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BERTH OPERABILITY ESTIMATION RELATED TO SHIP MOTION

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Summary

The method of exposed berth operability estimation based on moored ship criteria for safe working and mooring is presented. The solution methodology consists of modelling a ship as a panel model used to calculate the hydrodynamic loads and responses from the potential theory. The mooring lines are modelled by ship-to-ground spring elements. The stiffness of those elements is accumulated in the global restoring matrix of the rigid body equations of motion. The obtained system of differential equations is solved by the frequency domain procedure taking explicitly into account the influence of shallow water. The effect of irregular waves is taken into account by an appropriate wave spectrum. The wave scatter diagram and wave direction statistics allow the estimation of the probability and parameters of most severe sea based on long-term statistics. Illustrative applications of the method are given for several ships moored on the outer side of a jetty. The irregular sea is described by the Tabain spectrum. The significant values of the ship ramp displacements and velocities are compared with specific criteria limits.

Key words: *ship mooring, ship motion, berth operability*

1. Introduction

Knowledge of ship behaviour at berth is of fundamental importance for the design of harbours and marine terminals. The motion amplitude of moored ship is affected by not only sea waves but also by the mooring arrangement. Because of exaggerated ship displacement, these motions can affect the possibility of loading and unloading or cause the damage to ship or jetty and consequently reduce the efficiency of berth. Therefore, it is important to make a probability assessment of the number of non-operative days during a year or a season. For the purpose of transfer function calculation, it is necessary to make a reliable model of ship and mooring lines that must satisfy the equilibrium equation and compatibility relations. The sea can be described by an appropriate sea spectrum. If the water at the berth is shallow, the sea depth must be taken into account. Significant amplitudes of absolute horizontal and vertical motion as well as the rolling angle are accepted as a criterion for the safe working condition. The governing parameter for a safe mooring condition, defined as the limiting conditions for damage to ship or jetty, is the recommended surge, sway, and roll velocity.

2. Operability estimation

The measure of operability is the percentage of time that an operation can satisfactory be performed under the conditions which are expected at the given location. An operability analysis of berthing operation related to ship motion comprises the seakeeping analysis of moored vessel, the climate at a specific location and the season and criteria for maximum responses.

2.1 Seakeeping analysis

Seakeeping analysis is performed by linear seakeeping method taking into account sea depth at the berthing place and mooring arrangements [3].

(a) Wave loads on ship

The submerged half part of the ships under considerations is modelled with 3D panels as presented in Figure 1 using the SESAM Software Package [6]. The radiation and diffraction velocity potentials on the wet part of the body surface are determined from the solution of an integral equation obtained by using Green's theorem with the free surface source potentials such as Green's functions. The source strengths are evaluated based on the source distribution method using the same source potentials. The integral equation is discretised into a set of algebraic equations by approximating the body surface with a number of plane quadrilateral panels. The source strengths are assumed to be constant over each panel. One plane of symmetry of the body geometry is present. The solution of the algebraic equation system provides the strength of the sources on the panels. The equation system, which is complex and indefinite, is solved by an iterative method.

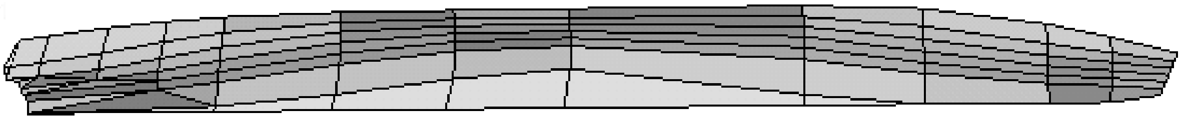


Fig. 1 3D panel model of a ferryboat

(b) Mooring modelling

The mooring lines are assumed to be weightless and with linear stiffness characteristics. The external restoring forces from the mooring lines in the ship motion model are included by mooring elements. The mooring elements are defined at appropriate nodes on the ship model (Figure 2). The hydro properties of a mooring element include the element orientation, the pre-tension and the restoring characteristics [4], [5], [3]. The restoring contributions from the mooring elements are assembled in the body restoring matrix and hence contribute to the rigid body motion. The computed rigid body motion yields dynamic restoring forces acting in the mooring element nodes.

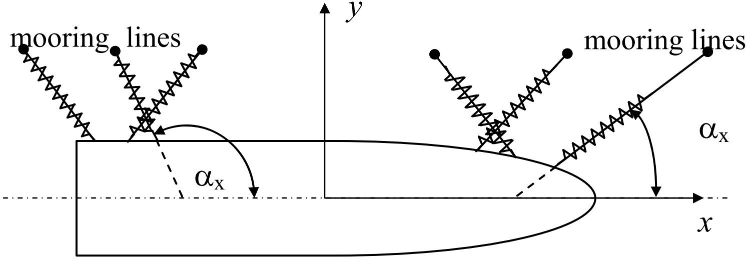


Fig. 2 Mooring element definitions

(c) Global motion responses

The equation of motion in established for the harmonic motion of rigid body systems expressed in the global coordinate system (Figure 3).

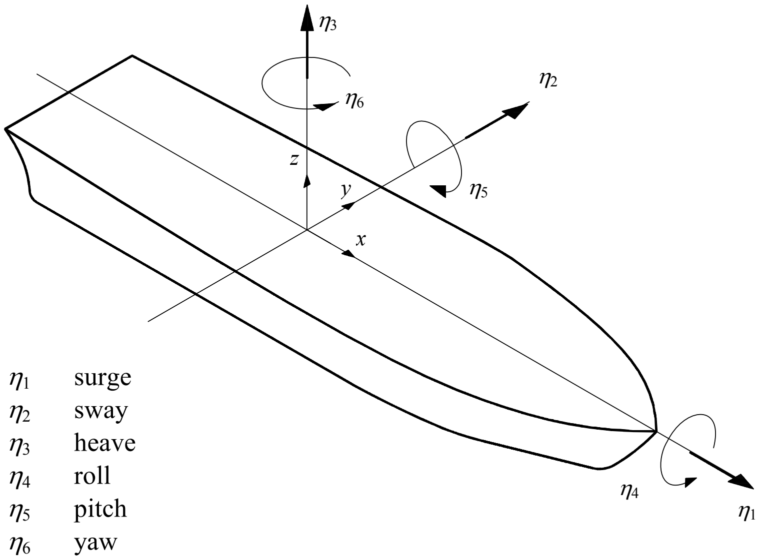


Fig. 3 Global coordinate system

By applying Newton's law and including the added mass, the damping and the exciting force contributions acting on the panel, and parts of a mooring hydro model, the complex motion vector $\mathbf{H}(\omega, \beta) = (\eta 1, \eta 2 \ldots \eta 6)$ can be found from the equation of motion

$$\left[\ -\omega^2\left(\mathbf{M}+\mathbf{A}(\omega)\right)+i\omega\left(\mathbf{B}_p(\omega)+\mathbf{B}_v\right)+\mathbf{C}+\mathbf{C}_e\ \right]\mathbf{H}(\omega,\beta)=\mathbf{F}(\omega,\beta) \qquad (1)$$

where $\mathbf{M}$ represents the body inertia matrix, $\mathbf{A}(\omega)$ represents the frequency dependent added mass matrix, $\mathbf{B}_p(\omega)$ represents the frequency dependent potential damping matrix, $\mathbf{B}_v$ represents the linearised viscous damping matrix, $\mathbf{C}$ represents the hydrostatic restoring matrix, $\mathbf{C}_e$ represents the external restoring matrix, and $\mathbf{F}(\omega, \beta)$ is the complex exciting force vector for frequency ω and incident wave heading angle β.

2.2 Environmental description

The ship moored in or outside the harbour is disturbed by irregular waves which can be seen as a superposition of many simple, regular harmonic wave components, each with its own amplitude, length, period or frequency, and direction of propagation. The regular waves are described by the Airy wave theory. The incident waves may be specified by wave lengths, wave angular frequencies or wave periods. The direction of the incident waves are specified by the heading angle β between the positive x-axis and the propagation direction.

The sea must be described by an appropriate wave spectrum. The local sea conditions can be described by adequate significant wave height statistics. The probabilities for the significant wave height for a particular area are known from the wave scatter diagram.

For the implementation of the moored ship response corresponding design wind parameter where the passenger embarkation and disembarkation is enabled is as follows:

wind gust $V_{30\mathrm{s}}^{<2g}$ = 22.70 m/s which corresponds to ten minute average $V_{10\mathrm{min}}^{<2g}$ = 7 B.

2.3 The criteria limits

The chosen criteria and their limits are of fundamental importance in the process of berth operability estimation. They differ for different vessel types and are usually based on interviews with ship crew members and port operators. The criteria limits are expressed as acceptable motions or velocity amplitude that, if exceeded, may cause difficulty during loading (safe working condition) or damage to ship or jetty (safe mooring condition). The limiting sea state may be defined as a sea state during which the limiting wave amplitude occurs with low probability.

3. Numerical example

The application of the computational method is given for two ferryboats (ships A and B) and one cruiser (ship C) moored on the outer side of an Adriatic Sea harbour jetty. The characteristic parameters of ships A, B and C are given in Table 1. The moored ship transfer functions of absolute horizontal and vertical motion of ships A, B and C have been computed by using the software package SESAM for the range of wave frequencies corresponding to the wave length–ship length ratio from 0.04 to 2. The sea depths for the ships A, B and C are 6.5 m, 10 m, and 15 m, respectively. They are used in the calculation of Green's functions for the finite water depth.

Table 1 Ship characteristics

Ship characteristics	Ship A	Ship B	Ship C
Displacement, t	1940	8100	28155
Length over all, m	85.0	128.1	220.6
Length between perpendiculars, m	76.7	124.0	181.9
Breadth, m	15.8	19.6	30.9
Draft, m	3.7	5.8	7.6

The corresponding response spectra for the absolute longitudinal, transverse, and vertical ramp motion and the response spectrum of rolling of ships A, B, and C are calculated by the Tabain wave spectrum [7]:

$$S_\zeta(\omega) = 0.862\frac{0.0135g^2}{\omega^5}\exp\left(-\frac{5.186}{\omega^4 H_s}\right)1.63^{\exp\left(-\frac{(\omega-\omega_m)^2}{2\sigma^2\omega_m^2}\right)} \tag{2}$$

for the range of significant wave heights Hs from 0.5 to 2.5, where the modal frequency ωm is estimated by $\omega_m = 0.32 + \dfrac{1.80}{H_s + 0.60}$ and the parameter σ is calculated as:

$$\begin{aligned} \sigma &= 0.08 \quad \text{for} \quad \omega < \omega_m \\ \sigma &= 0.10 \quad \text{for} \quad \omega > \omega_m \end{aligned} \tag{3}$$

The resulting spectra are then processed [6] to obtain the corresponding order statistics. They constitute the input data for the estimation of exceeding the criteria limit. Figures 4, 5, 6, and 7 show the double value of the significant absolute longitudinal, transverse and vertical motion significant amplitude as well as the double significant rolling amplitude of all three ships as a function of the sea state defined by the significant wave height. The significant amplitudes of surge, sway, roll and yaw velocities are shown in Figures 8, 9, 10, and 11. The heading is supposed to be as for waves from the South wind that seem to be the highest waves in this area during summer. From those diagrams and from the sea state statistics for the considered area (Sea State curve in figures) it is possible to estimate the limiting significant wave height and the number of non-operative days (NOD) during the summer season as shown in Table 2 and Table 3 for the berths at the outer side of the Adriatic Sea port. For example, in Figure 4 one can note that the safe working criterion limit of ship ramp vertical motion is exceeded for the ferryboat at the sea state described by the significant wave height of 1.3 m. According to the local sea state statistics, it is expected that this sea state will be exceeded ten days during the season. Regarding the safe mooring conditions, all criteria are expected to be exceeded at the significant wave height of 2 m and above, which should not occur at the considered location.

The criteria limits have been implemented according to the recommendation of the Permanent International Association of Navigation Congresses (PIANC) [2], [1]. The chosen criteria and criteria limits are also based on interviews with actual ships captains. Vessel types considered are characterised by loading and unloading operations taking place horizontally via ramps and walkways. The recommended criteria for allowable ship motions for a safe working condition are vertical and horizontal motions on the ship ramp as well as the rolling angle. The limits for significant amplitude are set to be 0.5 m for the vertical and the transverse motion and 0.1 m for the longitudinal motion. The criteria limit for the significant amplitude of rolling motion is set to be 0.5 deg. The governing parameter for the safe mooring condition, defined as the limiting conditions for damage to ship or jetty, is the kinetic energy, which is characterised by the ship size and velocities. The recommended velocity criteria are 0.3 m/s for surge and sway velocities and 1.0 °/s for roll and yaw velocities. For defining the wave climate, a so-called wave scatter diagram shown in Table 4 is used. A varying wind speed can be linked to each individual wave condition.

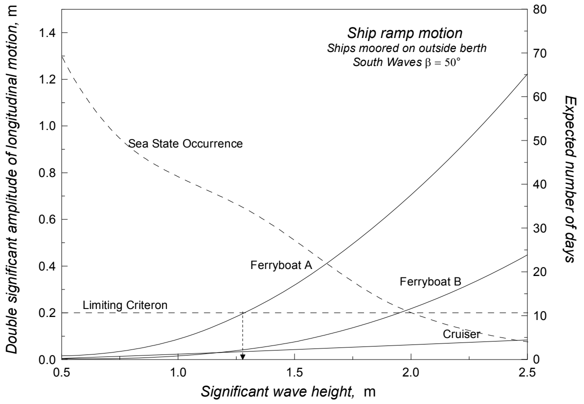


Fig. 4 Significant amplitude of ship ramp longitudinal motion

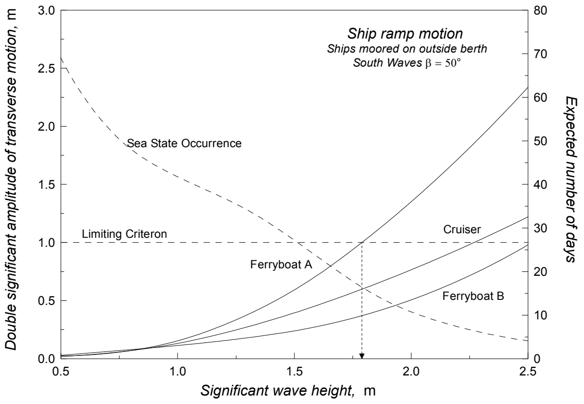


Fig. 5 Significant amplitude of ship ramp transverse motion

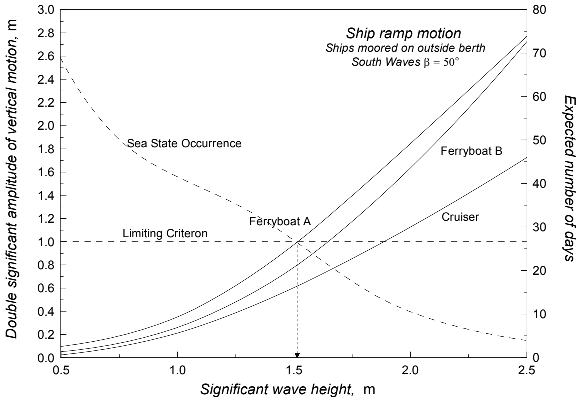


Fig. 6 Significant amplitude of ship ramp vertical motion

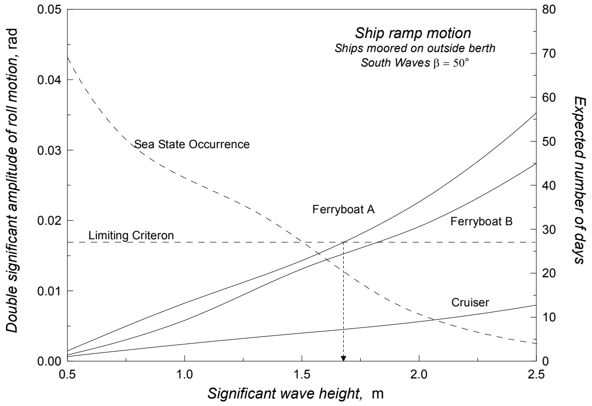


Fig. 7 Significant amplitude of rolling motion

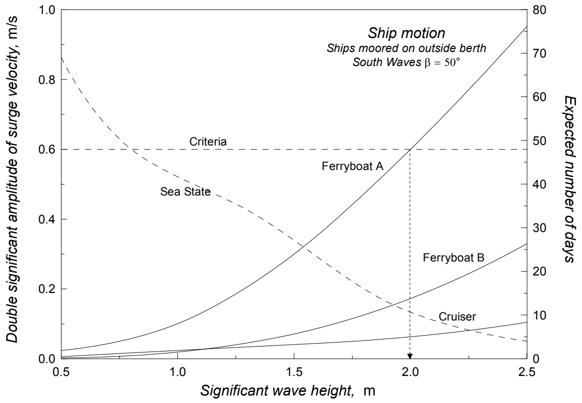


Fig. 8 Significant amplitude of surge velocity

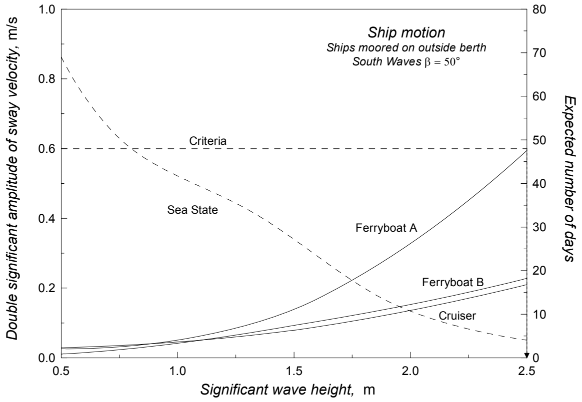


Fig. 9 Significant amplitude of sway velocity

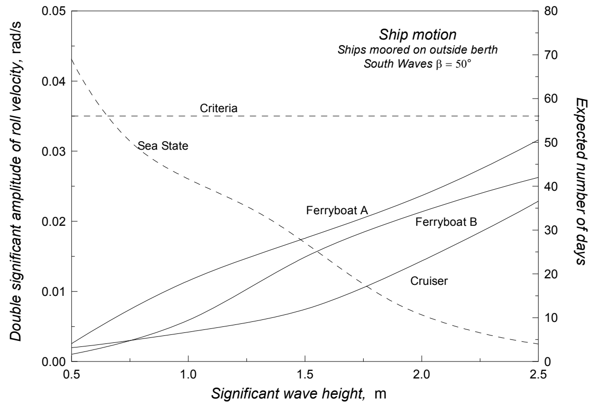


Fig. 10 Significant amplitude of roll velocity

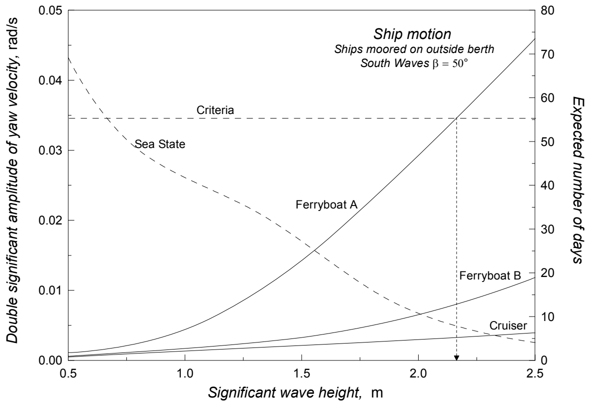


Fig. 11 Significant amplitude of yaw velocity

Table 2 Limiting significant wave height (South waves) for the Ferry boat A

Safe working		Safe mooring	
Criteria	Limiting *Hs*, m	Criteria	Limiting *Hs*, m
Long. motion	1.3	Surge vel.	2.0
Transv. motion	1.8	Sway vel.	-
Vert. motion	1.5	Roll vel.	-
Rolling motion	1.6	Yaw vel.	2.2
Combined	1.3	Combined	2.0

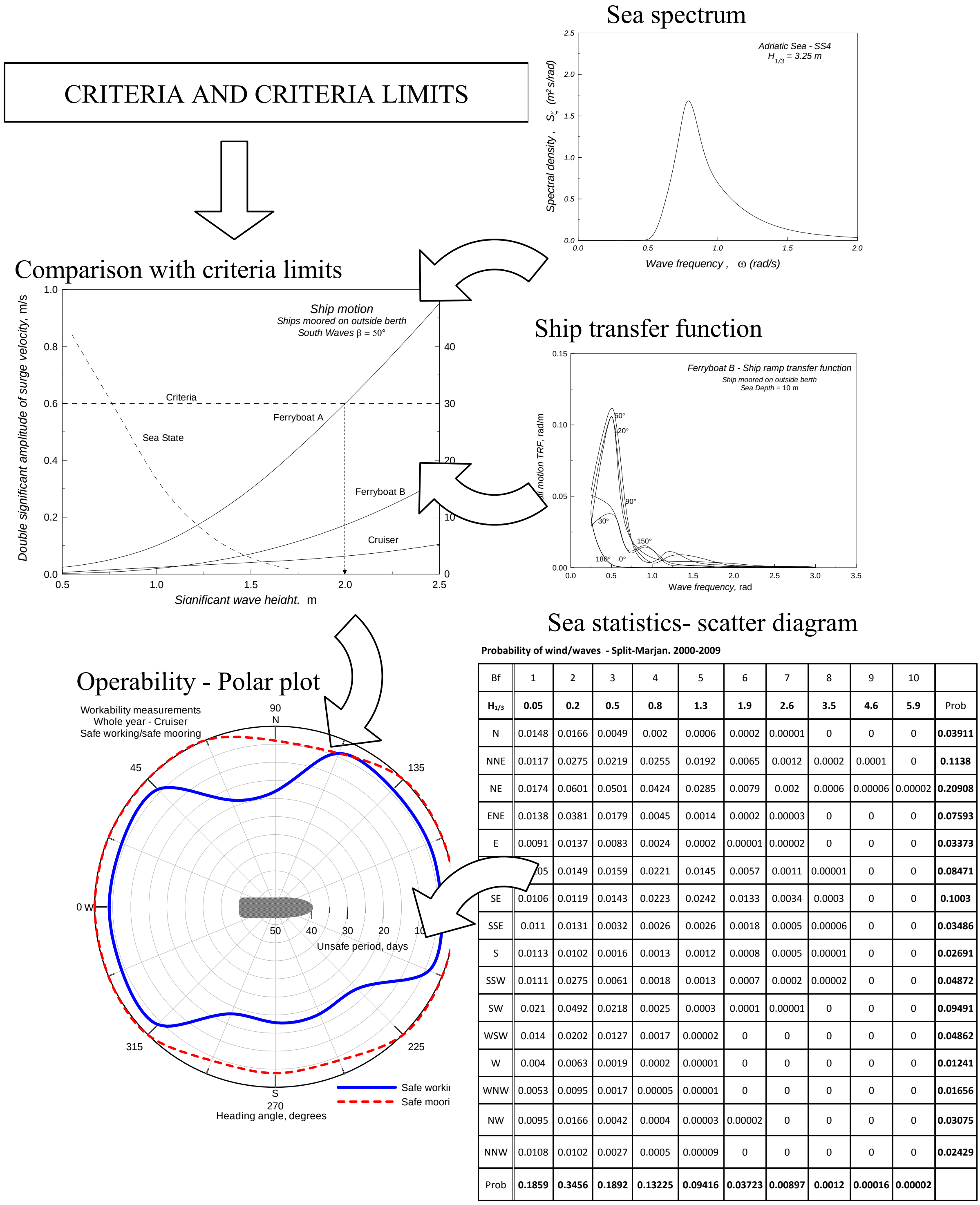
Table 3 Operating limits and non-operative days for all ships

Ship	Whole year (South waves)			
	Unsafe working conditions		Unsafe mooring conditions	
	Hs. m	*NOD*. days	*Hs*. m	*NOD*. days
Ferryboat A	1.3	35	2.0	10
Ferryboat B	1.8	15	>2.5	0
Cruiser C	1.9	0	>2.5	0

Table 4 Wave scatter diagram - Probability of wind/waves - Split-Marjan, 2000-2009

Bf	1	2	3	4	5	6	7	8	9	10	
$H_{1/3}$, m	**0.05**	**0.2**	**0.5**	**0.8**	**1.3**	**1.9**	**2.6**	**3.5**	**4.6**	**5.9**	Prob
N	0.0148	0.0166	0.0049	0.002	0.0006	0.0002	0.00001	0	0	0	**0.03911**
NNE	0.0117	0.0275	0.0219	0.0255	0.0192	0.0065	0.0012	0.0002	0.0001	0	**0.11380**
NE	0.0174	0.0601	0.0501	0.0424	0.0285	0.0079	0.002	0.0006	0.00006	0.00002	**0.20908**
ENE	0.0138	0.0381	0.0179	0.0045	0.0014	0.0002	0.00003	0	0	0	**0.07593**
E	0.0091	0.0137	0.0083	0.0024	0.0002	0.00001	0.00002	0	0	0	**0.03373**
ESE	0.0105	0.0149	0.0159	0.0221	0.0145	0.0057	0.0011	0.00001	0	0	**0.08471**
SE	0.0106	0.0119	0.0143	0.0223	0.0242	0.0133	0.0034	0.00030	0	0	**0.1003**
SSE	0.011	0.0131	0.0032	0.0026	0.0026	0.0018	0.0005	0.00006	0	0	**0.03486**
S	0.0113	0.0102	0.0016	0.0013	0.0012	0.0008	0.0005	0.00001	0	0	**0.02691**
SSW	0.0111	0.0275	0.0061	0.0018	0.0013	0.0007	0.0002	0.00002	0	0	**0.04872**
SW	0.021	0.0492	0.0218	0.0025	0.0003	0.0001	0.00001	0	0	0	**0.09491**
WSW	0.014	0.0202	0.0127	0.0017	0.00002	0	0	0	0	0	**0.04862**
W	0.004	0.0063	0.0019	0.0002	0.00001	0	0	0	0	0	**0.01241**
WNW	0.0053	0.0095	0.0017	0.00005	0.00001	0	0	0	0	0	**0.01656**
NW	0.0095	0.0166	0.0042	0.0004	0.00003	0.00002	0	0	0	0	**0.03075**
NNW	0.0108	0.0102	0.0027	0.0005	0.00009	0	0	0	0	0	**0.02429**
Prob	**0.1859**	**0.3456**	**0.1892**	**0.13225**	**0.09416**	**0.03723**	**0.00897**	**0.0012**	**0.00016**	**0.00002**	

The presented analysis must be performed for each wave direction. As shown in Figure 12, the input for the operability analysis consists of transfer functions, wave scatter diagram and criteria. The basic outcome of the calculation is the average fraction of time in which the adopted criteria are exceeded in a particular (wave) climate. One convenient way of showing results could be a polar plot which shows the number of non-operative days for each wind direction. Polar plots for the ferryboat A and the cruiser are shown in Figures 13 and 14. The calculation takes into account wave direction statistics shown in Table 4. The overall operability measure for the safe working and safe mooring can be estimated as shown in Tables 5 and 6. The combined operability measure is chosen as a result of operability for the worst condition at each wave (wind) direction.



Probability of wind/waves - Split-Marjan. 2000-2009

Bf	1	2	3	4	5	6	7	8	9	10	
$H_{1/3}$	**0.05**	**0.2**	**0.5**	**0.8**	**1.3**	**1.9**	**2.6**	**3.5**	**4.6**	**5.9**	Prob
N	0.0148	0.0166	0.0049	0.002	0.0006	0.0002	0.00001	0	0	0	**0.03911**
NNE	0.0117	0.0275	0.0219	0.0255	0.0192	0.0065	0.0012	0.0002	0.0001	0	**0.1138**
NE	0.0174	0.0601	0.0501	0.0424	0.0285	0.0079	0.002	0.0006	0.00006	0.00002	**0.20908**
ENE	0.0138	0.0381	0.0179	0.0045	0.0014	0.0002	0.00003	0	0	0	**0.07593**
E	0.0091	0.0137	0.0083	0.0024	0.0002	0.00001	0.00002	0	0	0	**0.03373**
[illegible]	05	0.0149	0.0159	0.0221	0.0145	0.0057	0.0011	0.00001	0	0	**0.08471**
SE	0.0106	0.0119	0.0143	0.0223	0.0242	0.0133	0.0034	0.0003	0	0	**0.1003**
SSE	0.011	0.0131	0.0032	0.0026	0.0026	0.0018	0.0005	0.00006	0	0	**0.03486**
S	0.0113	0.0102	0.0016	0.0013	0.0012	0.0008	0.0005	0.00001	0	0	**0.02691**
SSW	0.0111	0.0275	0.0061	0.0018	0.0013	0.0007	0.0002	0.00002	0	0	**0.04872**
SW	0.021	0.0492	0.0218	0.0025	0.0003	0.0001	0.00001	0	0	0	**0.09491**
WSW	0.014	0.0202	0.0127	0.0017	0.00002	0	0	0	0	0	**0.04862**
W	0.004	0.0063	0.0019	0.0002	0.00001	0	0	0	0	0	**0.01241**
WNW	0.0053	0.0095	0.0017	0.00005	0.00001	0	0	0	0	0	**0.01656**
NW	0.0095	0.0166	0.0042	0.0004	0.00003	0.00002	0	0	0	0	**0.03075**
NNW	0.0108	0.0102	0.0027	0.0005	0.00009	0	0	0	0	0	**0.02429**
Prob	**0.1859**	**0.3456**	**0.1892**	**0.13225**	**0.09416**	**0.03723**	**0.00897**	**0.0012**	**0.00016**	**0.00002**	

Fig. 12 Operability measurement procedure

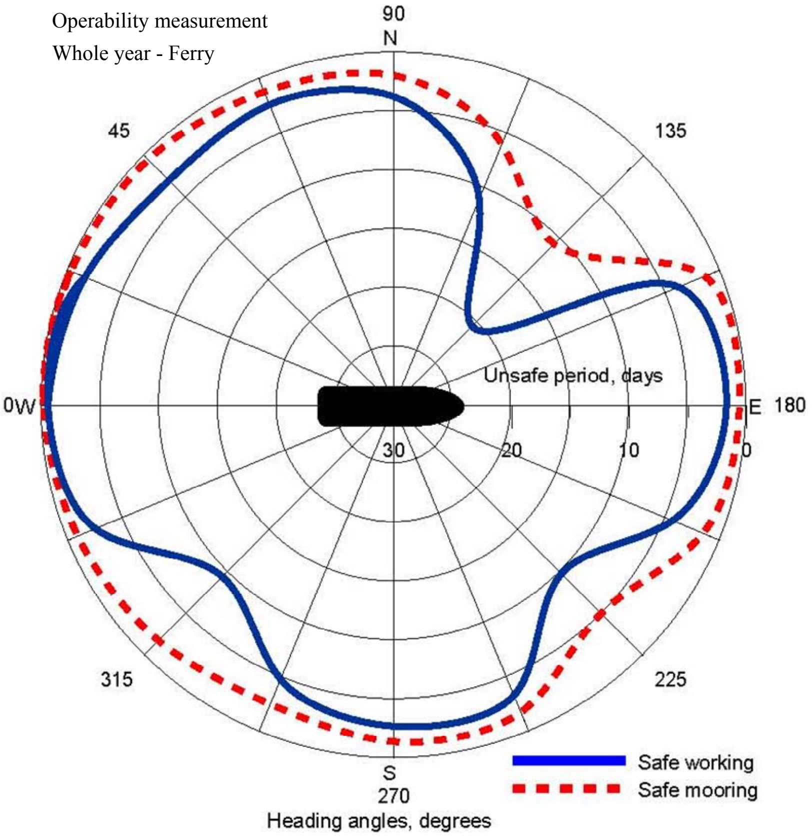


Fig. 13 Polar plot of the number of unsafe days (Ferryboat A)

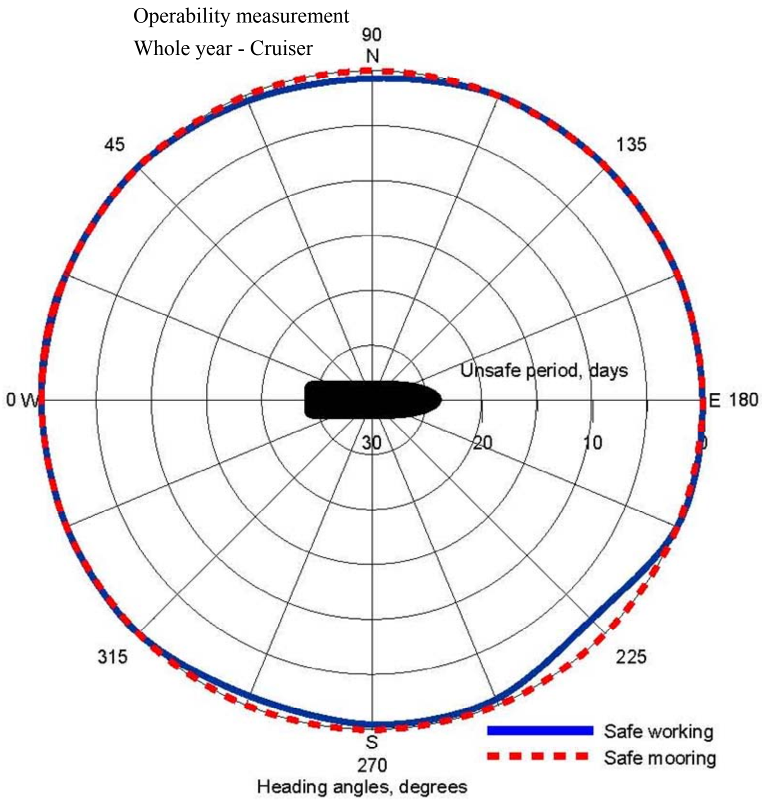


Fig. 14 Polar plot of the number of unsafe days (Cruiser)

Table 5 Operability measurement – safe working

RespVar	RMSallow	$\beta = 0^o$	$\beta = 22.5^o$	$\beta = 45^o$	$\beta = 67.5^o$	$\beta = 90^o$	$\beta = 112.5^o$
MOTSPX, m	2.00E-01	0.86	0.73	0.73	0.73	0.73	0.73
MOTSPY, m	1.00E+00	0.86	0.86	0.86	0.86	0.86	0.86
MOTSPZ, m	1.00E+00	0.95	0.95	0.86	0.86	0.86	0.86
ROLL, rad	1.75E-02	0.86	0.86	0.73	0.73	0.73	0.73
Combined		0.86	0.73	0.73	0.73	0.73	0.73

RespVar	RMSallow	$\beta = 135^o$	$\beta = 157.5^o$	$\beta = 180^o$	$\beta = 202.5^o$	$\beta = 225^o$	$\beta = 247^o$
MOTSPX, m	2.00E-01	0.73	0.86	0.86	0.86	0.73	0.73
MOTSPY, m	1.00E+00	0.86	0.86	0.86	0.86	0.86	0.86
MOTSPZ, m	1.00E+00	0.86	0.95	0.95	0.95	0.86	0.86
ROLL, rad	1.75E-02	0.73	0.86	0.86	0.86	0.73	0.73
Combined		0.73	0.86	0.86	0.86	0.73	0.73

RespVar	RMSallow	$\beta = 270^o$	$\beta = 292.5^o$	$\beta = 315^o$	$\beta = 337.5^o$
MOTSPX, m	2.00E-01	0.73	0.73	0.73	0.86
MOTSPY, m	1.00E+00	0.86	0.86	0.86	0.86
MOTSPZ, m	1.00E+00	0.86	0.86	0.86	0.95
ROLL, rad	1.75E-02	0.73	0.73	0.73	0.86
Combined		0.73	0.73	0.73	0.86

Table 6 Operability measurement – safe mooring

RespVar	RMSallow	$\beta = 0^o$	$\beta = 22.5^o$	$\beta = 45^o$	$\beta = 67.5^o$	$\beta = 90^o$	$\beta = 112.5^o$
VEL01, rad/s	6.00E-01	0.95	0.95	0.95	0.95	0.95	0.95
VEL02, rad/s	6.00E-01	0.99	0.95	0.95	0.86	0.86	0.86
VEL04, rad/s	1.00E+00	1	1	1	1	1	1
Combined		0.95	0.95	0.95	0.86	0.86	0.86

RespVar	RMSallow	$\beta = 135^o$	$\beta = 157.5^o$	$\beta = 180^o$	$\beta = 202.5^o$	$\beta = 225^o$	$\beta = 247^o$
VEL01, rad/s	6.00E-01	0.95	0.95	0.95	0.95	0.95	0.95
VEL02, rad/s	6.00E-01	0.86	0.95	0.95	0.95	0.86	0.86
VEL04, rad/s	1.00E+00	1	1	1	1	1	1
Combined		0.86	0.95	0.95	0.95	0.86	0.86

RespVar	RMSallow	$\beta = 270^o$	$\beta = 292.5^o$	$\beta = 315^o$	$\beta = 337.5^o$
VEL01, rad/s	6.00E-01	0.95	0.95	0.95	0.95
VEL02, rad/s	6.00E-01	0.86	0.86	0.95	0.95
VEL04, rad/s	1.00E+00	1	1	1	1
Combined		0.86	0.86	0.95	0.95

The overall operability is calculated by taking into account the sea state and wind direction statistics (1=100% of operability):

$$\text{Operability (safe working)} = \sum_{\text{Wave direction}} p_\beta \, p_{SW} = 0.76 \tag{4}$$

$$\text{Operability (safe mooring)} = \sum_{\text{Wave direction}} p_\beta \, p_{SM} = 0.88 \tag{5}$$

where p_β is the probability of wave direction. Values p_{SW} and p_{SM} are respectively probabilities of safe working and safe mooring for a specific wave direction.

4. Conclusion

In this paper, the reliability approach and the probabilistic method have been applied for the estimation of exposed berth operability. The transfer functions of moored ship absolute motion have been evaluated in the frequency domain taking into account shallow water. The influence of mooring lines on the ship motion is taken into account by appropriate restoring contributions from the mooring elements that are assembled in the body restoring matrix. The criteria for safe working condition are chosen to be the horizontal and the vertical absolute motion of ship ramp as well as significant amplitude of rolling motion. The kinetic energy is assumed to be the governing parameter for a safe mooring condition, defined as the limiting conditions for damage to ship or jetty, which is characterised by the ship size and velocities. The influence of shallow water is taken into consideration by Green's functions for finite water depth. The sea is described by the Tabain wave spectrum. As a result, based on the chosen criteria limit, the number of non-operative days is calculated and presented in polar diagrams. The method provides a reliable estimation of exposed berth operability during the year or season.

As an example, the operability of hypothetic berths on the outer side of an Adriatic Sea port is calculated. Once when the limiting sea state is calculated for all wave directions, the methodology allows a quick change of polar plot and operability calculation for different seasons and weather statistics. Moreover, it is possible to check various mooring arrangements and to find the more appropriate ones for each season.

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