_{pos}	[m]	positive surge motion amplitude
e_{Xn}'	[ ]	e_{Xn}, including line elasticity factor	X_p	[ton]	surge force passing ship
F_{pas}	[varies]	general ship passing force	y_M	[m]	lateral motion midship
F_{rel}	[ ]	relative line force	y_A	[m]	lateral motion aft perp.
F_{lines}	[ ]	reaction force lines	y_F	[m]	lateral motion fore perp.
$F_{fenders}$	[ ]	reaction force fenders	Y_{pA}	[ton]	transversal force passing ship aft perp.
ℓ	[m]	line length	Y_{pF}	[ton]	transversal force passing ship fore perp.
ℓ_{ref}	[m]	reference line length	α	[°]	line angle in horizontal plane
ℓ_{tail}	[m]	mooring tail length	β	[°]	line angle in vertical plane
L_{OA}	[m]	length overall	ε_{br}	[%]	breaking strain mooring line
L_{PP}	[m]	length between perpendiculars	ξ	[ ]	dimensionless position passing ship

EN	equipment number	MC		mooring configuration
IACS	Int. Association of Classification Societies	OCIMF		Oil Companies Int. Maritime Forum
IMO	International Maritime Organisation	PIANC		World Association for Waterborne Trans. Infra.
HMPE	high-modulus polyethylene	TEU		twenty foot equivalent unit
		ULCV		ultra large container vessel

1   INTRODUCTION

Ship sizes keep on increasing, and ports have a hard time keeping up. When quays and jetties want to welcome large (design) vessels, ensuring the moored vessels' safety is an essential step in the feasibility study of a project. The mooring system needs to counteract the external effects posed by wind, current, passing ship and wave effects. In ports sheltered from (direct) wave action, the main concern is the effect of wind. Due to often limited dimensions of channels and docks however, ships pass the moored ships at close distances. In order to fulfil manoeuvring and traffic flow requirements, a minimum passing speed is often needed.

It is important that ship have adequate mooring equipment on board and that berths are provided with sufficient mooring points. For oil tankers, the jetty design and mooring plan is fixed, with limitations for maximum line angles, based on OCIMF guidelines [1]. In this approach, it is assumed that there is sufficient distance between the ship's side and the mooring points, allowing for efficient breast lines to be applied. For most dry bulk operations however, the ship is moored at a quay wall equipped with cranes/conveyor belts to (un)load the ships. This limits the available space for mooring points to a zone of only a few meters, between the quay face and crane tracks. The dynamics of the system change as well, with the passing ship surge force being dominant when considering a quay wall, compared to large sway forces for the open water (jetty) case.

 For mooring line properties, international guidelines are issued by IMO and IACS. A first set of recommendations, dating from 2005 [2] [3], were updated in 2016 [4]. The latest formulation however fails to set demands for line elasticity, which means that very elastic lines are in use worldwide. These result in large motions of the moored ships under external loads.

The current research focuses on the mooring equipment (winches, mooring lines) in use on large containerships, where optimisation procedures are proposed to enhance the safety of a moored containership under a passage by an identical ship. A case study, based on open data from the magazine *Significant Ships* [5] for the ULCV *UASC Barzan,* is presented. The behaviour of the moored ship is simulated using the UGent time-domain mooring software Vlugmoor, showing that the surge motions of the moored ship are critical.

Three optimisation methods are proposed that aim to lower the ship motions, starting with an optimal spatial positioning of the lines, using the existing equipment on board *Barzan* and a representative container quay layout. In a second approach, the positioning of the winches is examined, without interfering with the cargo space. For example, the winches on the forecastle deck are repositioned to a lower deck level, in order to reduce the steepness of the lines. In another example, two pairs of winches are added underneath the funnel and bridge, for extra spring lines to cope with surge forces. A third proposition involves using very stiff HMPE lines, in combination with elastic tails, in order to limit the motions of the moored ship.

A last section offers a method to compare and optimise mooring configurations based on so-called efficiency parameters. This method has already been presented in [6], but it is now tested for all the optimisation cases, and expanded to cope with lines with varying elasticity.

2   DESIGN SHIP CASE STUDY - MOORING ARRANGEMENT

The optimisation study is presented for the case of a moored container ship, under the passage of a container ship of identical size. The dimensions of ship and properties of the mooring equipment on the moored vessel are based on open data to reflect what is actually found on the vessel. A typical mooring arrangement, as well as a comparison of the equipment with existing guidelines, are presented.

2.1   Mooring arrangement 19,870 TEU ship

The moored vessel is the *UASC Barzan*, a 19,870 TEU containership [5]. The main properties can be found in Table 1. Note that the wind surfaces, A_l and A_f are given for the design draft, estimated based on the general arrangement plan which is present in the document.

Table 1: Main dimensions *UASC Barzan*.

Variable [unit]	Value	Variable	Value
L_{OA} [m]	400.0	T_d [m]	14.5
L_{PP} [m]	383.0	T_s [m]	16.0
B [m]	58.6	A_f [m²]	3146
D [m]	30.6	A_l [m²]	17583

There are 16 single drum winches on board the ship, 8 on the (lower) aft deck and 8 on the forecastle deck. A common configuration at a container quay is given in Figure 1, defined as configuration MC0. The bollards on the quay are positioning every 20 m and two lines can be safety attached on each. 9 high capacity fenders, with negligible friction, are added to restrain the ship in the negative y-direction. As the fender loads are limited in these passing ship cases, they are not further discussed in this paper. The quay level is set at +2.00 m, relative to the water surface level, which is the reference plane for the (z) coordinates in this paper. This low quay level leads to steep lines, which are not well suited to cope with forces in the horizontal plane.

The container ship is modelled at scantling draft (16.00 m), leading to aft and forecastle deck levels of +9.00 m (estimated based on general arrangement) and +14.60 m respectively. Each mooring line is denoted by three spatial parameters (Figure 2). The angles in the horizontal and vertical plane are α and β, respectively. The total line length (ℓ), the sum of length between fairlead and bollard on quay and between fairlead and winch on board, determines the response of the line. A short line attracts large loads, with long lines being loaded less. α, β and ℓ for lines are given in Table 2.

The actual line properties are not specified in [5]. A monitoring campaign performed in [7] shows that the line types are variable, even within the same 'class' of 400 m long ships. The breaking strength, MBL, seems to be within a narrow range, with 140 tons as a representative value. The elasticity on the other hand is highly variable, ranging from elastic nylon lines to stiff HMPE lines. In the reference situation, a medium stiff line with elongation at break of 15% (ε_{br}) is considered. This is compared with the use of stiff line (HMPE) and elastic tail, as an optimisation step of the mooring configuration.
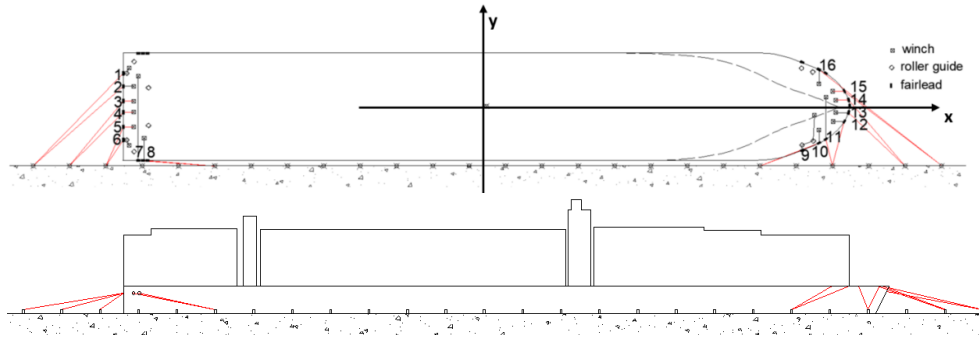

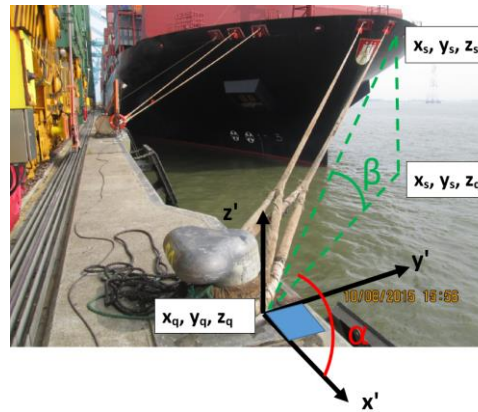Figure 1: Mooring configuration 'MC0' for design vessel; Top : Top view ; Bottom : Profile view

Figure 2 : Definition of mooring line angles (α,β), local bollard coordinate system O'-x',y',z'
– Image courtesy of Antwerp Port Authority.

Table 2: Mooring line angles (α,β) and length ℓ for configuration MC0 (Figure 1).

Line n°	α [°]	β [°]	ℓ [m]	Line n°	α [°]	β [°]	ℓ [m]
1	45	6	76	9	20	27	52
2	41	6	72	10	21	20	45
3	50	9	53	11	102	40	42
4	44	9	48	12	74	27	34
5	65	17	30	13	137	17	51
6	55	22	24	14	131	15	56
7	176	10	88	15	143	11	74
8	176	10	51	16	142	8	94

2.2   Mooring line guidelines

The basis for the determination of the number of lines (n_{lines}) and MBL is formed by the definition of the equipment number (EN), postulated for quantifying towing and anchoring equipment [3]. In the 2005 guidelines, a relationship between EN and n_{lines}, MBL is expressed in tabular form. Based on the properties of the *Barzan* (Table 1 and [5]), the EN number is 10,980, hence 16 lines are required, with an MBL of 736 kN ($\approx$ 75 ton). The MBL is much lower than the lines used on board, with an MBL of 140 tons. These 2005 guidelines are thus not representative for large (container) ships. This is however not surprising, as the EN was defined for towing and anchoring, where the frontal wind surface is more important.

The 2016 guidelines explicitly incorporate the lateral wind surface, A_l, in the calculation of the MBL and the number of lines. The sum of the number of head and stern lines is given by Eq. (1)

$$n_{head+stern} = 8.3 \cdot 10^{-4} \cdot A_{l,s} + 6 \text{ [4]} \tag{1}$$

For an unshielded quay, 21 lines are required. If shielding is present, with wind coming from land, the hull can be assumed to be shielded over a height of 3 m (defined here as $A_{l,s} = 16434$ m²), still requiring 20 lines. For vessels with an EN above 5000, 4 springs are required additionally. The demanded MBL for all lines is given by Eq. (2). Lines with MBL of 1993 kN are recommended here.

$$MBL = 0.1 \cdot A_{l,s} + 350 \text{ (kN) [4]} \tag{2}$$

It is clear that the demand of 24 lines with 1993 kN is far from met. Of course, the *Barzan* was built before this document was published. It remains to be seen however if newly built vessels will have 24 winches on board. It is also surprising that the new rules fail to incorporate the elasticity of lines as a design parameter. It will become clear in the next section that this is a critical parameter when assessing dynamic ship behaviour, certainly when ship motions form the limiting factor.

2.3   Mooring arrangement guidelines

The mooring arrangement should aim to keep all line forces below OCIMF limits and restrain the ship in the horizontal plane as much as possible. From this definition, it becomes obvious that steep lines need to be avoided. OCIMF [1] sets a maximum of 25° for the vertical angle (β, Figure 2). For the configuration MC0, this means that lines 9,11 and 12 exceed this criterion.

In order to keep the vessel moored safely, the mooring lines need to counteract external forces, which work in surge (x) and sway (y) direction (see axis system Figure 2). Spring lines are positioned along the quay wall and counteract surge forces, with angles $\pm$ 10° from the longitudinal axis (OCIMF). Breast lines restrain the ship in the transversal direction, defined as having angles $\pm$ 15° to the axis perpendicular on the quay. When applying this definition to Table 2, one breast line (11) and two spring lines (7 and 8) are present. All other lines take up forces in surge and sway, but are less efficient. Due to the limitations of having only bollards close to the quay face, it is impossible to comply with OCIMF definitions. An alternative method to evaluate a mooring arrangement of a large ship at a quay wall is thus required. The current paper presents an integrated approach, which aims at evaluating the mooring configuration as a whole, rather than looking at the individual lines, allowing for assessment, comparison and improvement of the mooring arrangement.

3   MOORING ARRANGEMENT OPTIMISATION

In [6], a set of efficiency parameters has been defined and used to evaluate the mooring arrangement. These parameters are re-used here to quantify mooring line optimisation steps, based on simple rules of thumb. The present study focuses on passing ship effects. A numerical calculation example is first shown, to motivate the focus on longitudinal efficiency of the configuration. This assumption is confirmed later on (section 5.2), when assessing the behaviour of the moored ship and comparing with criteria for forces and motions.

3.1   Passing vessel effect

The primary pressure wave travelling with the passing ship affects the moored ship substantially [8]. These forces are calculated here with the numerical potential package RoPES [9]. For detailed discussion of

the passing ship effect and calculation procedure and its limitations, refer to [10][11][12]. In this study, the passing ship has identical dimensions to the moored ship (Table 1), passing at two times beam distance (measured side-to-side), at a forward velocity of 6 knots. The hull shape of the *Barzan* is not given in [5], which is why a similar hull file in the possession of UGent is used here to calculate passing ship forces, as well as moored ship hydrodynamics. This hull has a block coefficient (C_B) of 0.74 at scantling draft, which differs from the *Barzan*, [5], having a C_B of 0.70 at design draft. The forces acting on the moored ship are depicted in Figure 3. They are given as a function of the position of the passing ship (Eq. (3), see Figure 4).

$$\xi = \frac{x_p}{L_{OA}} \tag{3}$$

The longitudinal force is significantly larger than the transversal forces, which are presented as lateral force at fore (Y_{pF}) and aft (Y_{pA}) perpendicular . Note that the forces given in Figure 3 are corrected for shallow and confined water, according to Talstra and Bliek [10]. For this exercise, the total section width equals eight times the beam of the ship (Figure 4) and the water depth is 20 m (ukc of 25%). Further discussion of the modelling of high blockage cases in RoPES are outside of the scope of this paper, but will be the focus of future research, including validation using model tests.
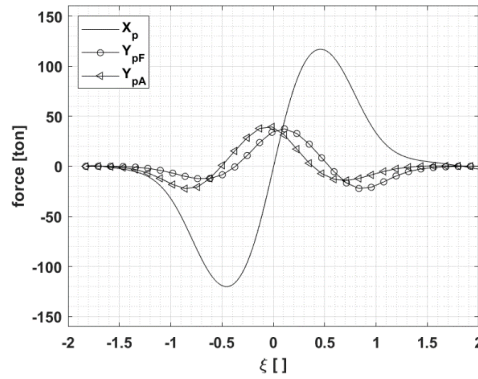

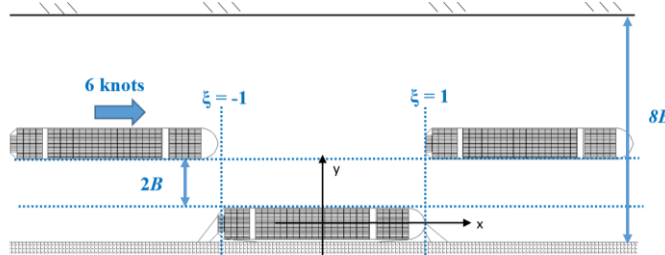Figure 3 : Passing ship forces in function of ξ (RoPES, with correction factor [10])

Figure 4 : Passing event : Definition of ξ , passing distance and section width.

3.2   Efficiency parameters

In [6], a set of four efficiency parameters, based on the mooring line angles (α,β) and the line length (ℓ), has been defined. Only the longitudinal efficiency parameters are discussed here. For the transversal efficiency, which becomes more relevant in open water (jetty) passing cases and wind events, reference is made to [6].

$$e_{Xp} = \sum_{i=1}^{n_{\alpha<90}} \cos^2 \beta_i \cdot \cos^2 \alpha_i \cdot \left(\frac{\ell_i}{\ell_{ref}}\right)^{-1} \tag{4}$$

$$e_{Xn} = \sum_{i=1}^{n_{\alpha>90}} \cos^2 \beta_i \cdot \cos^2 \alpha_i \cdot \left(\frac{\ell_i}{\ell_{ref}}\right)^{-1} \tag{5}$$

$$\ell_{ref} = \frac{1}{n} \cdot \sum_{i=1}^{n} \ell_i \tag{6}$$

Eq. (4-5) express the capacity of the configuration to deal with positive (e_{Xp}) and negative (e_{Xn}) external forces. ℓ_{ref} is the average length of all the lines. The elasticity of the lines, which is a vital parameter, is not yet included in these formulae. This will be done when discussing the mooring simulation results.

3.3   Rules of thumb for increase of mooring arrangement performance

Optimising a mooring line configuration at a quay wall is mostly case specific, as the bollard position, quay level, design vessel(s) etc. differ for each terminal. There are however some basic principles which apply to all cases:
1. A mooring line is essentially a spring, building up force through elongation. Short lines will thus build up forces quickly compared to long lines. Lines working in the same sense (breast or spring), should be of similar length. Always take into account line lengths on deck.
2. Long lines make the configuration more elastic, short lines create more stiffness. Note that this also influences the eigenperiod of the system.
3. The mooring configuration should be balanced at all times, as OCIMF indicates. The longitudinal efficiencies, in positive and negative sense, should thus be similar.
4. The terms in cos (α) and sin (α,β) are squared in Eq. (4-5), underlining the importance of spring line orientation along the quay face (α ≈ 0° or 180°).

3.4   Proposed optimisation procedure

In the current paper, three different optimisation procedures are presented, starting from the configuration 'MC0', given in Figure 1. All three aim at limiting the ship motions and mooring line forces.
1. Spatial arrangement of the mooring lines.
2. Position of winches on deck and possibility of added winches, without losing cargo space.
3. The use of stiff lines in combination with an elastic tail

All mooring configurations which are presented here in detail, are given in the attachment.

3.4.1 Procedure 1 : Optimisation of spatial arrangement

Firstly, the spatial configuration of the lines is enhanced changing only the line positions. In MC0, the aft springs have different lengths, 88 m and 52 m for lines 7 and 8 (Table 2). By moving the bollard to which the longer line (line 7) is attached, line lengths become more similar (Figure 5).
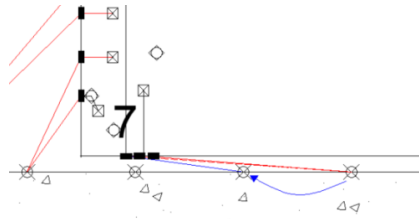

Figure 5 : Optimisation of spatial arrangement : Repositioning aft spring (MC1).

Crossing of the lines optimises the line angles (α closer to 0,180° for springs and 90° for breasts). In MC2, the aft lines are crossed (Figure 6); whereas in MC3, the fore lines are crossed (Figure 6). MC4 combines both crossing fore and aft lines. Note that under tidal differences and/or draft changes, crossing of lines might not always be possible.
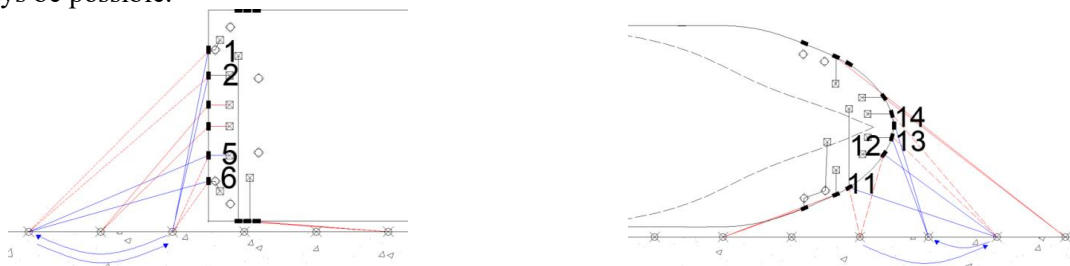

Figure 6 : Optimisation of spatial arrangement
Left : Crossing aft lines (MC2 and MC4); Right : Crossing fore lines (MC3 and MC4).

3.4.2 Procedure 2 : Winch positioning and number of winches

Container ships have very similar winch and fairlead positions, certainly within the same 'TEU class'. They are positioned fore and aft of the ship, maximizing cargo space. There are however alternative winch positions which do not impact cargo space, but could greatly benefit the response of the mooring system. Arrangement MC5 (Figure 7), shows a lower fore mooring deck, which limits the steepness of the fore lines (β). The winches are positioned on a lower deck level assumed to be at level +9.00 m (same as aft mooring deck). Of course, the structural integrity, as well as the operational feasibility needs to be checked before putting this idea in practice. Combining a lower and higher fore mooring deck, would allow to install additional winches.

In mooring configuration MC6 (Figure 8), two extra pairs of winches are added underneath the funnel and bridge house (again at +9.00 m), where no container stacks are present. By doubling the amount of spring lines, the capacity to deal with longitudinal forces is highly increased. The lower deck position also ensures that the line angle steepness is lowered compared to forecastle deck positions.
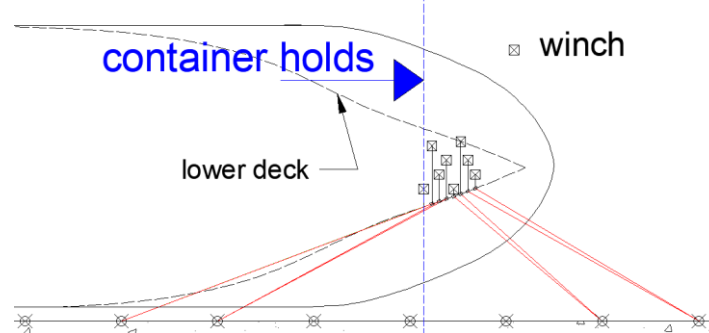

Figure 7 : Mooring configuration MC5 : Lower fore mooring deck (level +9.00 m)
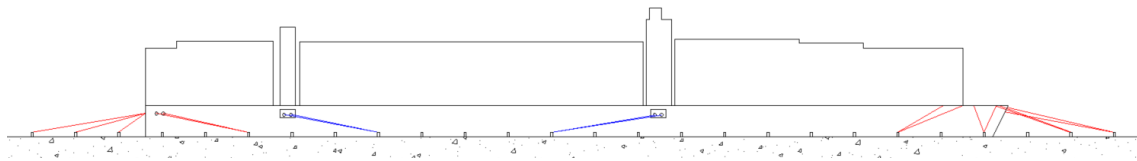

Figure 8 : Mooring configuration MC6 : addition of winches underneath funnel and bridge

3.4.3 Procedure 3 : Line properties

Innovative line manufacturers are constantly seeking ways to produce lines that suit industry most, driven by the new demands for high quality lines stated in OCIMF's MEG4 [1]. For container ships, a variation in the elasticity of lines on board ships is observed. A case study example shows the gains that can be achieved using higher-quality lines, which would be beneficial for all. This is shown in the simulations by changing the lines from a medium stiff line (denoted as linear line 1 (L1)) with breaking strain of 15% to a combination of a stiff HMPE line (linear line 2 (L2)) and a non-linear elastic tail (non-linear line 1 (NL1)). The tail length is 11 m (ℓ_{tail}). The properties of these lines are shown in Figure 9.
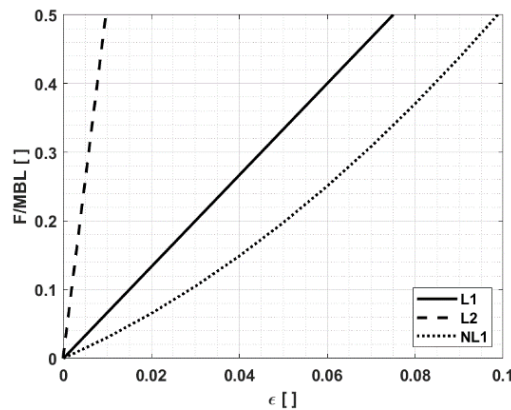

Figure 9 : Line properties linear deforming lines L1 and L2, non-linear deforming line NL1.

3.4.4 Optimisation overview table

Table 3 below presents an overview of nine different simulations, arising from the three methods outlined in the Section 3.4.1 – Section 3.4.3. An additional arrangement, MC7, combines crossing aft lines (MC2), lower fore mooring deck (MC5), two additional springs (MC6) and stiffer lines (L2 + NL1), in a best possible optimisation result. Table 3 gives a short description of the action, the line type and the efficiency parameters. Note that a change of line type (L1 to L2 + NL1) does not affect the efficiency parameters defined in Eq. (4-5), as the elasticity is not included in the formulation. This is discussed in section 5.3.

Table 3 : Mooring configurations and efficiency parameters e_{Xp}, e_{Xn}.

Config	Action	Line type	e_{Xp}	e_{Xn}
MC0	Reference configuration	**L1**	4.60	3.44
MC0	Stiffer lines	**L2 +NL1**	4.60	3.44
MC1	Change position aft spring	**L1**	4.50	3.47
MC2	Crossing aft lines	**L1**	4.69	3.53
MC3	Crossing fore lines	**L1**	4.61	4.15
MC4	Crossing fore + aft lines	**L1**	4.70	4.25
MC5	Lower fore mooring deck	**L1**	5.64	4.60
MC6	2 additional spring pairs	**L1**	6.50	5.52
MC7	Action MC2+MC5+MC6	**L2 +NL1**	7.68	6.84

4   VLUGMOOR CALCULATION

Vlugmoor is a dynamic mooring analysis (DMA) tool, developed at Ghent University, calculating the behaviour of moored ships based on input from RoPES (section 3.1) and a seakeeping tool, in this case Hydrostar [13]. For the specific case of the behaviour under passing ship effects, the equations of motion are solved in 4DOF (surge, sway, yaw and roll), with coupling between sway and yaw. Eq. (7) shows the general representation of the equation of motion

$$(m + a) \cdot \ddot{X} + b \cdot \dot{X} + c \cdot X = F_{pas}(t) + F_{\text{lines}}(t) + F_{\text{fenders}}(t) \tag{7}$$

In Eq. (7), X represents a general motion vector. m represents the mass, with a being the added mass. b is the hydrodynamic damping and c represents the linear restoring terms. On the right hand of the equation, the sum of the external forces is given. The passing vessel force (F_{pas}) is in this case case the disturbing force, with F_{lines} and F_{fenders} being the response of the mooring system. Validation is found through observations and measurements at project sites where studies have been performed. One validation effort has been published so far, based on full-scale measurements for the Port of Antwerp (Van Zwijnsvoorde et al, 2018), where good agreement has been observed between measured and simulated results.

5   SIMULATION RESULT MOORING OPTIMISATION

The behaviour of the moored ship, under the ship passage, is modelled using Vlugmoor. The outputs of the simulation are motions of the moored ship, as well as line and fender forces, at each time step. These are evaluated based on criteria for each variable. The current section elaborates on these criteria, gives an example of Vlugmoor output and shows the simulation results for all configurations presented in Table 3.

5.1   Criteria

The results of the mooring simulations need to be checked against criteria for motions and forces. Line force limits can be found in [1], set at 50% MBL for synthetic lines. Motion criteria are more difficult to set, as they are a function of the external load (singular, continuous) and the target (safety, efficiency). For a discussion reference is made to [14] and several PIANC documents (WG24 [15], 115 [16] and 212 (WG in progress)). For the current discussion, the limits are listed in Table 4.

Table 4 : Limiting criteria line forces and ship motion amplitude.

Type	Limit	Type	Limit	Type	Limit
Line force	50% MBL	Longitudinal motion	0.50 m	Transversal motion	0.50 m

5.2 Vlugmoor simulation configuration MC0

Explaining the behaviour of a moored ship under passing ship effects is out of the scope of the present paper, refer to [17] for details. The ship motions of the moored vessel and line forces during the passage of an identical vessel at 6 knots velocity and 2 beam passing distance, are given in Figure 10.
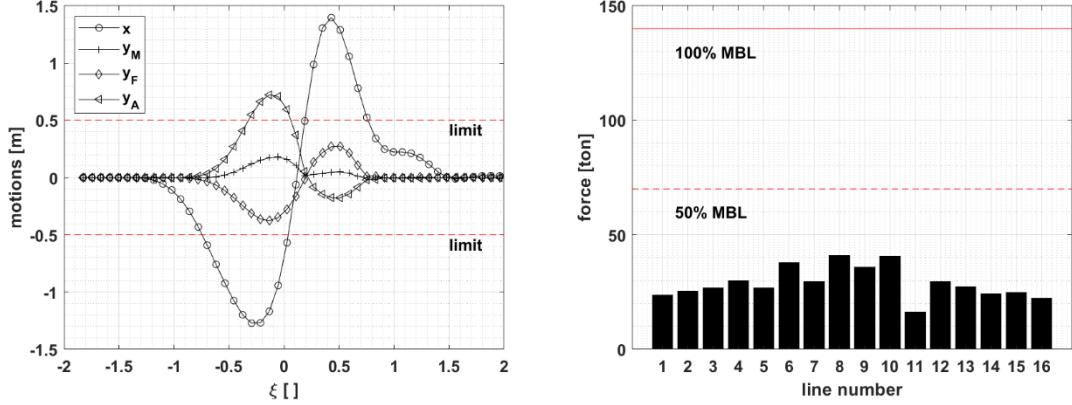

Figure 10 : Vlugmoor simulation results configuration MC0 ; Left : Ship motions; Right: Line forces

It can be clearly seen that for a typical passing ship event for a container ship, the line forces are limited, and thus much lower than the limiting value of 50% MBL (70 tons). The motions however are larger and exceed the set limits, with the longitudinal motions (x) being significantly higher than the transversal motions (y_M, y_F, y_A). This motivates the choice to focus on longitudinal motions and efficiency parameters.

5.3 Summary of simulation results

The results of the Vlugmoor simulations are shown in Table 5, for all mooring configurations depicted in Table 3. The maximum relative line force (F_{rel}), longitudinal motion amplitude (x_{pos}, $|x_{neg}|$) and efficiency parameters are given. It has already been mentioned that the definition of e_{Xp} and e_{Xn} does account for difference in line elasticity. For this reason a term is added, which expresses the difference in elasticity between two cases, given in Eq. (8-10). It adds the ratio between the elasticities at a given force. Due to the non-linearity, this ratio is a function of the force present in the lines. Therefore, an estimation needs to be made of the expected forces. Here, F_{exp} is set equal to 25% MBL, based on the results in Table 5. For the combination of linear main line (L2) and non-linear elastic tail (NL1), both contributions to the total elasticity of the system need to be taken into account.

$$e_{Xp}' = e_{Xp} \cdot \frac{E_{L1}}{E_{L2+NL1}} \tag{8}$$

$$e_{Xn}' = e_{Xn} \cdot \frac{E_{L1}}{E_{L2+NL1}} \tag{9}$$

$$E_{L1} = \varepsilon_{L1}(F_{exp}); \quad E_{L2+NL1} = \frac{\varepsilon_{L2}(F_{exp}) \cdot (\ell_{ref} - \ell_{tail}) + \varepsilon_{NL1}(F_{exp}) \cdot (\ell_{tail})}{\ell_{ref}} \tag{10}$$

Table 5 : Results Vlugmoor simulations : Line forces and longitudinal motions ;
Efficiency parameters e_{Xp}, e_{Xn} and e_{Xp}' , e_{Xn}'.

Config	Line type	F_{rel} [-]	x_{pos} [m]	$|x_{neg}|$ [m]	e_{Xp}	e_{Xn}	e_{Xp}'	e_{Xn}'
MC0	L1	0.29	1.40	1.28	4.60	3.44		
MC0	L2 +NL1	0.30	0.42	0.51	4.60	3.44	10.92	8.16
MC1	L1	0.29	1.34	1.23	4.50	3.47		
MC2	L1	0.27	1.19	1.13	4.69	3.53		
MC3	L1	0.30	1.26	1.11	4.61	4.15		
MC4	L1	0.27	1.09	1.00	4.70	4.25		
MC5	L1	0.24	0.93	0.87	5.64	4.60		
MC6	L1	0.20	0.65	0.64	6.50	5.52		
MC7	L2 +NL1	0.18	0.21	0.22	7.68	6.84	18.66	16.62

Table 5 shows how changes in mooring configuration impact the moored ship motions along the quay wall. In the reference case (MC0), the motion amplitude reaches 1.40 m, which is almost three times the limit of 0.50 m. With small changes in the configuration (crossing lines), the motions can be lowered to 1.09 m (MC4). By lowering the fore mooring deck (MC5), a significant decrease in motion is observed (from 1.40 m to 0.93 m). The addition of two sets of spring lines (MC6) of course has the biggest impact, lowering the motions to 0.65 m, which is already close to the target limit.

A change from medium stiff lines (L1) to a combination of very stiff HMPE (L2) and elastic forerunner (NL1), reduces the motions to 0.51 m. Mooring lines can be changed to stiffer ones during maintenance, as lines need to be replaced every few years, as long as compatibility between line diameter and winch drum is ensured. In other conditions (e.g. waves), some additional elasticity might need to be added not to overload the lines, by changing the length of the tail, at the cost of larger motions under passing ships. A last case, MC7, shows the impact of a combined optimisation, leading to a motion amplitude of 0.22 m. This means that the passing ship could even increase passing speed, without hampering the safety of the moored ship.

To conclude this section, the results are summarized in Figure 11, which gives the ratio of the motions and the efficiency parameters, with respect to the reference case (MC0, line L1). The decrease in motions when moving to a better (and more stiff) configuration is clearly shown. The ratio of the efficiencies is a good measure to predict the effect on the ship motions, without need for dynamic mooring simulations. It also shows that when comparing different line properties, the definition of e_{Xp}' and e_{Xn}' yields good results in the motion prediction. It is however not an exact prediction. This is of course due to the dynamic behaviour of the system, which is a function of the magnitude and period of the external load as well. It is also seen that even when the efficiency parameter is constant (e_{Xp}) (MC3), the positive motion amplitude decreases (x_{pos}). This is because the ship initially moves less in the negative direction, thus building up less momentum to move in the positive direction.
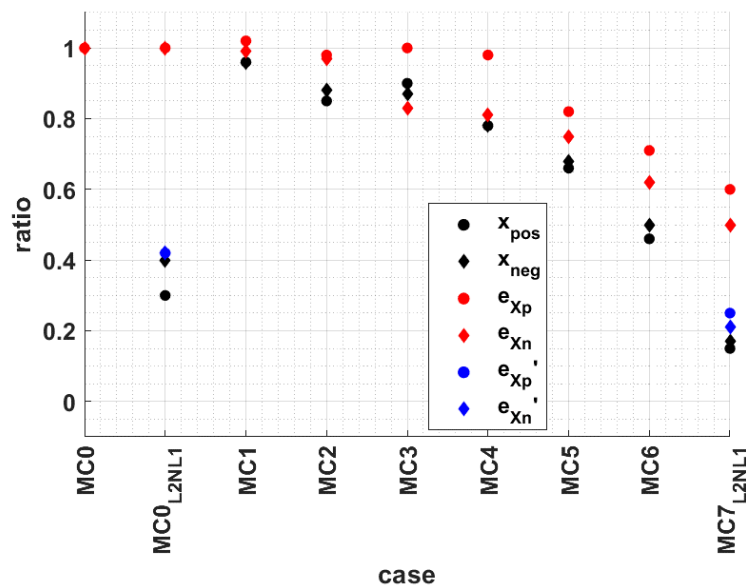

Figure 11 : Motion and efficiency ratios for all cases shown in Table 5.

6   CONCLUSION

In this paper, three optimisation procedures for the mooring configuration of an ULCV moored at a quay wall have been presented. The effect of these proposed changes has been evaluated by performing numerical time domain simulations where the effect of an identical passing ship on the moored ship was modelled. In these simulations, the surge motion of the moored ship always proves to be the critical parameter when evaluating moored ship safety.

The results show that by optimising the spatial configuration of the mooring lines, a small decrease in ship motions can be observed. Lowering the position of the fore mooring deck already leads to larger gains, as the steepness of the lines decreases, increasing the line efficiency. Positioning two extra winches under the funnel and bridge location shows a large decrease in longitudinal ship motions, as the number of fore and aft springs is doubled. This comes with no loss of cargo space. The simulation with stiff lines in combination with an elastic tail, shows a substantial decrease in motions. A combination of repositioning and adding winches, as well as using stiffer lines, shows that the motions are much lower than in the reference case. This means that an unsafe situation given the passing event at hand is turned into a safe situation, where the passing speed could even be increased without exceeding safe mooring limits.

As OCIMF demands regarding line angles cannot be applied to the case where a ship is moored at a quay wall, an alternative assessment tool, named efficiency parameters, is used to evaluate and optimise mooring configurations. A comparison between motion prediction based on the efficiency parameters and actual simulation results show fairly good agreement.

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ATTACHMENT

MC0

MC1

MC2

MC3

MC4

MC5

MC6

MC7