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Operability Estimation of the Adriatic Sea Port Outside Berth

Original scientific paper

A ship moored in or outside the harbour is disturbed by sea waves and also by the waves generated by the ship entering or leaving the port. The motion analysis of moored ships is a very important factor in considering the berth efficiency during the year. The solution methodology consists of modelling a ship as a panel model used to calculate 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 into the global restoring matrix for the rigid body equation of motion. The system of obtained differential equations is solved by the frequency domain procedure taking explicitly into account the influence of shallow water. The effect of sea waves is taken into account by an appropriate wave spectrum and ship-generated wave characteristics are obtained by empirical relations.

Illustrative applications of the method are given for two ferryboats and one cruiser moored on the outside of the Adriatic Sea harbour jetty. The irregular sea is described by the Tabain spectrum. The results are presented as significant values of the ship ramp motion compared with the specific criteria limit.

Keywords: *ship mooring, ship motion, terminal operability, berth efficiency, ship waves*

Procjena operativnosti vanjskog veza jadranske luke

Izvorni znanstveni rad

Na brod vezan u luci ili izvan lukobrana djeluju morski valovi kao i valovi nastali prolaskom drugih brodova koji izlaze ili ulaze u luku. Analiza njihanja vezanog broda veoma je značajna sa stanovišta iskoristivosti pojedinog privezišta tijekom godine ili sezone. Metodologija rješenja sastoji se u modeliranju broda panel metodom u cilju proračuna hidrodinamičkih opterećenja i odziva primjenom potencijalne teorije. Linije veza modelirane su kao posebni opružni elementi i njihov je utjecaj na gibanje uključen preko matrice povratnih koeficijenata. Sustav dobivenih diferencijalnih jednadžbi riješen je u frekvencijskoj domeni uzimajući u obzir utjecaj dna. Utjecaj morskih valova uzet je u obzir pomoću odgovarajućeg spektra valova a značajke valova koji nastaju prolaskom brodova dobivene su empirijskim izrazima.

Prikaz primjene postupka dan je na primjeru dva trajekta i jednog broda za krstarenje vezanih na hipotetskom vanjskom vezu jadranske luke. More je opisano Tabainovim spektrom valova. Rezultati su prikazani kao značajne vrijednosti gibanja brodske rampe koje su uspoređene s graničnim vrijednostima zadanih kriterija.

Ključne riječi: *privez broda, njihanje broda, iskoristivost privezišta, brodski valovi*

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1 Introduction

The motion amplitude of a ship moored in a harbour is affected by not only sea waves but also by the waves generated by other ships during entering or leaving the port. Because of the exaggerated ship ramp motion these motions can affect the possibility of loading and unloading and consequently reduce the efficiency of berth. Therefore, it is important to make the reliability assessment of the number of non-operative days during the year or season. For the calculation of transfer function it is necessary to make a reliable model of the ship and mooring lines that must satisfy the equilibrium equation and compatibility relations. The sea waves can be described by an appropriate sea spectrum, and the passing ship-generated waves must be estimated for a given sea depth and ship speed. If the water at the berth place is shallow, the sea depth must be taken into account. Significant amplitudes of absolute longitudinal and vertical ramp motion as well as the rolling angle are accepted as criteria for the moored ship operability.

2 Mathematical background

2.1 Wave loads on ship

The assumption of potential flow allows the defining of the velocity flow as the gradient of the velocity potential Φ that satisfies the Laplace equation

$$\nabla^2\Phi = 0 \tag{1}$$

in the fluid domain [1]. The harmonic time dependence allows the defining of a complex velocity potential ϕ related to Φ by

$$\Phi = \mathrm{Re}\left(\phi\, e^{i\omega t}\right) \tag{2}$$

where ω is the frequency of the incident wave and t is time. The associated boundary-value problem will be expressed in terms of the complex velocity potential with the understanding that the product of all complex quantities with the factor $e^{i\omega t}$ applies. The liberalized form of the free-surface condition is

$$\frac{\partial\Phi}{\partial z}+\frac{1}{g}\frac{\partial^2\Phi}{\partial t^2}=0 \tag{3}$$

where g is the acceleration of gravity. The velocity potential of the incident wave is defined by

$$\phi_0=\frac{ig\zeta_a}{\omega}\frac{\cosh k(z+H)}{\cosh kH}e^{-k(x\cos\beta+y\sin\beta)} \tag{4}$$

where ζ_a is the wave amplitude, the wave number k is the real root of the dispersion relation, H is the sea depth and β is the angle between the direction of propagation of the incident wave and the positive x-axis. The linearization of the problem permits the decomposition of the velocity potential ϕ into the diffraction and radiation components, ϕ_D and ϕ_R respectively:

$$\phi\ =\phi_D+\phi_R=\phi_0+\phi_7+\sum_{j=1}^{6}\xi_j\phi_j \tag{5}$$

where constants ζ_j denote the complex amplitudes of the body oscillatory motion in its six rigid-body degrees of freedom and ϕ_j the corresponding unit-amplitude radiation potentials. The velocity potential ϕ_7 represents the disturbance of the incident wave by a body fixed at its undisturbed position. The total diffraction potential ϕ_D denotes the sum of ϕ_7 and the incident wave potential.

On the undisturbed position of the body boundary, the radiation and diffraction potentials are subjected to the conditions

$$\begin{aligned}\frac{\partial\phi_j}{\partial n}&=i\omega n_j\\ \frac{\partial\phi_D}{\partial n}&=0\end{aligned} \tag{6}$$

where $(n_1,n_2,n_3)\equiv\mathbf{n}$, $(n_4,n_5,n_6)\equiv\mathbf{r}\times\mathbf{n}$ and $\mathbf{r}=x\mathbf{i}+y\mathbf{j}+z\mathbf{k}$. The unit vector $\mathbf{n}$ is normal to the body boundary and points out of the fluid domain. The boundary value problem must be supplemented by a condition of outgoing waves applied to the velocity potentials ϕ_j,j=1,...,6. The boundary defined in this way assumes a ship anchored in the open sea. The influence of berth presence on the velocity potential is neglected. Possible contacts between the ship and the berth are also neglected.

The submerged half part of the ship under consideration is modelled with 3D panels, as presented in Figure 1, using the SESAM Software Package [2]. 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 as Green's functions. The source strengths are evaluated based on the source distribution method by 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.

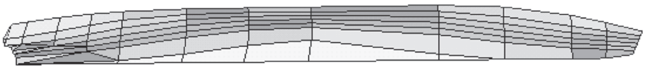


Figure 1 **3D panel model of ferryboat**
Slika 1 **3D panel model trajekta**

2.2 Mooring modelling

The mooring lines are assumed to be weightless and with linear stiffness characteristics. The external restoring forces from mooring lines in the ship motion model are included by mooring elements. The mooring elements are defined at appropriate nodes on the ship model. The hydro properties of a mooring element include the element orientation, the pre-tension and the restoring characteristics [1, 3, 4]. The restoring contributions from the mooring elements are assembled into the body hydrostatic 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.

The mooring stiffness matrices $\mathbf{C}_m$ for each mooring element in a model are described by horizontal and vertical spring constants and the pre-tension in x, y, and z direction. The $\mathbf{C}_m$ matrices are assembled into the global restoring matrix for the rigid body equation of motion. Since the $\mathbf{C}_m$ matrices are established directly in the motion reference coordinate system, no transformations are needed in the assemblage process. Having solved the equation of motion $\mathbf{x}_g$ represents the global motion of the rigid body system. The force vector $\mathbf{f}_g$ for each fairlead node, described in the result reference coordinate system, is then computed as

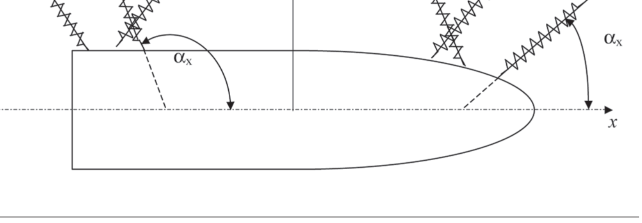
$$\mathbf{f}_g=\mathbf{C}_m\mathbf{x}_g \tag{7}$$

The terms in the matrix $\mathbf{C}_m$ are defined as follows:

$$\begin{bmatrix}\cos^2\alpha_x & \cos\alpha_x\cos\alpha_y & \cos\alpha_x\cos\alpha_z & k_{31}y-k_{21}z & k_{11}z-k_{31}x & k_{21}x-k_{11}y\\ & \cos^2\alpha_y & \cos\alpha_y\cos\alpha_z & k_{32}y-k_{22} & k_{21}z-k_{32}x & k_{22}x-k_{21}y\\ & & \cos^2\alpha_z & k_{33}y-k_{32}z & k_{31}z-k_{33}x & k_{32}x-k_{31}y\\ & & & k_{43}y-k_{42}z & k_{14}z-k_{43}x & k_{24}x-k_{41}y\\ & \text{symmetrical} & & & k_{51}z-k_{53}x & k_{52}x-k_{43}y\\ & & & & & k_{62}x-k_{61}y\end{bmatrix} \tag{8}$$

where α_x, α_y,α_z are the angles of a mooring line relative to the axes (α_x is defined in Figure 2), (x, y, z) are the coordinates of the mooring chock relative to the motion reference point.

Figure 2 **Mooring element definitions**
Slika 2 **Definicija veznih elemenata**



2.3 Global motion responses

The equation of motion is established for the harmonic motion of rigid body systems expressed in the global coordinate system (Figure 3). By applying Newton's law and including the added mass, damping and exciting force contributions acting on the panel and parts of a mooring hydro model, the complex motion vector $H(\omega,\beta) = (\eta_1, \eta_2 ..., \eta_6)$ can be found from the equation of motion

$$[-\omega^2(\mathrm{M} + \mathrm{A}(\omega)) + i\omega\left(\mathrm{B}_p(\omega) + \mathrm{B}_v\right) + \mathrm{C} + \mathrm{C}_e]\ \mathbf{H}(\omega,\beta) = \mathbf{F}(\omega,\beta) \quad (9)$$

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 total external restoring matrix and $\mathbf{F}(\omega,\beta)$ is the complex exciting force vector for frequency and incident wave heading angle β.

The eigenvalues λ and eigenvectors Ψ of the rigid body system is obtained for a given incident wave frequency by solving the eigenvalue problem

$$[-\lambda(\mathbf{M} + \mathbf{A}(\omega)) + \mathbf{C}]\mathbf{\Psi} = 0 \quad (10)$$

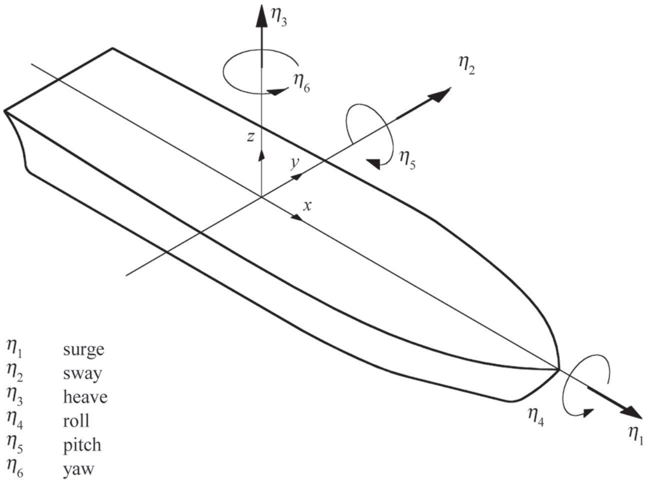


Figure 3 **Global coordinate system**
Slika 3 **Globalni koordinatni sustav**

2.4 Environmental description and sShip-generated waves

A ship moored in or outside the harbour is disturbed by both sea waves and the waves generated by the ship entering or leaving the port. The sea waves 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 direction of the incident waves is specified by the heading angle β between the positive x-axis and the propagating direction. The incident wave is defined as

$$\eta = \mathrm{Re}\left[\ \zeta_a e^{i(\omega t - k(x\cos\beta + y\sin\beta))}\ \right] \quad (11)$$

which alternatively may be written as

$$\eta = \zeta_a \cos(\omega t - k(x\cos\beta + y\sin\beta)) \quad (12)$$

The finite depth dispersion relation used in the above expressions is

$$\omega^2 = gk\tanh(kd) \quad (13)$$

The sea is described by an appropriate wave spectrum.

The Ship Wave Research Committee of the Japanese Association for Preventing Marine Accidents [5] has proposed the following equation for giving a rough estimate of the height of ship waves:

$$H_o = \left(\frac{L_S}{100}\right)^{\frac{1}{3}} \sqrt{\frac{E_{HPW}}{1620 L_S V_K}} \quad (14)$$

where H_o is the characteristic wave height of ship waves, L_S is the length of a vessel, E_{HPW} is the wave-making power in horse power and V_K is the full-load cruising speed in knots. Equation (14) has been obtained by assuming that the energy consumed through the wave making resistance is equal to the propagation energy of ship waves, while the values of the coefficients have been determined as averages form data from ship towing tank tests. For the purpose of this research, equation (14) has been adjusted for the catamarans, taking into consideration two hulls, and calibrated according to the known wave heights that this ships are generating [6], [7]. Since the value E_{HPW} is the main unknown in equation (14), the main work to be done is to estimate the variables included in E_{HPW} calculation. This included the calculation of wetted surface value and shaft power at various ship speeds where we used data of known wave heights at known ship speeds.

3 Numerical example

The application of the computational method is given for two ferryboats of approximately 75 m (ship A) and 115 m (ship B) in length and a cruiser of approximately 200 m in length (ship C) moored to a pier on the outside of an Adriatic Sea harbour jetty. The moored ship transfer functions of absolute horizontal and vertical ramp motion as well as the rolling angle of the ships A, B and C, shown in Figures 4 to 15, have been computed by using the software package SESAM [2] for the range of wave frequencies corresponding to the wave length – ship length ratio from 0.04 to 2. The sea depth for the ships A, B and C are respectively 6.5 m, 10 m and 15 m. It is used in the calculation of Green's functions for finite water depth.

The corresponding response spectrums for the absolute longitudinal, transversal and vertical ramp motion (at the end point of ramp-to-ship hinge) and the response spectrum of rolling of the ships A, B and C are calculated for the Tabain wave spectrum [8]:

$$S_\zeta(\omega) = 0.862\frac{0.0135g^2}{\omega^5}\exp\left(-\frac{5.186}{\omega^4 H_s}\right)\ 1.63^{\left(-\frac{(\omega-\omega_m)^2}{2\sigma^2\omega_m^2}\right)} \quad (15)$$

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

$$\begin{aligned} \sigma &= 0.08 \quad \text{za} \quad \omega < \omega_m \\ \sigma &= 0.10 \quad \text{za} \quad \omega > \omega_m \end{aligned} \tag{16}$$

The resulting spectrums are then processed [2] to obtain the corresponding order statistics. They constitute the input data for the estimation of criteria limit exceedance. Figures 16, 17, 18 and 19 show the double value of the significant absolute longitudinal, transversal and vertical motion amplitude as well as the double significant rolling amplitude of all three ships as a function of sea state defined by the significant wave height. The heading is supposed to be as for waves from the South wind (50^0 or 130^0) that seem to be the highest waves in this area during summer. From these diagrams and from the sea state statistics for the considered area from May to October it is possible to estimate the limiting significant wave height and the number of non-operative days *NOD* during the season. These data and the operability are shown in Table 1 for the exposed berths of a port in the Adriatic Sea.

The prescribed speed limit for ships entering the port is 10 kn. Ship-generated waves are calculated for the two relevant ships with the following results:

- Catamaran L_{oa}= 82.3 m , Δ = 1250 t,
  for the V= 10 kn, H_{max}= 0.57 m, ω= 2.34 s^{-1}
  for the V= 15 kn, H_{max}= 0.98 m, ω= 1.56 s^{-1}
- Ferryboat L_{oa}= 86.6 m , Δ=2351 t,
  for the V= 10 kn, H_{max}= 0.48 m, ω= 2.34 s^{-1}

where H_{max} is the height of ship waves at the observation point which is in our case equal to the length of the relevant ship obtained by the following equation:

$$H_{\max} = H_o \left(\frac{100}{s}\right)^{\frac{1}{3}} \left(\frac{V_k}{V_K}\right)^3 \tag{17}$$

In this equation it is considered that the wave height decays as $s^{-1/3}$, where s is the distance of the observation point from the sailing line. It is also considered that the wave height is proportional to the cube of the cruising speed of the vessel, where V_k is the actual cruising speed of the vessel in knots.

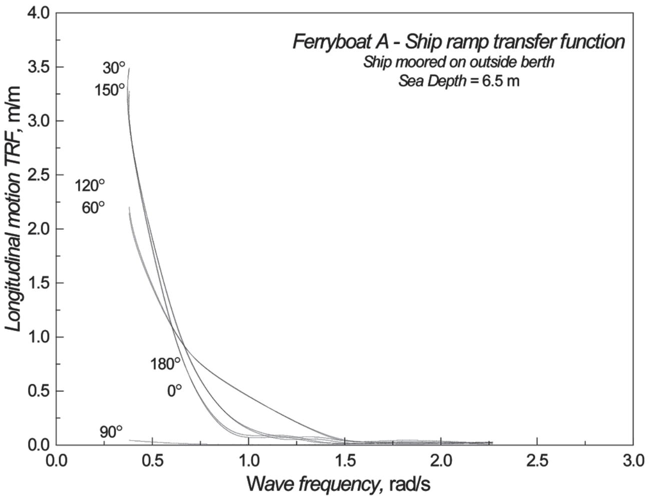
The criteria limits have been implemented according to the recommendation of the PIANC (Permanent International Associations of Navigation Congresses) [9] where acceptable motions were determined based on interviews with ship crews and port operators [10]. The chosen criteria and criteria limits are also based on interviews with actual ship 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 safe working conditions are vertical and horizontal motions on the ship ramp as well as the rolling angle. The limits for the significant amplitude of vertical and transversal motion are set to be 0.5 m and the limit for significant amplitude of longitudinal motion 0.1 m. The criteria limit for significant amplitude of rolling motion is set to be 0.5 deg.

The amplitudes of ship-generated waves for several ship types and several ship speeds have been calculated according to the theory presented in Section 2. These waves are supposed to be regular and the response of a specific ramp point is calculated as the absolute motion on the regular wave of given frequency, heading and amplitude. Generally speaking, considering responses caused by ship-generated waves at different ship speeds and a given criteria limit, it is possible to restrict the speed of passing ships to some acceptable value. However, in this case, the frequencies of ship-generated waves of both passing ships are well beyond the area of significant values of transfer functions for the ships B and C, so the response of these ships is not a limiting factor for safe working or safe mooring. As expected, the response of the smallest ship (ship A) on the waves generated by a catamaran passing at the speed of 15 kn is the most serious but also below the prescribed limits.

Table 1 **Operating limits and non-operative days**
Tablica 1 **Granična stanja mora i broj neoperativnih dana**

Ship	From May to October (Jugo)			
	Hs, m	*NOD*, days	Operability, %	Limiting criterion
Ferryboat A	1.25	7	96	Longitudinal motion
Ferryboat B	1.70	1	99	Vertical motion
Cruiser C	1.90	0	100	Vertical motion

Figure 4 **Longitudinal motion transfer function of ship A ramp**
Slika 4 **Prijenosna funkcija uzdužnog pomaka rampe broda A**



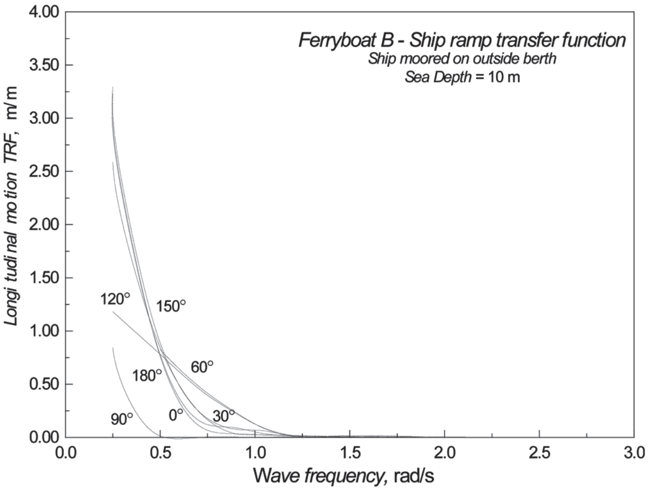


Figure 5 **Longitudinal motion transfer function of ship B ramp**
Slika 5 **Prijenosna funkcija uzdužnog pomaka rampe broda B**

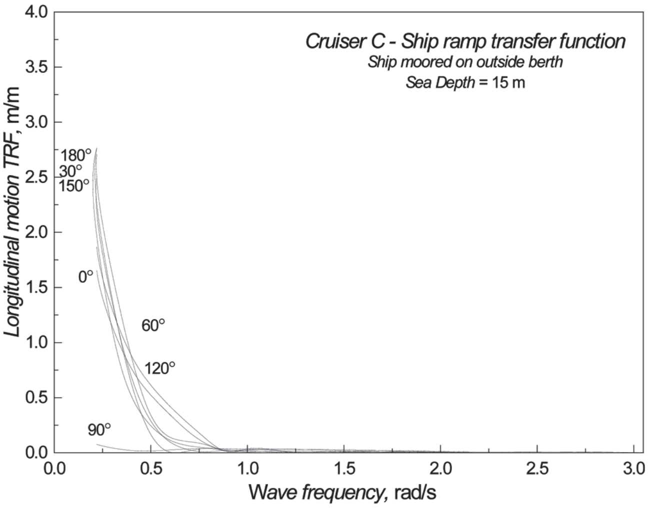
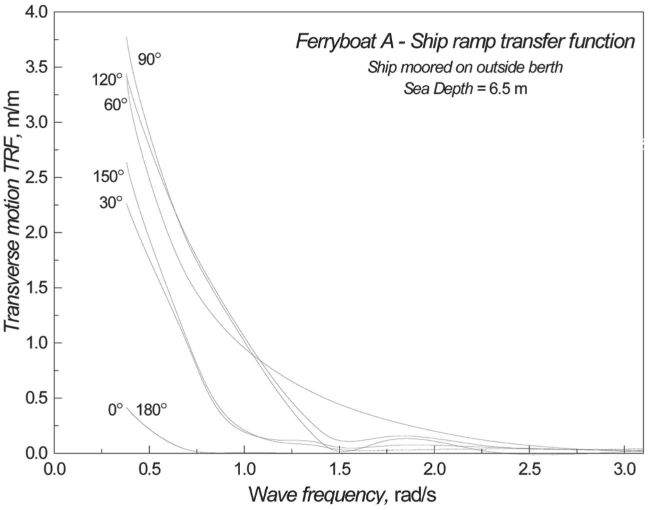


Figure 6 **Longitudinal motion transfer function of ship C ramp**
Slika 6 **Prijenosna funkcija uzdužnog pomaka rampe broda C**

Figure 7 **Transverse motion transfer function of ship A ramp**
Slika 7 **Prijenosna funkcija poprečnog pomaka rampe broda A**



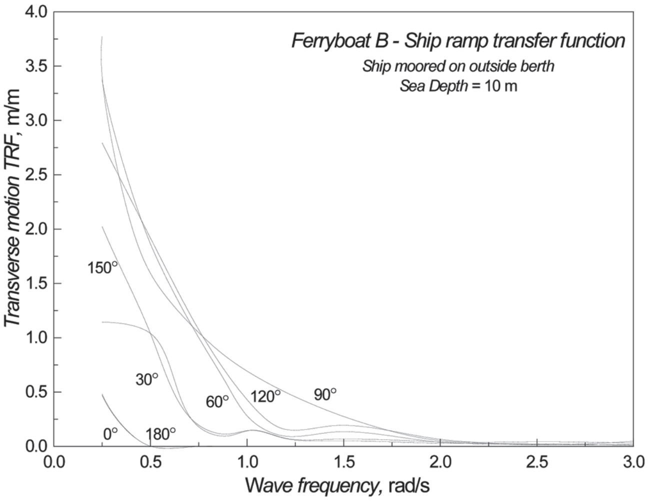


Figure 8 **Transverse motion transfer function of ship B ramp**
Slika 8 **Prijenosna funkcija poprečnog pomaka rampe broda B**

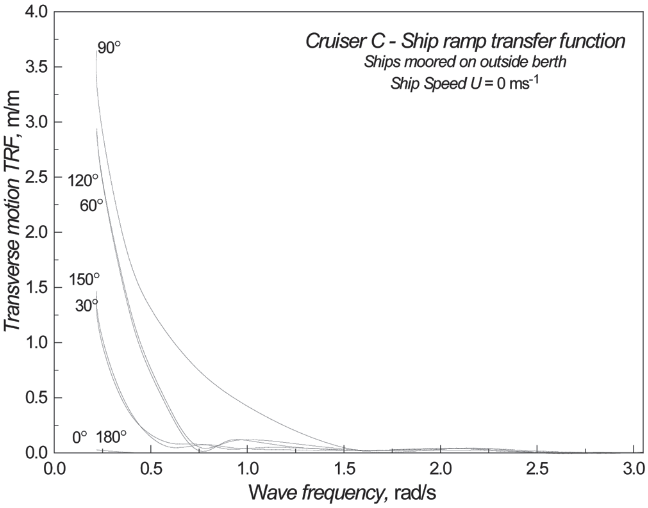
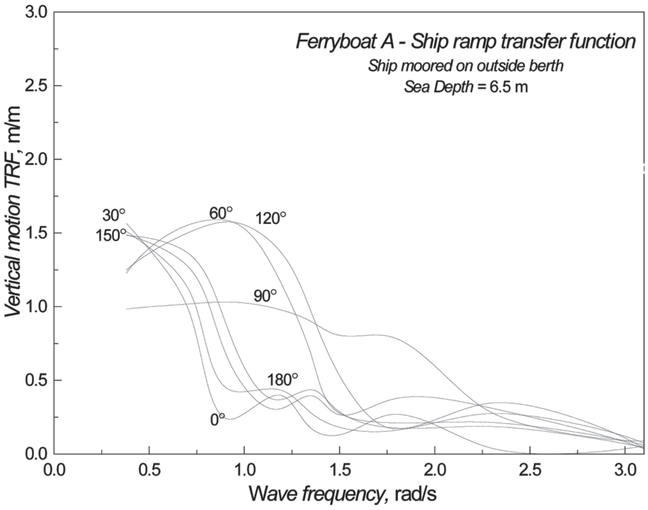


Figure 9 **Transverse motion transfer function of ship C ramp**
Slika 9 **Prijenosna funkcija poprečnog pomaka rampe broda C**

Figure 10 **Vertical motion transfer function of ship A ramp**
Slika 10 **Prijenosna funkcija vertikalnog pomaka rampe broda A**



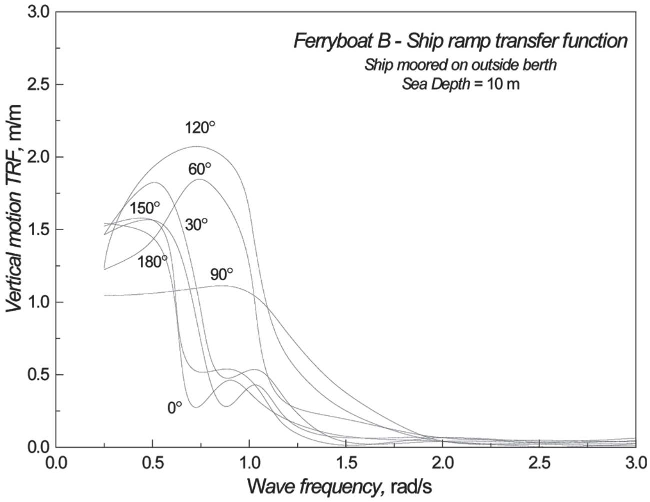


Figure 11 **Vertical motion transfer function of ship B ramp**
Slika 11 **Prijenosna funkcija vertikalnog pomaka rampe broda B**

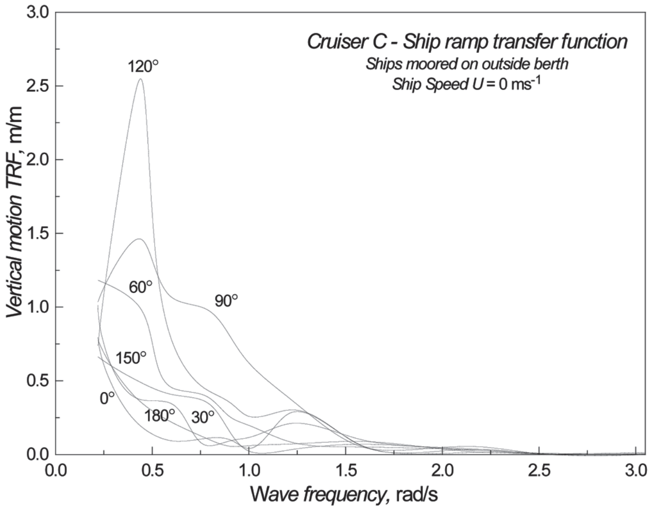
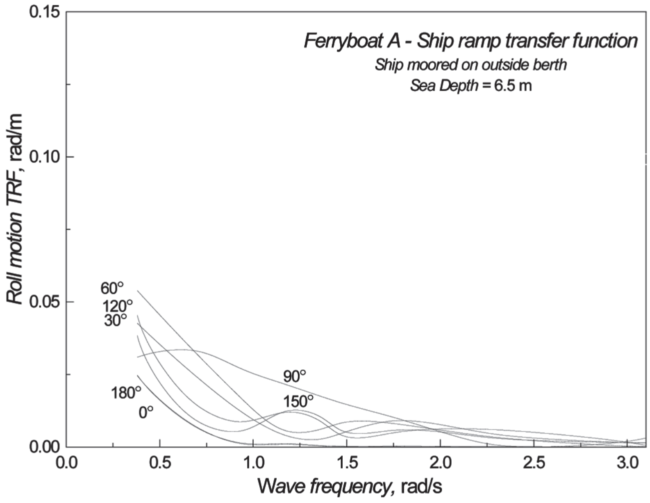


Figure 12 **Vertical motion transfer function of ship C ramp**
Slika 12 **Prijenosna funkcija vertikalnog pomaka rampe broda C**

Figure 13 **Roll transfer function of ship A**
Slika 13 **Prijenosna funkcija ljuljanja broda A**



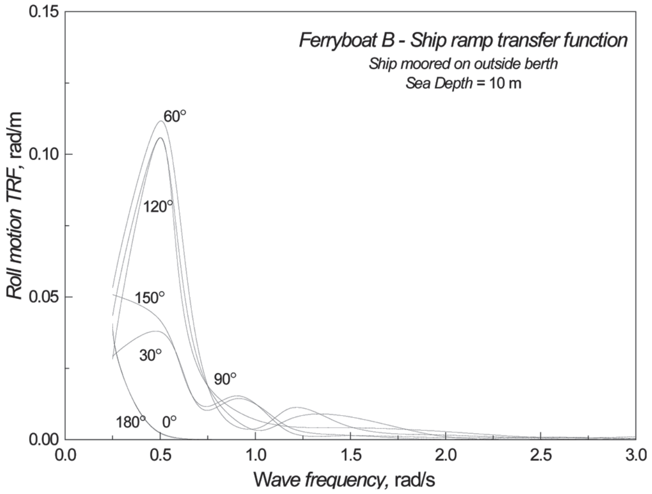


Figure 14 **Roll transfer function of ship B**
Slika 14 **Prijenosna funkcija ljuljanja broda B**

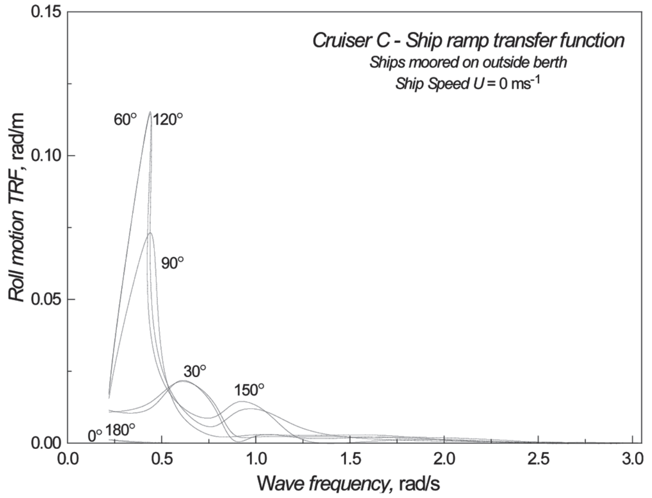
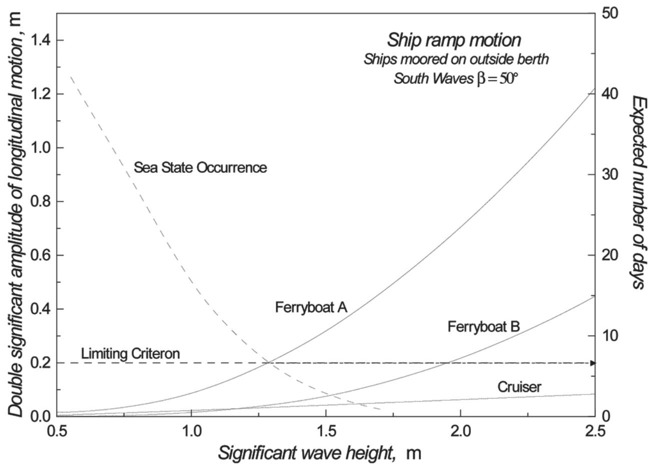


Figure 15 **Roll transfer function of ship C**
Slika 15 **Prijenosna funkcija ljuljanja broda C**

Figure 16 **Significant amplitude of ship ramp longitudinal motion**
Slika 16 **Značajna amplituda uzdužnog pomaka točke rampe broda**



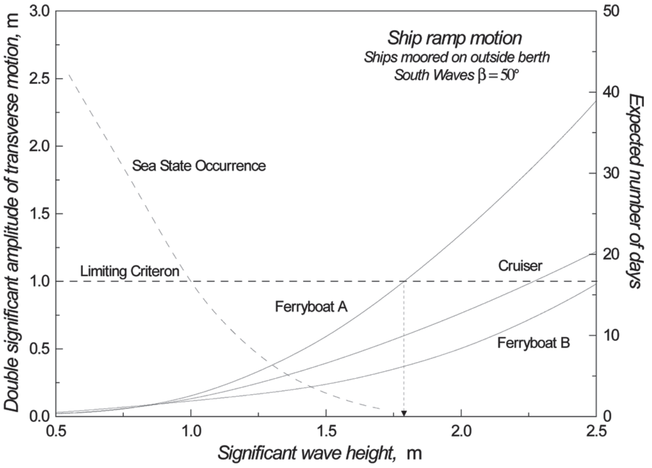


Figure 17 **Significant amplitude of ship ramp transverse motion**
Slika 17 **Značajna amplituda poprečnog pomaka točke**

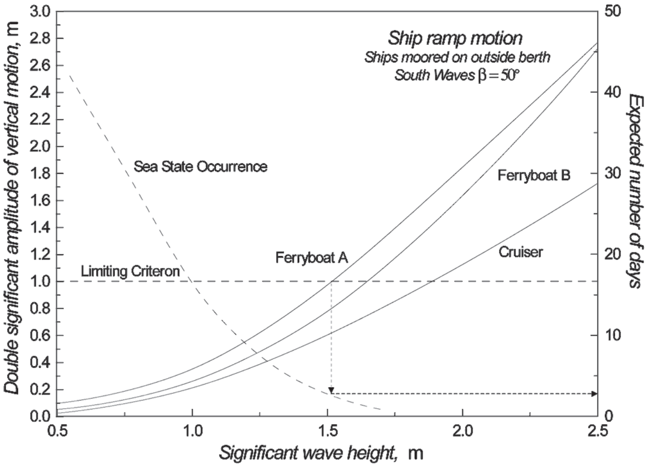
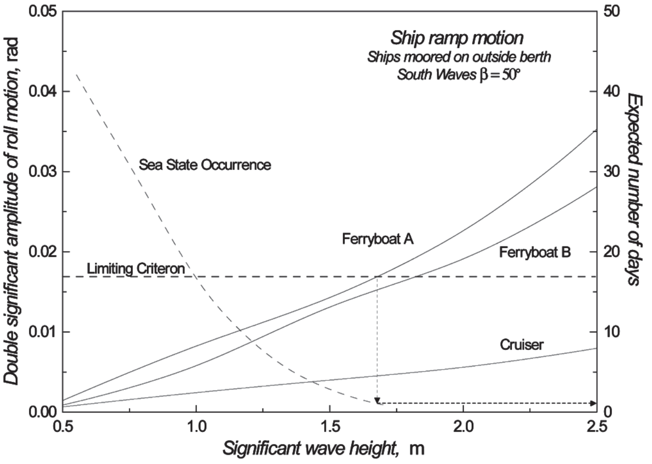


Figure 18 **Significant amplitude of ship ramp vertical motion**
Slika 18 **Značajna amplituda vertikalnog pomaka točke**

Figure 19 **Significant amplitude of rolling motion**
Slika 19 **Značajna amplituda ljuljanja**



4 Conclusion

In this study, the operability of pier is discussed by the use of reliability approach and the probabilistic method to evaluate the significant amplitude of specific point absolute motion for a moored ship. The specific point is chosen to be the point on the end of the ramp-to-ship hinge. The chosen criteria are the horizontal and vertical absolute motion as well as the roll significant amplitude. The influence of mooring lines on the ship motion is taken into account by appropriate restoring contributions from the mooring elements that are assembled into the body restoring matrix. The sea is described by the Tabain spectrum.

As an example, the operability of hypothetic outside berths in an Adriatic Sea port is calculated taking into account the effect of both sea waves and ship-generated waves. As a result, based on the chosen criteria limit, the number of non-operative days is calculated and the response of moored ships on passing ship waves is estimated. The analysis showed that the construction of outside berths is justified because the main use of the berths is planned to be during summer months.

Regarding disturbances due to ship-generated waves, the response of moored ships is well below the prescribed limit for the bigger ships B and C and acceptable for the ship A. Considering this, no particular restriction the speed of passing ships is needed. However, it must be pointed out that the speed of passing ships is not only limited by the moored ship motion criteria limits, but also by the full influence of these waves on the environment, particularly on the sea sediment, shore erosion, small fishing or pleasure boats as well as persons on beaches. Consequently, these criteria must be determined for each specific location.

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