

# Analytical technique for ship-fender interaction

Autor(en): **Jiang, Chen-Wen / Janava, Richard C.**

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**Analytical Technique for Ship-Fender Interaction**  
**Méthode d'analyse de l'interaction navire-défense**  
**Analytisches Verfahren zur Untersuchung der Wechselwirkung von**  
**Schiffsstoßfängersystemen**

**Chen-Wen JIANG**  
Senior Ocean Engineer  
Giannotti & Assoc., Inc.  
Arlington, VA, USA



Chen-Wen Jiang, born in 1946, received his PhD from MIT, Cambridge, MA. He has been involved in R&D in the areas of dynamics and hydrodynamics of ocean vehicles.

**Richard C. JANAVA**  
Department Head,  
Giannotti & Assoc. Inc.  
Arlington, VA, USA



Richard Janava, born in 1942, received his MS from Brooklyn Polytechnic Institute, NY. He has been involved in the areas of static and dynamic analyses of ship structures, shock and vibration, survivability and fender performance.

#### **SUMMARY**

The design and selection of appropriate fender systems must consider the dynamic interaction between the ship and port or pier structure. An analytical technique is developed to study the dynamic interaction of marine fender systems expressed by generic algorithms with ship's hull structure. The frequency dependence of the hydrodynamic coefficients is considered in the form of a simplified convolution integral. The calculated values presented are compared with existing experimental and theoretical results.

#### **RÉSUMÉ**

La conception et le choix d'infrastructures appropriées de défense doivent prendre en considération l'interaction dynamique entre le navire et la structure du port ou des piliers. Une méthode d'analyse est ainsi mise au point pour étudier l'interaction dynamique de systèmes de défenses maritimes, exprimés à l'aide d'algorithmes génériques, avec la carène d'un navire. La dépendance de fréquence des coefficients hydrodynamiques est envisagée sous la forme d'une intégrale simplifiée d'enroulement. Les valeurs calculées présentées ici sont comparées aux conclusions d'expériences et aux résultats théoriques déjà connus.

#### **ZUSAMMENFASSUNG**

Bei der Konstruktion und der Auswahl geeigneter Stoßfängersysteme muß die dynamische Wechselwirkung zwischen Schiffen und Hafen- oder Pfeilerstrukturen berücksichtigt werden. Es wird ein analytisches Verfahren zur Untersuchung der dynamischen Wechselwirkung von Stoßfängersystemen in der Schifffahrt entwickelt, das sich durch artmäßige Algorithmen der Schiffsaußenwände ausdrückt. Die Frequenzabhängigkeit von den hydrodynamischen Koeffizienten wird in Form eines vereinfachten Faltungsintegrals berücksichtigt. Die dargestellten, errechneten Werte werden mit vorhandenen experimentellen und theoretischen Ergebnissen verglichen.



## 1. INTRODUCTION

In order to achieve more appropriately designed marine fender systems, an understanding of the vessel-fender dynamic interaction is essential. The dynamic analysis can describe more accurately the fender's energy absorption characteristics and operational performance requirements.

There are several approaches which consider the total energy of a berthing ship to be absorbed by the fender/pier system in addition to the magnitude of the fender reaction force generated. A simple and commonly used approach is the energy method; e.g., Lee [8], Broolsma et.al. [1]. Accurate predictions using this method involve knowledge of hydrodynamic coefficients and system stiffnesses for the total system. Empirical values are commonly used in this method. System damping has been ignored in this approach. Alternate statistical approaches consider information obtained from model measurements to determine the design energy value of the berthing impact and fender energy absorption; e.g., Svendsen [10]. With the design risk selected, the design value of the energy to be absorbed by the fender system can be determined. The disadvantage of this method is in obtaining the necessary statistical information for problem solution. Kim [5] proposes an approximate and simpler method. The idea is based on the use of time average of the kinetic energy of the berthing ship during the time interval of fender compression. This method is applicable only to the ship in calm water and berthing broadside.

The time domain solutions of forces and motions have been developed by van Oortmerssen [12] and Fontijn [3]. Both of these methods use Impulse Response Function techniques. It is easy to adopt different external forces and some other factors in the time domain method. The procedure presented herein is based upon a simplified convolution integral for added mass and damping calculations, which eliminates the disadvantage of the expensive calculation in the above time domain solutions. Although the mathematical problem is formulated herein in sway, yaw, surge and roll motions, only the lateral motion results are presented here. The hydrodynamic coefficients, as functions of frequency, can be determined theoretically using two-dimensional strip theory or three-dimensional source distribution method. In order to verify the current technique with Fontijn's results, the same hydrodynamic coefficients are used herein.

## 2. DYNAMIC RESPONSE OF THE SHIP AND THE BERTHING STRUCTURE

During the berthing, the ship will undergo dynamic motion which has six degrees of freedom; namely, swaying, yawing, rolling, surge, heave and pitch. The heave and pitch motions are of little consequence in energy dissipation and may be neglected. In the following analysis, it is assumed that there is no sliding contact along the fender's surface. Also, the coupling effects between each mode have been neglected.

Consider the dynamic equilibrium of the center of gravity of the ship as shown in Figure 1. The equations of motion are:

$$(m_k + a_k) \ddot{x}_k + b_k \dot{x}_k = f_k \quad k = 1, 2, 4, 6 \quad (1)$$

where  $x_1$ ,  $x_2$ ,  $x_4$  and  $x_6$  are the surge motion ( $x$ , positive forward), sway motion ( $y$ , positive to port), roll motion ( $\phi$ ), and yaw motion ( $\theta$ ), respectively. The  $m_k$ ,  $a_k$  and  $b_k$  are inertia mass, hydrodynamic mass and hydrodynamic damping in the corresponding directions.  $f_k$  represents the external fender reaction force on the ship in the  $k$  direction.

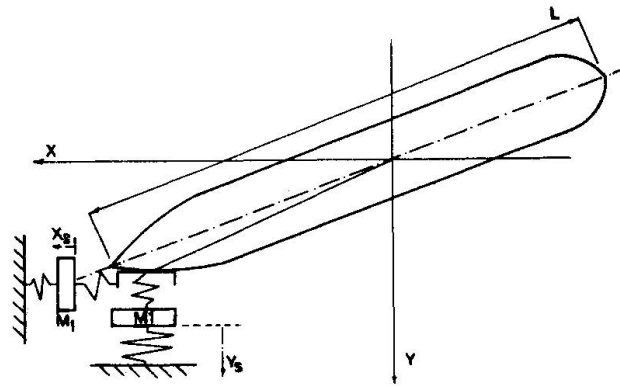


Fig. 1 Definition Sketch of Plan Section

For the berthing structure with the effective mass,  $M_s$ , the dynamic equations are:

$$M_s \ddot{x}_s + \mu_x \dot{x}_s + k_x x_s = -f_1 \quad (2)$$

$$M_s \ddot{y}_s + \mu_y \dot{y}_s + k_y y_s = -f_2 \quad (3)$$

where  $K_{x,y}$  and  $\mu_{x,y}$  are the structure stiffness and damping, respectively. The displacement of the point of contact can be calculated after the dynamic equations (1) to (3) are solved.

If the elastic deformation of the ship hull is under consideration, let  $K_h$ , and  $S_h$  and  $\mu_h$  define the stiffness, deflection and the damping coefficients of the hull at the point of contact respectively. The equations of motion of the ship hull are:

$$M_h \ddot{S}_{hx} + \mu_{hx} \dot{S}_{hx} + K_{hx} S_{hx} = f_1 \quad (4)$$

$$M_h \ddot{S}_{hy} + \mu_{hy} \dot{S}_{hy} + K_{hy} S_{hy} = f_2 \quad (5)$$

In the case of a very rigid berth, the deflection of berthing structure can be neglected due to the high stiffness of the structure. The effects of the ship's local stiffness can be investigated with this method.

The solution of dynamic equations is carried out by the numerical integration method with appropriate choice of problem parameters.

### 3. HYDRODYNAMIC MASS AND DAMPING

The hydrodynamic mass and damping are important parameters to be considered in the determination of the berthing forces. The hydrodynamic mass is governed by the following factors:

- Ship characteristics (beam, draft, size)
- Under-keel clearance
- Water depth



- Type of berthing structures (open, semi-open, solid)
- Fender characteristics
- Berthing modes
- Berthing velocity.

Most of the methods to determine the hydrodynamic characteristics do not take into account all of the above-mentioned factors. A recent review by Kray [7] has presented a good summary of the state-of-the-art on hydrodynamic mass determination. The most common practice is to have a constant added mass as presented by Vasco Costa [13], Komatsu and Salman [6]. Hayashi and Shirai [4] presented a theoretical formulation of ship added mass in shallow water as a function of the ratio of draft to water depth, the Froude number of the ship and the coefficient of head loss of the counter flow under the hull. Oda [9] conducted experiments to verify their theory. In order to have better agreement in very shallow water berthing, Oda modified the theory by neglecting the shear stress acting on the hull and also used a friction parameter as a function of sway force coefficient, contraction coefficient and water depth to draft ratio. The theory modified by Oda will be used to compare with the existing experiments and present method.

The constant added mass coefficient is not appropriate for berthing of ships in shallow water with different berthing speeds. van Oortmerssen [12] and Endo [2] calculated the hydrodynamic characteristics of ship as function of frequencies in the shallow water based on a three-dimensional approach. Comparisons have been made with the results for cases available in the literature. Generally speaking, the agreement is good. In the study by Fontijn [3], the two-dimensional hydrodynamic characteristics at low frequencies were modified to fit the experimental data. Time histories of fender force in Fontijn's paper compared well with the present method.

#### 4. MATHEMATICAL METHOD

As mentioned earlier, a basic difficulty arises in the time domain solution dealing with the frequency-dependent hydrodynamic coefficients. The force derived from drag and added inertia is a complex function of ship movement at each given frequency. The time history of a force denoted by  $f(t)$  can be described by means of the convolution integral as:

$$f(t) = \int_{-\infty}^t K(t-\tau) y(\tau) d\tau \quad (6)$$

where  $y(\tau)$  is the time history of the ship motion, e.g., sway. The Kernal function  $K(t)$  is the Fourier transformation of the complex transfer function of  $F(\omega)$  with respect to the ship motion, which is given by:

$$K(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) e^{i\omega t} d\omega \quad (7)$$

This procedure has been used in a number of investigations to obtain the histories of forces, e.g., Fontijn [3] and van Oortmerssen [12].

In the present application, the convolution operation is implemented by digital computation in a different manner. Tou [11] has shown that, for a single input sinusoidal frequency of amplitude  $a$ , the instantaneous value of the output time sequence,  $f(n\Delta t)$ , can be predicted by a weighted sequence of  $n$  previous time history steps as follows:

$$f(n\Delta t) = a \sum_{m=1}^n w_m \sin [\omega(n-m)\Delta t] \quad (8)$$

where:

$w_m$  = weighting coefficients

$\Delta t$  = time interval

However, the instantaneous values of this function can also be given in terms of an input sinusoid as:

$$f(n\Delta t) = |F(\omega)| a \sin (\omega n\Delta t + \alpha) \quad (9)$$

Where  $\alpha$  is the phase angle of the output relative to the input. Equations (8) and (9) set equal to each other give a single equation relating the transfer function,  $F$ , to the weighting coefficients,  $w_m$ , for a given frequency  $\omega$ . When dealing with inputs containing a number of frequencies, this method leads to a set of simultaneous equations for the value of  $w_m$  in terms of the values of the transfer function at each frequency. These equations can be solved by using a least squares approach for a set of weighting coefficients,  $w_m$ . When applying this method, the operation is over the past time history of the ship motion. The convolution integral is then replaced by a truncated summation:

$$f(n\Delta t) = \sum_{m=1}^n w_m y[(m-n)\Delta t] \quad (10)$$

After the evaluation of the added inertia force and drag force, the differential equations are solved by Runge-Kutta step-by-step integration procedure.

## 5. RESULTS

The analytical technique described herein has been applied to the case in Fontijn's paper [3]. The main dimensions of the ship used in the model are: waterline length = 2.438 m, beam = 0.375 m, draft = 0.15 m, block coefficient = 1.0, ship mass = 137.24 kg, water depth = 0.2 m. The added mass and damping coefficients were determined by Fontijn using ship theory three-dimensional effects on the low frequency range. The same hydrodynamic coefficients are used in order to have a fair comparison. Two types of fenders are considered: a linear fender of constant stiffness,  $k_1$ , equal to 140 kg/m, and a nonlinear fender force represented by  $k_1\Delta y_f + k_2(\Delta y_f - d_f)$ , in which  $k_1 = 64$  kg/m,  $k_2 = 113$  kg/m,  $d_f = 0.00664$  m and  $\Delta y_f$  is the deflection of fender.

Figure 2 shows the comparison between present method with Fontijn's calculated and measured fender forces as a function of time. This analytical method gives good agreement with the experiment. Hydrodynamic coefficients have great influence on the fender response. The use of the existing results is the first step in the development of this method. The nonlinear fender stiffness is calculated for the same ship in Figure 3. Theoretically, the program has been formulated to accept characterization of any fender system for the calculation of energy absorption. Various generic fender system algorithms have been developed which will be part of further program development.

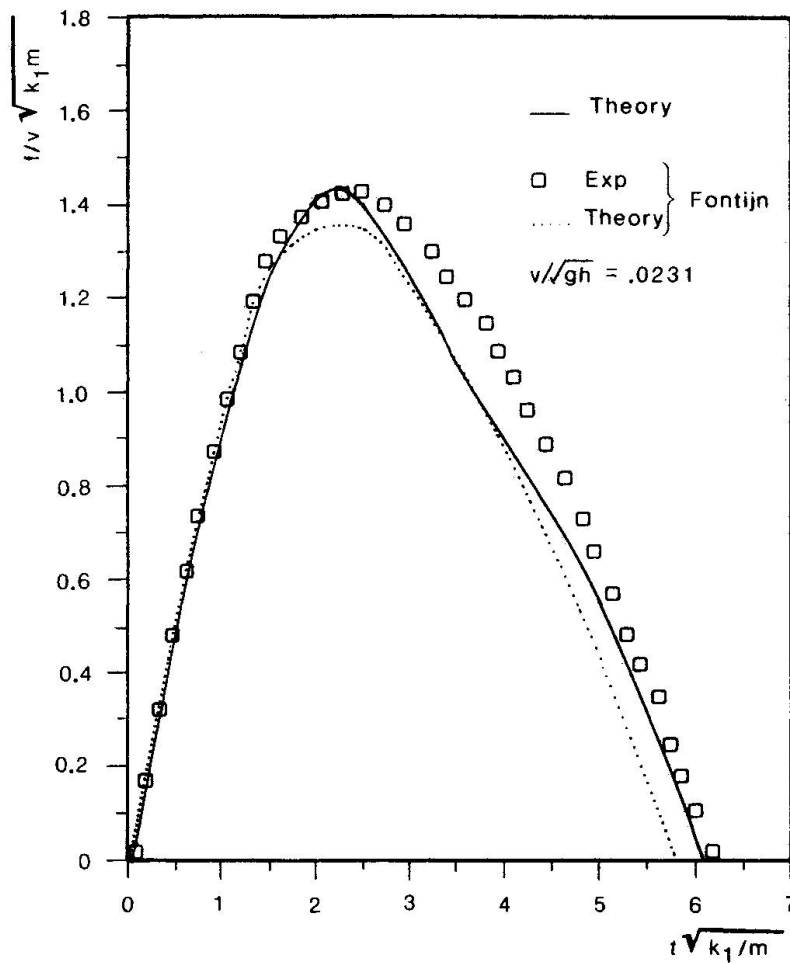


Fig. 2 Time History of Fender Force: Linear Fender

Hayashi and Shirai's method [4] is considered a simple way to calculate the added mass coefficient. They took into account the shallow water, ship speed and characteristics. That method was modified by Oda [9] to have a better agreement with experiments. Based on the modified theory, fender force on the same model used in this paper is presented in Figure 4. The approaching phase shows better agreement than the detaching phase; Oda shows the similar behavior in his results.

## 6. CONCLUSIONS

The frequency dependence of the hydrodynamic coefficients can be easily represented by a simplified convolution integral. This method has good agreement with existing theory and experiment. The hydrodynamic coefficients significantly affect the vessel-fender interaction. More experimental and theoretical studies are needed in order to include additional environmental effects. This method provides a means of analyzing the dynamic ship/fender problem in a simplified cost-effective manner.

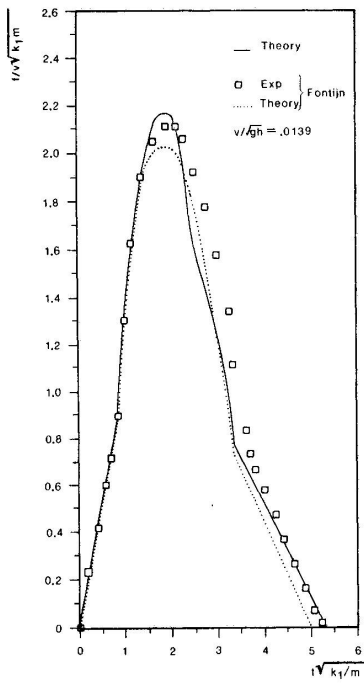


Fig. 3 Time History of Fender Force: Nonlinear Fender

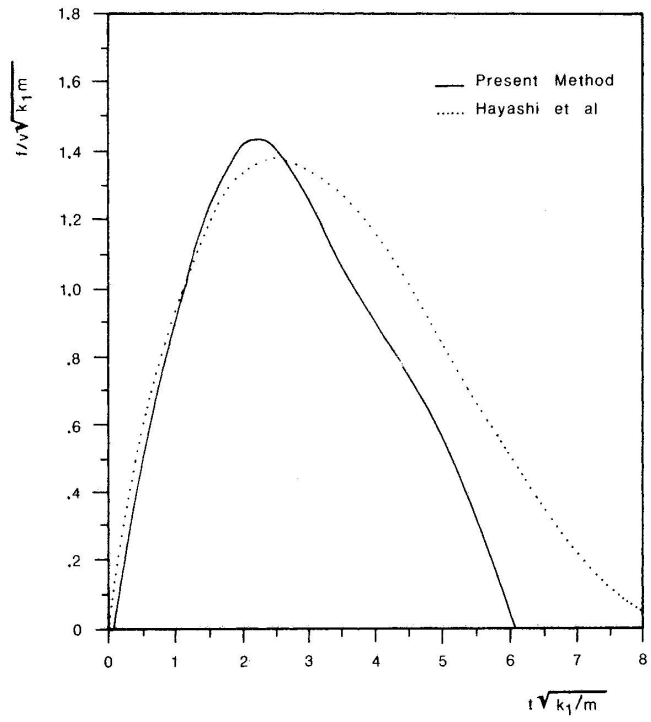


Fig. 4 Time History of Fender Force: Comparison





## 7. ACKNOWLEDGEMENTS

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