Jasna Prpić-Oršić*
Roko Dejhalla**

ISSN 0469 - 6255
(1-10)

AUXILIARY SEAKEEPING CHARACTERISTICS DIAGRAMS ADAPTED TO SHIP CREW

POMOĆNI DIJAGRAMI POMORSTVENIH KARAKTERISTIKA PRILAGOĐENI POSADI BRODA

UDK 656.61.052
Review
Pregledni članak

Summary

The estimation of ship seakeeping characteristics is very important because of high requirements of motions as regards all extra demands about voyage comfort, respectively to crew and ship equipment efficiency. Hard voyage conditions with high ship oscillation amplitudes import different unfavourable dynamic effects. High ship motions amplitudes on wave may jeopardise people and equipment, cargo, and in extreme cases, the ship construction. The diagrams that permit the captain or ship crew to reduce the ship motion on regular waves are proposed in the paper.

Key words: seakeeping, transfer functions, auxiliary seakeeping diagrams

Sažetak

Procjena pomorstvenih karakteristika broda neobično je važna zbog visokih kriterija njihanja s obzirom na sve strože zahtjeve o udobnosti plovidbe, odnosno učinkovitosti djelovanja posade i opreme na brodu. U težim uvjetima plovidbe velike amplitude oscilacija broda uzrokuju različite nepovoljne dinamičke efekte. Velike amplitude njihanja broda na valovima mogu ugroziti ljude i opremu, teret, a u iznimnim slučajevima i samu konstrukciju broda. U radu je dan prijedlog dijagrama koji zapovjedniku i posadi broda omogućuju smanjenje amplituda njihanja broda na valovima.

Ključne riječi: pomorstvenost, prijenosne funkcije, pomoćni dijagrami pomorstvenosti

1. Introduction
Uvod

The response of ship advancing in a seaway is complicated phenomenon involving the interaction between the vessel dynamics and several distinct hydrodynamic forces. Ocean ships must be designed to act in wave environment which is often uncomfort, and sometimes even unfriendly. The motions and structural loads of hull are two basic engineer problems during ship project. It is possible, for the ship that advances with arbitrary heading and speed, to estimate the seakeeping characteristics. Analysing of given data may, for several load and sea cases, permit the captain to avoid unfavourable combinations of heading angle and ship speed and to choose the most convenient cargo distribution.

*Ph.D. Jasna Prpić-Oršić, Naval Architect
**M.Sc. Roko Dejhalla, Naval Architect
Technical Faculty, University of Rijeka, Vukovarska 58, 51000 Rijeka, Republic of Croatia

1. Analysis of ship motion on regular waves
Analiza njihanja broda na pravilnim valovima

The dynamic of ship motions is defined by equation of motions which balance the outside forces and moments which act on ship with the inside gravitation and inertia forces and moments.

If we suppose that the ship on calm water is in equilibrium, its weight is in balance with force of hydrostatic pressure. Stationary forces of resistance and propulsion are similarly balanced. Those stationary forces may be ignored, and the attention would be oriented to nonstationary disturbance.

The most important unsteady force which affect the floating object is resultant of hydrostatic and hydrodynamic components of normal pressure that act on wetted surface. Added force components, which are currently ignored, include ship propeller force, viscous force acts on submerged hull surface and aerodynamic force on ship above free surface.

1.1. Motion equations formulation
Formulacija jednadžbi gibanja

The theory with satisfactory engineering accuracy, which can be applied to predict motions of the ship, which advances at steady mean forward speed with arbitrary heading in a train of regular waves, was developed by Salvesen, Tuck and Faltinsen [1] (STF theory). A ship is assumed to behave as a rigid body having six degrees of freedom. As shown in Fig.1, the right-handed coordinate system (x, y, z), with axes z vertically upward through the centre of gravity of the ship, x in the direction of forward motion, and the origin in the plane XY of the undisturbed free surface, is adopted.

The translatory displacements in the x, y and z directions with respect to the origin are η_1, η_2, η_3, so that η_1 is the surge, η_2 is the sway, and η_3 is the heave displacement. Furthermore the angular displacement of the rotational motion about x, y, and z axes are η_4, η_5, η_6, respectively, so that η_4 is the roll, η_5 is the pitch, and η_6 is the yaw angle.

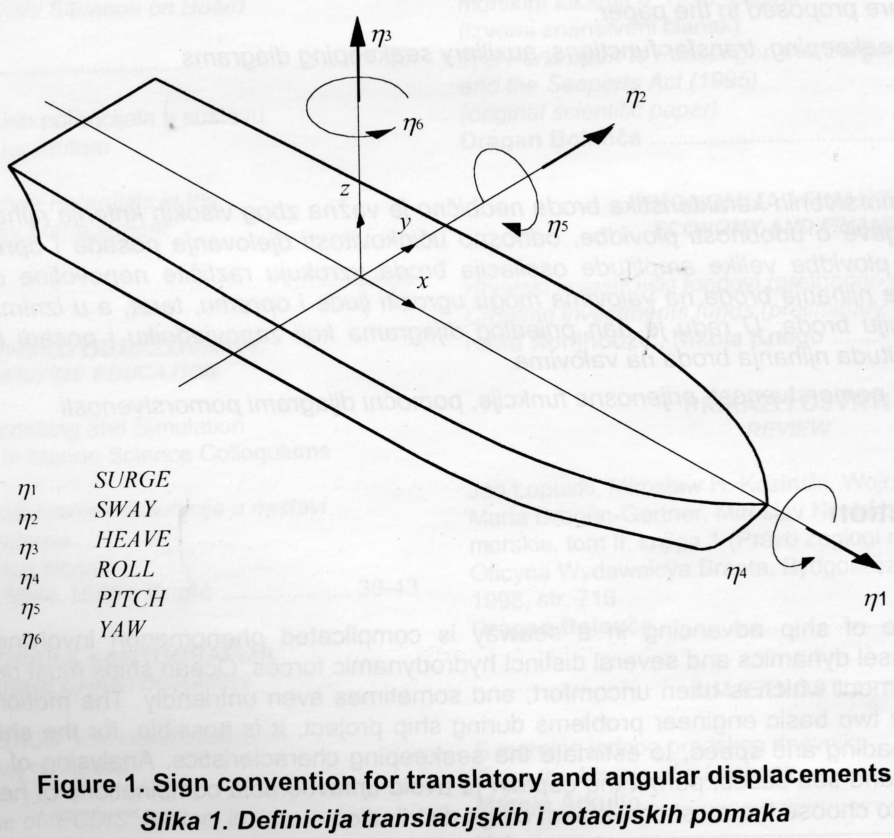

Figure 1. Sign convention for translatory and angular displacements

Slika 1. Definicija translacijskih i rotacijskih pomaka

Under the assumption that the responses are linear and harmonic, the six linear coupled differential equations of motion can be written:

$$\sum_{k=1}^{6}\left[(M_{jk}+A_{jk})\ddot{\eta}_k+B_{jk}\dot{\eta}_k+C_{jk}\eta_k\right]=F_j e^{i\omega t}, \qquad j=1,...,6 \tag{1}$$

where M_{jk} is the component of the generalised mass matrix for the ship, A_{jk} and B_{jk} are the added mass and damping coefficients, C_{jk} is the hydrostatic restoring coefficient, and F_j is the complex amplitude of the exciting force and moment, ω is the frequency of encounter and is the same as the frequency of the response. The dots stand for time derivatives so that $\dot{\eta}_k$ and $\ddot{\eta}_k$ are velocity and acceleration terms.

Under the assumption that the ship has lateral symmetry and the center of gravity is located at (0, 0, z_G), then the generalised mass matrix is given by:

$$M_{jk}=\begin{bmatrix} M & 0 & 0 & 0 & Mz_G & 0 \\ 0 & M & 0 & -Mz_G & 0 & 0 \\ 0 & 0 & M & 0 & 0 & 0 \\ 0 & -Mz_G & 0 & I_{44} & 0 & -I_{46} \\ Mz_G & 0 & 0 & 0 & I_{55} & 0 \\ 0 & 0 & 0 & -I_{46} & 0 & I_{66} \end{bmatrix} \tag{2}$$

where M is the mass of the ship, I_j is the moment of inertia in the jth mode, and I_{jk} is the product of inertia. For ships with lateral symmetry it also follows that the added mass (or damping) coefficients are:

$$A_{jk}\,(\text{ or } B_{jk})=\begin{bmatrix} A_{11} & 0 & A_{13} & 0 & A_{15} & 0 \\ 0 & A_{22} & 0 & A_{24} & 0 & A_{26} \\ A_{31} & 0 & A_{33} & 0 & A_{35} & 0 \\ 0 & A_{42} & 0 & A_{44} & 0 & A_{46} \\ A_{51} & 0 & A_{53} & 0 & A_{55} & 0 \\ 0 & A_{62} & 0 & A_{64} & 0 & A_{66} \end{bmatrix} \tag{3}$$

Furthermore, for a ship in the free surface the only nonzero linear hydrostatic restoring coefficients are:

$$C_{33},\ C_{44},\ C_{55}\ \text{i}\ C_{35}=C_{53} \tag{4}$$

Under the assumption that the hydrodynamic forces associated with the surge motion are much smaller than the forces associated with other modes of motion, from equation (1) to (4) follows that for the ship with lateral symmetry and a slender hull there are two sets of coupled equations; for heave and pitch and; for sway, roll and yaw.

Hydrodynamic coefficients of motion equations are expressed as integration of harmonic part of the potential ψ_k (k = 1, 2, ..., 6) over wetted hull surface. Using the assumption of slender hull, expression for coefficients can be reduced to the integrals of cross section added mass and damping over ship length.

The added mass and damping coefficients for the ship advancing with speed U, according to Salvesen, Tuck and Faltinsen are written as follows:

Added mass coefficients

$$A_{33} = \int_L a_{33}\,\mathrm{d}\xi - \frac{U}{\omega^2} b_{33}^{A}$$

$$A_{35} = -\int_L \xi\, a_{33}\,\mathrm{d}\xi - \frac{U}{\omega^2} B_{33}^{A} + \frac{U}{\omega^2} x_A\, b_{33}^{A} - \frac{U^2}{\omega^2} a_{33}^{A}$$

$$A_{53} = -\int_L \xi\, a_{33}\,\mathrm{d}\xi + \frac{U}{\omega^2} B_{33}^{0} + \frac{U}{\omega^2} x_A\, b_{33}^{A}$$

$$A_{55} = -\int_L \xi^2\, a_{33}\,\mathrm{d}\xi + \frac{U^2}{\omega^2} A_{33}^{0} - \frac{U}{\omega^2} x_A^{\,2}\, b_{33}^{A} + \frac{U^2}{\omega^2} x_A\, a_{33}^{A}$$

$$A_{22} = \int_L a_{22}\,\mathrm{d}\xi - \frac{U}{\omega^2} b_{22}^{A}$$

$$A_{24} = A_{42} = \int_L a_{24}\,\mathrm{d}\xi - \frac{U}{\omega^2} b_{24}^{A}$$

$$A_{26} = \int_L \xi\, a_{22}\,\mathrm{d}\xi + \frac{U}{\omega^2} B_{22}^{0} - \frac{U}{\omega^2} x_A\, b_{22}^{A} + \frac{U^2}{\omega^2} a_{22}^{A}$$

$$A_{44} = \int_L a_{44}\,\mathrm{d}\xi - \frac{U}{\omega^2} b_{44}^{A}$$

$$A_{46} = \int_L \xi\, a_{24}\,\mathrm{d}\xi + \frac{U}{\omega^2} B_{24}^{0} + \frac{U}{\omega^2} x_A\, b_{24}^{A} + \frac{U^2}{\omega^2} x_A\, b_{24}^{A}$$

$$A_{62} = \int_L \xi\, a_{22}\,\mathrm{d}\xi - \frac{U}{\omega^2} B_{22}^{0} - \frac{U}{\omega^2} x_A\, b_{22}^{A}$$

$$A_{64} = \int_L \xi\, a_{24}\,\mathrm{d}\xi - \frac{U}{\omega^2} B_{24}^{0} - \frac{U}{\omega^2} x_A\, b_{24}^{A}$$

$$A_{66} = \int_L \xi^2\, a_{22}\,\mathrm{d}\xi + \frac{U^2}{\omega^2} A_{22}^{0} - \frac{U}{\omega^2} x_A^{\,2}\, b_{22}^{A} + \frac{U^2}{\omega^2} x_A\, a_{22}^{A}$$

Damping coefficients

$$B_{33} = \int_L b_{33}\,\mathrm{d}\xi - \frac{U}{\omega^2} a_{33}^{A}$$

$$B_{35} = -\int_L \xi\, b_{33}\,\mathrm{d}\xi + U A_{33}^{0} - U x_A\, a_{33}^{A} - \frac{U^2}{\omega^2} a_{33}^{A}$$

$$B_{53} = -\int_L \xi\, b_{33}\,\mathrm{d}\xi - U A_{33}^{0} - U x_A\, a_{33}^{0}$$

$$B_{55} = \int_L \xi^2\, b_{33}\,\mathrm{d}\xi + \frac{U^2}{\omega^2} B_{33}^{0} + U x_A^2\, a_{33}^{A} + \frac{U^2}{\omega^2} x_A\, b_{33}^{A}$$

$$B_{22} = \int_L b_{22}\,\mathrm{d}\xi + U a_{22}^{A}$$

$$B_{24} = B_{42} = \int_L b_{24}\,\mathrm{d}\xi + U a_{24}^{A}$$

$$B_{26} = \int_L \xi\, b_{22}\,\mathrm{d}\xi - U A_{22}^{0} + U x_A\, a_{22}^{A} + \frac{U^2}{\omega^2} b_{22}^{A} \qquad \textbf{(5)}$$

$$B_{44} = \int_L b_{44}\,\mathrm{d}\xi + U a_{44}^{A} + B_{44}^{*}$$

$$B_{46} = \int_L \xi\, b_{24}\,\mathrm{d}\xi - U A_{24}^{0} + U x_A\, a_{24}^{A} + \frac{U^2}{\omega^2} b_{24}^{A}$$

$$B_{62} = \int_L \xi\, b_{22}\,\mathrm{d}\xi + U A_{22}^{0} + U x_A\, a_{22}^{A}$$

$$B_{64} = \int_L \xi\, b_{24}\,\mathrm{d}\xi + U A_{24}^{0} + U x_A\, a_{24}^{A}$$

$$A_{66} = \int_L \xi^2\, b_{22}\,\mathrm{d}\xi + \frac{U^2}{\omega^2} B_{22}^{0} + U x_A^{\,2}\, a_{22}^{A} + \frac{U}{\omega^2} x_A\, b_{22}^{A}$$

All the hydrodynamic equation coefficients motions are expressed by the integration over length ship L, a_{jk} are b_{jk} two-dimensional added mass and damping in j-th direction because of motions in k-th direction. It should be accentuated that A_{jk}^{0} and B_{jk}^{0} are related to speed independent part of coefficients and that x_A, a_{jk}^{A}, b_{jk}^{A} refer to values for aftermost section. Hydrostatic restoring coefficients, which are frequency and speed independent, follow directly from hydrostatic considerations:

$$C_{33} = \rho g \int b\,\mathrm{d}\xi = \rho g\, A_{WP}$$

$$C_{35} = C_{53} = -\rho g \int \xi\, b\,\mathrm{d}\xi = -\rho g\, M_{WP} \qquad \textbf{(6)}$$

$$C_{55} = \rho g \int \xi^2 b\,d\xi = \rho g\, I_{WP}$$

$$C_{44} = \rho g\, V\, \overline{\mathrm{GM}_0}$$

where V is the displaced volume of the ship and $\overline{\mathrm{GM}_0}$ is the metacentric height, b is the sectional beam, ρ is mass density, g is the gravitational acceleration. A_{WP}, M_{WP} and I_{WP} are the area, first moment and moment of inertia of the water plane.

By defining the sectional Froude-Krylov f_j and diffraction force h_j for cross section C_x as:

$$f_j = g e^{-ikx\cos\beta} \int_{C_x} N_j\, e^{iky\sin\beta}\, e^{kz}\,\mathrm{d}l, \qquad j = 2,3,4$$

$$h_j = \omega_0\, e^{-ikx\cos\beta} \int_{C_x} (iN_3 - N_2)\, e^{iky\sin\beta}\, e^{kz}\, \psi_j\,\mathrm{d}l, \qquad j = 2,3,4$$

it is possible to write the exciting forces and moments using following expressions:

$$F_j = \rho\alpha \int (f_j + h_j)\,\mathrm{d}\xi + \rho\alpha \frac{U}{i\omega} h_j^{\mathrm{A}}, \quad j = 2,3,4$$
$$F_5 = -\rho\alpha \int \left[\xi\,(f_3 + h_3) + \frac{U}{i\omega} h_3 \right] \mathrm{d}\xi \; - \rho\alpha \frac{U}{i\omega} x_{\mathrm{A}}\, h_3^{\mathrm{A}} \qquad (7)$$
$$F_6 = -\rho\alpha \int \left[\xi\,(f_2 + h_3) + \frac{U}{i\omega} h_2 \right] \mathrm{d}\xi \; - \rho\alpha \frac{U}{i\omega} x_{\mathrm{A}}\, h_2^{\mathrm{A}}$$

Since, for determining both radiation ψ_j and diffraction potential ψ_D, it is necessary to solve very similar mathematical problems. For the calculation of diffraction potential, Haskind relation, which results from body boundary conditions and Green's theorem, can be used:

$$\iint_S \left(\psi_I \frac{\partial \psi_i}{\partial n} + \psi_i \frac{\partial \psi_D}{\partial n} \right) \mathrm{d}S = \iint_S \left(\psi_I \frac{\partial \psi_j}{\partial n} + \psi_i \frac{\partial \psi_I}{\partial n} \right) \mathrm{d}S$$

The Haskind relation connects exciting diffraction force with harmonic wave potential ψ_I and radiation potentials ψ_j and makes possible getting the solution of exciting force diffraction part without complicated calculation of diffraction potential.

Knowing the potential ψ_j for two-dimensional problem, which can be obtained by Frank's close-fit method [2, 3], it is possible, by integration, directly calculate all two-dimensional coefficients and exciting forces and moments.

1.1. Transfer functions
Prijenosne funkcije

On the basis of ship offsets, mass distribution, speed and heading angle it is possible to formulate the motion equations and determine the displacements [4].

The transfer function $H_j(\omega)$ can be expressed as:

$$H_j(\omega) = \frac{\eta_j}{\alpha} \qquad \text{za } j = 1,2,3$$
$$H_j(\omega) = \frac{\eta_j}{k\alpha} \qquad \text{za } j = 4,5,6 \qquad (8)$$

where η_j are the amplitudes of j-th motion modes, α is wave amplitude, and k is wave number defined as the number of wave length λ in 2π meters:

$$k = \frac{2\pi}{\lambda} \qquad (9)$$

Encounter frequency ω can be defined as:

$$\omega = \omega_{\mathrm{w}} - kU\cos\beta = \omega_{\mathrm{w}} - \frac{\omega_{\mathrm{w}}^2 U}{g}\cos\beta \qquad (10)$$

where ω_{w} wave frequency, β heading angle which can be defined as the angle between the intended track of the ship and the direction of wave propagation (Figure 2.). Figure 3. shows the calculation procedure of ship response on harmonic waves.

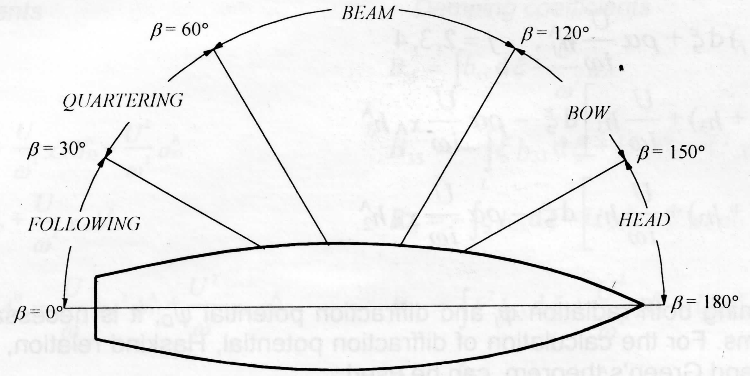

Figure 2. Heading angle definition

Slika 2. Definicija kursnog kuta

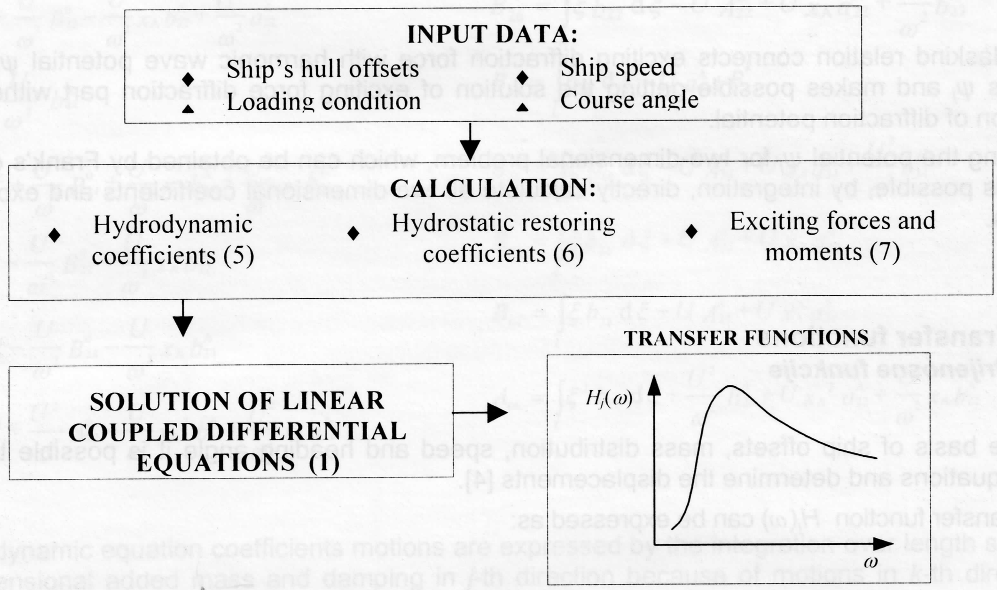

Figure 3. Ship response on harmonic waves calculation

Slika 3. Proračun odziva broda na harmoničnim valovima

Figures 4. and 5. show heave and pitch transfer functions for a container ship S175 advancing at speed of 22 knots with heading angle 120° in regular waves.

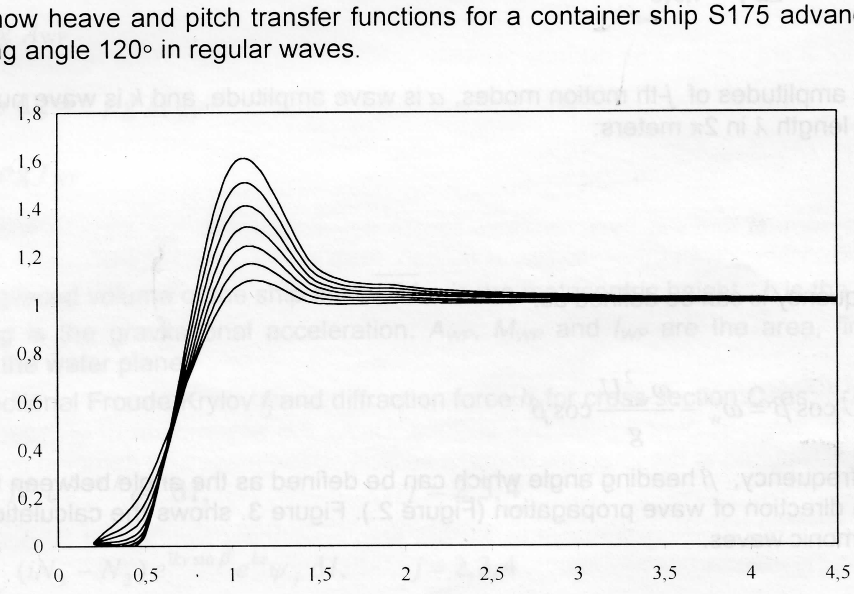

Figure 4. Heave transfer function

Slika 4. Prijenosna funkcija poniranja

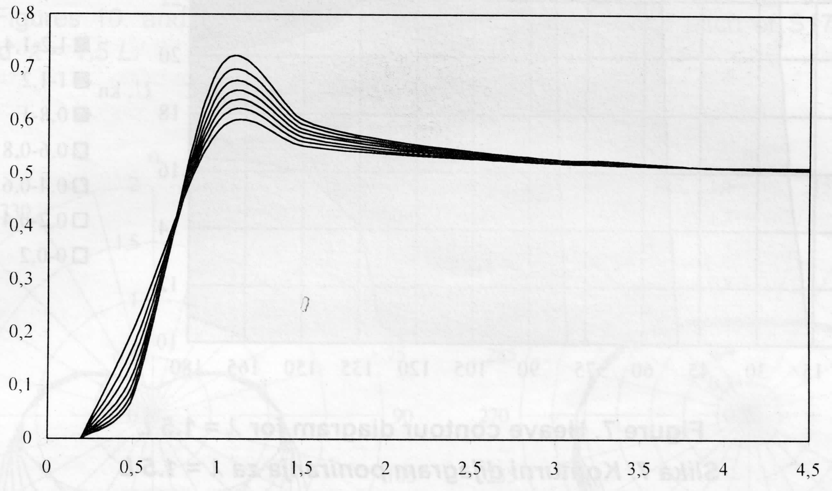

Figure 5. Pitch transfer function
Slika 5. Prijenosna funkcija posrtanja

3. Diagrams of unfavourable conditions for ship motion
Dijagrami nepovoljnih uvjeta za njihanje broda

Ship motions along with their associated effects, are known as dynamic effects [5, 6]. In general, dynamic effects in connection with ship motion can be listed as follows: shipping of green water, slamming, acceleration effects, speed loss and free racing. All effects can significantly affect the ship operability. The passengers and crew health, equipment and cargo safety, as well as structure local stress can be affected. At extreme conditions human lives and material goods can be jeopardised.

If the motion transfer functions are known for the range of ship speeds, heading angles and load conditions, the unfavourable combinations of speed and heading angle can be estimated for all wave lengths. From the transfer functions diagrams for one wave length it is possible to design three-dimensional diagrams which represent transfer function values at different speeds and heading angles. If those three-dimensional diagrams are intersected with the planes of constant transfer function value, we can get *contour diagrams*. Figures 6. to 9. show the heave and pitch contour diagrams of S175 ship for two different wave lengths.

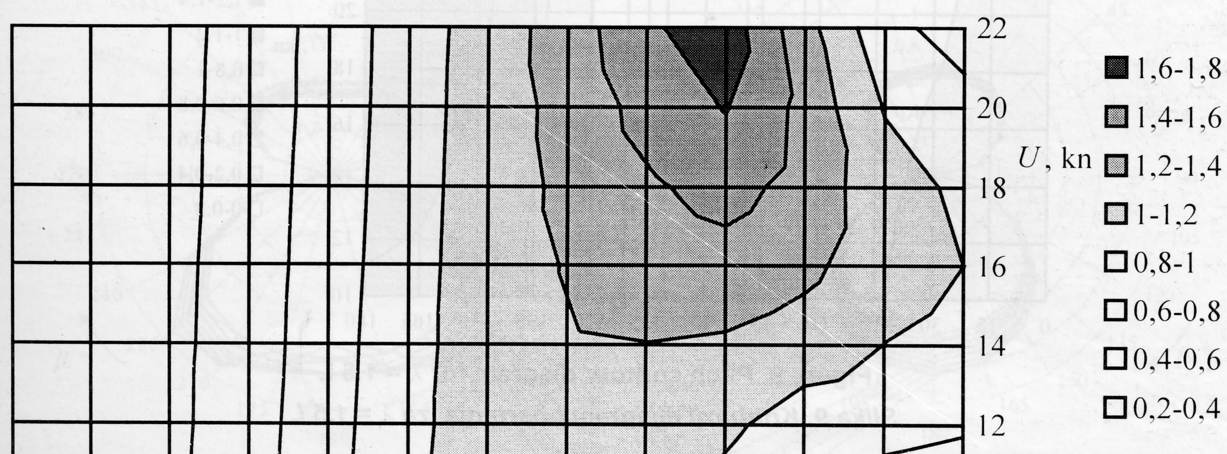

Figure 6. Heave contour diagram for λ = L
Slika 6. Konturni dijagram poniranja za λ = L

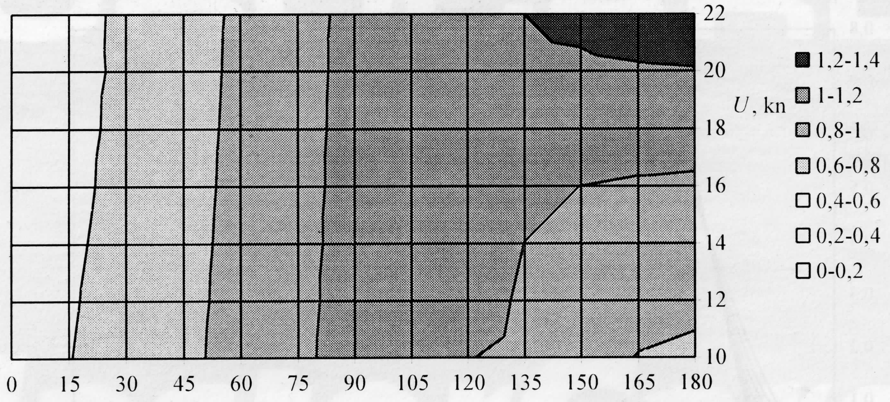

Figure 7. Heave contour diagram for λ = 1.5 *L*

Slika 7. Konturni dijagram poniranja za λ = 1.5 L

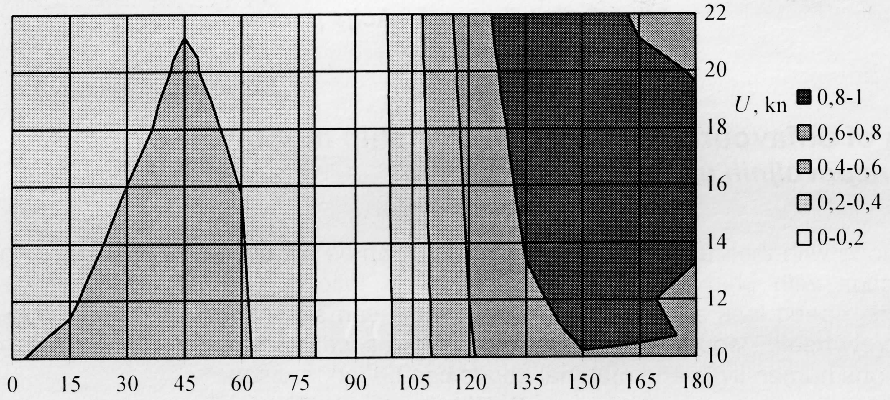

Figure 8. Pitch contour diagram for λ = *L*

Slika 8. Konturni dijagram posrtanja za λ = L

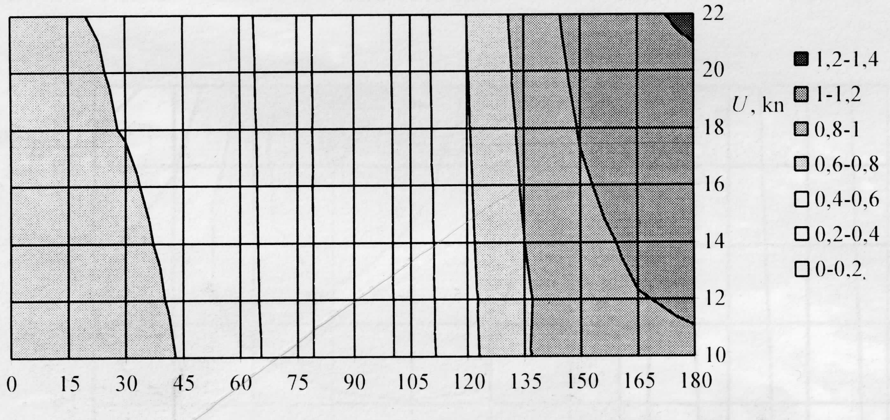

Figure 9. Pitch contour diagram for λ = 1.5 *L*

Slika 9. Konturni dijagram posrtanja za λ = 1.5 L

The corresponding ship speed and heading angle are related to each diagram point. Each pair of speed and angle is related to transfer function value for the corresponding motion mode, loading condition and wave length. By connecting diagram points of the same transfer function value, we can get corresponding contour plot. The darker zones mark the area of higher motion amplitudes. If the ship speed is constant, changing the value of heading angle can change the transfer function value. If the ship heading angle is constant, changing the value of speed can change the transfer function value. The diagrams are designed for the heading angle range from 0° to 180°. For the angles from 180° to 360° diagrams are mirror symmetric.

The values of transfer functions at the different speeds and heading angles can also be represented by polar diagrams. Figures 10. and 11. show polar diagrams of heave and pitch of S175 ship for two wave lengths: $\lambda = L$ and $\lambda = 1.5\,L$.

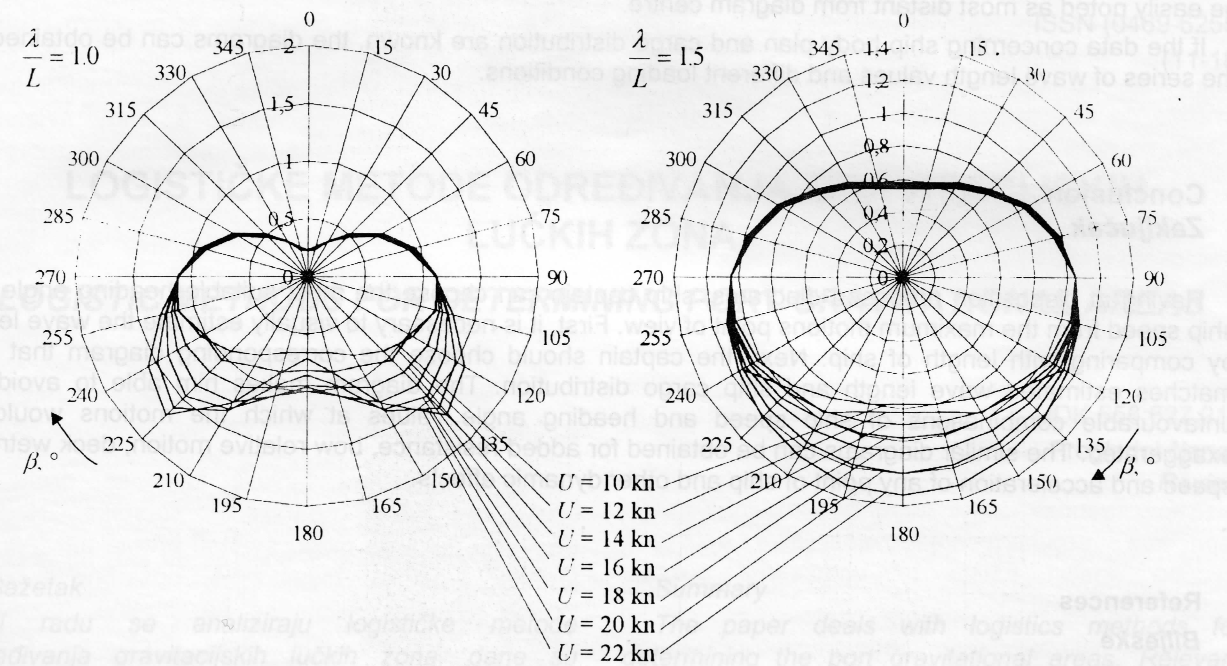

Figure 10. Have polar diagram

Slika 10. Polarni dijagram poniranja

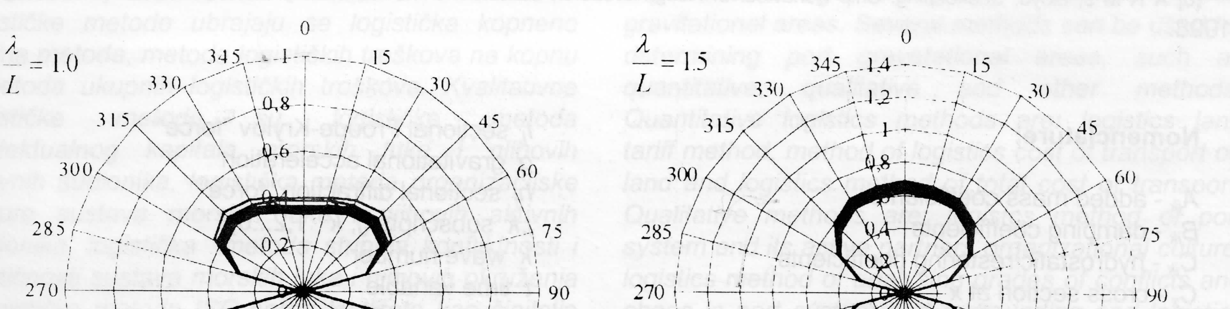

Figure 11. Pitch polar diagram

Slika 11. Polarni dijagram posrtanja

The concentric circles of polar diagram represent the values of transfer function for corresponding motion mode. Radial rays represent heading angles. Each diagram point is related to adequate heading angle and transfer function value. The values of transfer functions are calculated for the different ship speeds. The transfer function values obtained for particular speed are connected and form one closed curve. Analogously, the series of curves that corresponds to different speeds can be obtained. The areas of highest motions can be easily noted as most distant from diagram centre.

If the data concerning ship body plan and cargo distribution are known, the diagrams can be obtained for the series of wave length values and different loading conditions.

Conclusion
Zaključak

Having at disposition proposed diagrams, ship captain can choose the most suitable heading angle and ship speed from the maximum motions point of view. First, it is necessary to visually estimate the wave length by comparing with length of ship. Next, the captain should choose the corresponding diagram that best matches estimated wave length and ship cargo distribution. The diagram makes him able to avoid the unfavourable combinations of ship speed and heading angle values at which the motions would be exaggerated. The similar diagrams can be obtained for added resistance, bow relative motion, deck wetness, speed and acceleration of any point of ship and other dynamic effects.

References
Bilješke

[1] Salvesen, N., Tuck, E. O., Faltinsen, O., Ship Motion and Sea Loads, SNAME Transactions, vol. 78, 1970.

[2] Frank, W., Oscillation of Cylinders In or Below the Free Surface of Deep Fluids, NSRDC, Washington, D.C., Report 2375, 1967.

[3] Prpić-Oršić, J., Numerical Solution of Radiation Problem of Contemporary Slender Ship Forms, *Engineering Review*, Faculty of Engineering University of Rijeka, Vol. 14, Rijeka, 1994.

[4] Prpić-Oršić, J., Analysis of Ship Oscillation on Harmonic Wave, *Strojarstvo – Journal for the Theory and Application in Mechanical Engineering*, Croatian Union of Mechanical Engineers and Naval Architects, Vol. 39, No. 6, Zagreb 1997.

[5] Lewis, E., V., ed., Principles of Naval Architecture, Second Revision, The Society of Naval Architects and Marine Engineers, 601 Pavonia Avenue, Jersey City, NJ, 1989.

[6] A R M J, Lloyd, Seakeeping: Ship Behaviour in Rough Weather, Second Edition, ARJM Lloyd, Hampshire, United Kingdom, 1998.

Nomenclature:

A_{jk} - added mass coefficients
B_{jk} - damping coefficients
C_{jk} - hydrostatic restoring coefficients
C_x - cross section at x
F_j - exciting force and moment
F_n - Froude number
H_j - transfer function
I_{jj} - moment of inertia in jth mode
L - length between perpendiculars
M - mass of ship
U - ship speed
V - volume of displacement
a_{jk} - two-dimensional sectional added mass coefficients
b_{jk} two-dimensional sectional damping coefficients
f_j sectional Froude-Krylov "force"
g gravitational acceleration
h_j sectional diffraction "force"
j,k subscripts (j, k 1,2...6)
k wave number
t time variable
x, y, z - coordinate system
z_G - z-coordinate of gravity centre
α - wave amplitude
β - heading angle
η_j - displacements
λ - wave length
ρ - mass density of water
ω - encounter frequency
ω_w wave frequency

Rukopis primljen: 11.1.1999.