ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1138340

THE ANALYSIS OF EFFECTIVE ENERGY OF SHIP'S BERTHING TO THE QUAY

Wiesław Galor

Maritime University of Szczecin
Faculty of Navigation
Wały Chrobrego Street 1/2 , 70-500 Szczecin, Poland
tel.: +48 91 4809514, fax: +48 91 4809531
e-mail: w.galor@am.szczecin.pl

Abstract

The berthing of ship to the quay is last stage of navigation process. An ideal manoeuvre would be consisted in a total loss of speed at the moment the ship makes contact with the quay. In practice, the ship has some speed, which caused the impact of ship in the quay. The accident can be happened when kinetic energy overdone the admissible value during contact the ship-quay. In results, the damage of ship's hull or port structure can occur. The fenders improve the safety of berthing operations by partially absorbing the kinetic energy of ship. The fenders parameters should be properly selected relative to existing condition during ship's berthing. It depends on effective energy of berthing ship. There are used some method to calculate of its value. One of them is based on phenomena of ship turning relative to point of first contact to the quay. Then the part of ship's kinetic energy is altered to work of turn, and in result, energy of ship impact is decreased. This part can be determined by coefficient of eccentricy. Its value mainly depends on radius of ship's turning, which is equal of distance between point of ship, gravity and point of first contact with quay. Simplified method of calculation the eccentricy coefficient based on ships angle of approaching to the quay. But such estimated value is weighted some discrepancy. The paper presents the analysis of methods of calculation the kinetic energy during first impact in the quay. Especially, the geometrical shape of ship's hull is considered to achieve the accuracy value of ship's impact energy during the berthing to the quay. The application of elaborated method permits to optimize the parameters of fender system.

Keywords: *safety of navigation, ship's berthing, fenders*

1. Introduction

The marine navigation is the process of planning and leading the safe movement of ship from one place to another (port of destination).The main goal of navigation is to handle the ship in accordance with the aim of their movement when required parameters of this process should be retained. Realization of this goal depends on assurance of suitable level of ships safety during their manoeuvring in water area. The berthing manoeuvre of the ship to the quay is the last stage of that process (Fig. 1). An ideal manoeuvre would be consisted in a total loss of speed in the moment the ship makes contact with the berth. However, in reality, a dynamic ship's interaction takes place that causes a deformation and stress of the hull and the fender (when applied). The analyses of the manoeuvring tactics of the ship show that first contact of the ship is the most critical moment during berthing. The kinetic energy of the ship in the large part changes in the work of impact in the moment of the first contact of the hull with the berth. It depends on kinetic energy whether mooring will take place without the damages of ship and berth construction or not. It concerns all ships independently from their size, distance done or the kind of the cargo loaded. Therefore it applies to large vessels (bulk carriers, tankers) about the displacement of a few hundred thousands of tons, how and small barges, tugboats, passenger ships, the pleasure crafts (boats, motor boats, yachts) and others as well. Safe berthing is defined as such stop of the vessel near the berth so that losses do not happen. Reduction of the ship's speed to zero in the moment of impact to the quay would be the optimum way to avoid of the breakdown while berthing. It means that the kinetic

Fig. 1. The example of ship's berthing to Chorzowskie Quay in Port of Szczecin

energy of moving vessel is reduced to zero. Impact is the main reason of losses during berthing where either part or whole energy gives off in the area of contact ship – berth. This energy as the work can cause negative results. It requires special devices with the aim of the improvement of the safety of berthing operations, called fenders or fender systems. Fenders improve the safety of berthing operations by partially absorbing the kinetic energy of the ship. It consists in an elastic deflection (shape elasticity) of the material the ship is made of, and the energy of berthing turns into work of deflection. The fender absorbs a part of ship's kinetic energy. The remaining part of the energy is absorbed by the hull structure and the port structure [4].

The conditions of ship's safe berthing are as follows.

$$E \leq E_d \quad for \quad p \leq p_{dop}\,, \tag{1}$$

where:

E – ship's maximum kinetic energy absorbed by the berth-fender-ship,
E_d – ship's admissible kinetic energy absorbed by the berth-fender-ship,
p – maximum pressure of individual fender on ship's hull plating,
p_{dop} – admissible pressure of individual fender on ship's hull plating.

Admissible pressure of an individual fender on the ship's hull depends on her size and design. And according to the type of vessel (a general cargo carrier, a container ship, a tanker, a bulk carrier, a gas carrier) it can range from 200–700 kPa (kN/m^2) [7]. It is determined on the basis of the analysis of deflections during the stresses of the shell plating structure, which takes into account an adequate distribution of fender pressure on the shell, longitudinal girders, and frames. At the same time a phase of elasticity of ship's shell structure is assumed. There are situations in which work of deflection of a given part of the shell plating is taken into consideration and where a plastic strain in the form of dents of the shell is accounted for.

Factors, which have the influence on the size of the maximum kinetic energy of the ship's impact against the berth construction, are as follows:

- ship manoeuvrability (kind and the power of the propulsion, thrusters),
- hydrometeorological conditions (wind, current),
- tugs service (the number of tugboats, their power),
- the manoeuvring tactics (captain's or pilot's skill).

2. The energy of ship's berthing to the quay

An important phenomenon during the operation of ship's berthing is energy damping in water as a result of ship's turning. At a certain moment the ship touches the fender and its deformation takes place. Part of the kinetic energy changes then into work of reaction force related to a normal of the quay. For a maximum deformation the speed of ship's contact with the fender drops to zero. That part of energy, which as a result has been formed during the deformation of the fender, begins to change into a turn motion in relation to the contact point (Fig. 2).

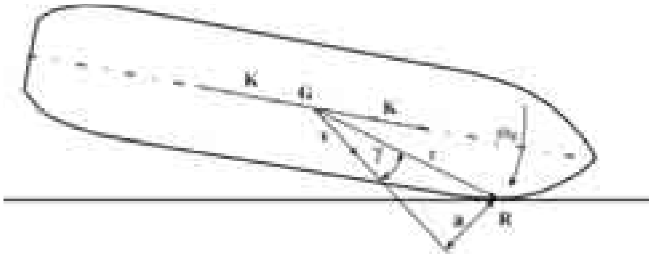

Fig. 2. Ship's impacting against the quay

It is expressed by gaining the angular velocity in relation to contact point, reaching the top value at the maximum deformation of the fender. Energy absorbed by the fender can be estimated from the difference of energy for the ship moving freely, prior to the first contact with the fender and the energy after the impacting (maximum deformation of the fender).The work done on the fender system from the beginning of contact until maximum deflection is reached can be evaluated as difference between the kinetics energy before and after impact. The dependence has been shown by F. Vasco Costa [8]:

$$E = \frac{m \cdot V^2}{2}\left(1 - \frac{a^2}{K^2 + r^2}\right) - m \cdot V \cdot \omega_0 \cdot \frac{K^2}{K^2 + r^2} + \frac{m \cdot \omega_0^2}{2} \frac{K^2 \cdot r^2}{K^2 + r^2}, \qquad (2)$$

where:
m – virtual ship's mass,
V – ship's linear velocity (translation),
a – the arm of ship's linear movement vector in relation to the point of contact R,
K – radius of moment of ship's mass inertia in relation to the point of gravity G,
r – distance between the point of gravity and the point of contact R,
ω_0 – ship's velocity of rotation before the impact.

Virtual ship's mass is equal of sum of ship' mass and mass of added water [2]:

$$m = m_s + m_w, \qquad (3)$$

where:
m_s – ship's mass,
m_w – mass of added water.

Ship's mass is calculated as:

$$m_s = L_{pp} \cdot B \cdot T \cdot \delta \cdot g_w, \qquad (4)$$

where:
L_{pp} – ship's length between perpendiculars,
B – beam of the ship,
T – ship's draft,
δ – ship's block coefficient,
g_w – density of water.

Mass of added water can be described as:

$$m_w = 0.25 \cdot \Pi \cdot T^2 \cdot L_{pp} \cdot g_w \text{ [kg]}, \qquad (5)$$

or as:

$$m = C_m \cdot m_s, \qquad (6)$$

where C_m is added water mass coefficient.

Added water mass coefficient C_m can be determined according to many dependencies. The most frequent are [2, 5]:

$$C_m = 1 + 2 \cdot \frac{T}{B} \cdot \qquad (7)$$

Above equation (2) gives the amount of kinetic energy of ship to be absorbed by fenders as function of:

– velocity of linear movement of ship,
– velocity of rotation before the impact to the quay.

In many causes there are not known both velocities. Then can be used the method of to determine effective energy of ship's berthing based on normal component to the quay of velocity vector [3].

3. The effective energy of ship's berthing

During ship's impact to the quay, the part of its kinetic energy has altered into the work of turning against of point of contact with fender. This part can be defined by eccentric coefficient [3, 5]. The rotating of the ship after impact into the fender takes place in relation to the point of contact (Fig. 3).

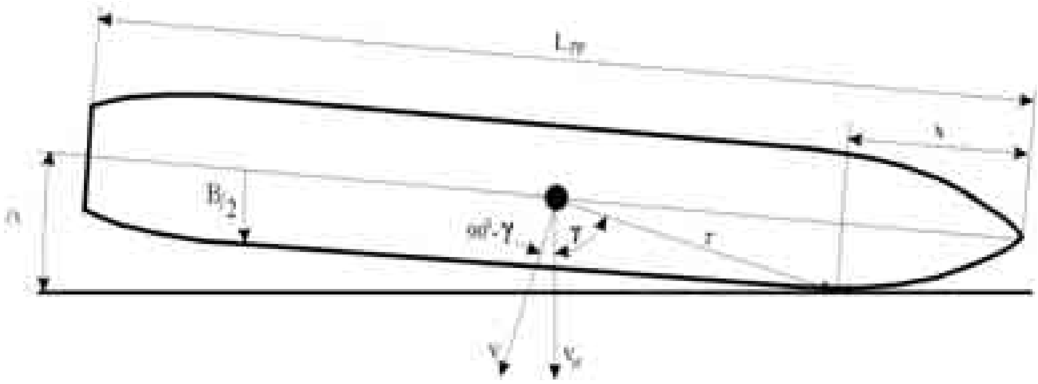

Fig. 3. The ship's berthing with normal component to the quay of velocity vector

For a maximum deformation the speed of ship's contact with the fender drops to zero. That part of energy, which as a result has been formed during the deformation of the fender, begins to change into a turn motion in relation to the contact point. Thus the effective energy E while berthing the ship to a port structure (bumping into the fenders) will equal :

$$E = E_K \cdot C_E , \qquad (8)$$

where:
E – effective energy of ship's impact the quay (fender),
E_K – kinetic energy before first contact,
C_E – eccentricity coefficient.

Coefficient of eccentricity can be defined as [6]:

$$C_E = \frac{K^2 + [r^2 \cdot \cos^2(\gamma)]}{K^2 + r^2} , \qquad (9)$$

where:
γ – an angle between the normal component of ship's velocity and the line crossing ship's gravity point and contact point with the fender

$$\gamma = 90° - \alpha , \qquad (10)$$

where:
α – ship's angle of approaching to the quay.

In many cases [8] the eccentricity coefficient is determined on the basis of a simplified relationship:

$$C_E = \frac{K^2}{K^2 + r^2}. \tag{11}$$

This simple formula conditioned value of coefficient on distance x (Fig. 3) of ship's hull contact from its bow. The estimated value is weighted some discrepancy. The value of coefficient contains in range 0.4–1.0 (Tab. 1) [6].

Tab. 1. Value of eccentricity coefficient for varying distance x of contact from the bow.

Distance x	C_E
$x = L_{pp}/4$	0.4–0.6
$x = L_{pp}/3$	0.6–0.8
$x = L_{pp}/2$	1.0

It should be noted that there is accurate dependence between the angle at which the ship approaches the berth and the location of the first contact point. The distance of that point to the bow depends on the curve radius of the ship's bow or the stern. Thus accuracy of distance between the ship's point of gravity and the point of contact with the quay decided about results of calculation of effective berthing energy.

4. The influence of ship's approaching to the quay on effective berthing energy

When analyzing the distance of the contact point from the bow or the distance of that point from the gravity centre [3, 5], it can be stated that the change of these values only occurs for a certain range of angles at which the ship approaches the berth (Fig. 4). The angle γ can achieved the value between zero and the maximal value, but not more then 90°. It will depend on ship's angle of approaching the quay. It should be taken into account that exist rigorous relationship between angle of ship's approaching the quay and position of first contact of impact. The distance of this point from bow perpendicular depends on radius of curve of bow or stern hull. The angle of ship's approaching the quay can change in interval from 0° up to 90°. To analyze the distance r between first point of ship's contact with fender and point of ship's centre of gravity, it can find that changing of its value occurs only for some range of angles of ship's approaching the quay α (0, α_N).

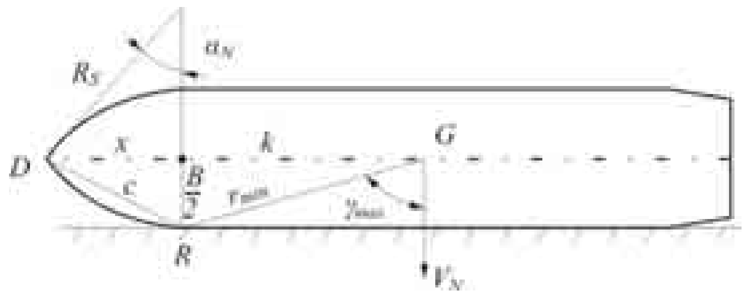

Fig. 4. Geometric parameters of ship's berthing

This distance r is called also as radius of ship rotation. Its value evolves from minimal magnitude $r_{\min}$ (for angle of approach $\alpha = 0°$) up to maximal magnitude $r_{\max}$ equals of distance between centre of ship's gravity and bow perpendicular – c.a. L_{pp}). For angles of approach in range from 90° up to same value α_N, the radius of ship's rotation has maximal and fixed magnitude. For angles less than α_N, the value of radius starts decreasing up to minimal magnitude for angle of ship's approaching the quay $\alpha = 0°$. The value of angle α_N will be called as specific value of angle of ship's approaching the quay. It can be calculated as:

$$\alpha_N = \arcsin\left(1 - \frac{B}{2 \cdot R_S}\right)[°], \tag{12}$$

where:
R_S – radius of ship's hull curves.
The minimal value of radius of ship rotation is equal:

$$r_{\min} = \sqrt{k^2 + \left(\frac{B}{2 \cdot R_S}\right)}, \tag{13}$$

where:
k – project of radius of rotation on ships diametrical [m]

$$k = \mathrm{DG} - x, \tag{14}$$

where:
DG – distance from point of ship's gravity to bow perpendicular,
x – the distance between points of ship's contact with fender and bow perpendicular projected on ships diametrical

$$x = \sqrt{c^2 - \left(\frac{B}{2}\right)^2}, \tag{15}$$

where:

$$c = R_S \cdot \sin\frac{\alpha_N}{2}. \tag{16}$$

The maximal value of angle $\gamma_{\max}$ between directions of minimal radius of ship rotation $r_{\min}$ (for angle of angle of ship's approaching the quay $\alpha = 0°$) and normal component of ships speed to the quay is equal:

$$\gamma_{\max} = \arcsin\frac{k}{r_{\min}}. \tag{17}$$

The angle γ will be achieved the value in range 0° to $\gamma_{\max}$ (but less than 90°).

5. The example of method application

The application of described method of eccentricity coefficient determination will be presented for three various dimensions of bulk carriers – A, B and C (Tab. 2). Main rule of that method is taking into account the shape of ship's hull, especially during the berthing when angle of approaching to the quay is grater the zero.

Tab. 2. The parameter of ship's berthing the quay

Ship	A	B	C
L_{pp}, [m]	150.8	202.0	254.3
B, [m]	17.2	22.4	32.3
δ, [–]	0.82	0.84	0.85
R_S, [m]	52.7	71.1	91.4
α_N, [°]	56.3	57.8	55.2
$r_{\min}$, [m]	49.7	68.6	87.3
$\gamma_{\max}$, [°]	80.19	80.97	79.38
C_E	0.401	0.383	0.377

The above presented results of calculations based on the developed method for calculating the coefficient of eccentricity, show that their values are smaller than 0.5. This means that the other method does not take into account changes in the shape of the hull causing overestimation ship's effective energy during berthing the quay.

6. Conclusions

The manoeuvre of ship's berthing is an important stage of the navigational process. During ships berthing the quay, the effective energy of ship's berthing decided on safety of ship manoeuvring. This energy as a part of kinetic energy of moving ship is absorbed by ship- fender-quay elements. The change of distance between the point of contact and the gravity centre (radius of ship's turning) which in many methods has been treated as a linear change in the function of the angle of approach to the berth, in fact varies in accordance with the radius of the curve of the hull making contact with the berth. The part of ship's kinetic energy is varied into a turn motion in relation to the contact point and mainly is determined by coefficient of eccentricity. There are used many methods of determining of eccentricity coefficient value. Practically recommended its value is greater than 0.5. The analysis of process of ship berthing the quay was carried out in paper and elaborated method of eccentric coefficient calculation permits to achieve the higher accuracy than other ones. The application of elaborated method of effective energy of ship's berthing the quay permits to optimize parameters of fender system. The application of elaborated method of effective energy of ship's berthing the quay permits to optimize the parameters of fender system.

7. References

[1] Galor, W., *Bezpieczeństwo żeglugi na akwenach ograniczonych budowlami hydrotechnicznymi.* Wyd. FRWSM Szczecin, 2002.

[2] Galor, W., *Analiza efektywnej energii dobijania statku do nabrzeża.* Zeszyty Naukowe nr 8(80) Akademii Morskiej w Szczecinie, Szczecin 2006.

[3] Galor, W., *Analiza zmian energii dobijania statku do nabrzeża dla różnych kątów podejścia.* Proceedings of the XII International Scientific and Technical Conference on Marine Traffic Engineering, Świnoujście 2007.

[4] Galor, W., *The modeling of buckling fenders to protect the ship berthing process.* Journal of KONES Powertrain and Transport. Vol. 14, No.3. Warsaw 2007.

[5] Galor, W., *The selected problems regard of ship's safety during berthing.* Monograph "Computer Systems Aided Science and Engineering Works in Transport, Mechanics and Electrical Engineering". TU Radom, No 121, 2008.

[6] *Guidelines for the design of fenders systems.* Supplement Bulletin PIANC. Brussels, 2002.

[7] Mazurkiewicz, B.: *Urządzenia odbojowe*, Studia i Materiały, Zeszyt nr 16, Wyd. KBM Politechnika Gdańska, Gdańsk 1991.

[8] Vasco, C. F., *Berthing manoeuvres of large ship*. The Dock & Harbour Authority. March 1968.