Journal of
Marine Science and Technology

Volume 20 | Issue 2 Article 11

SLAMMING INDUCED DYNAMIC RESPONSE OF A FLOATING STRUCTURE

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Recommended Citation

Lotfollahi-Yaghin1, Mohammad Ali; Rastgar, Mehdi; and Ahmadi, Hamid (2012) "SLAMMING INDUCED DYNAMIC RESPONSE OF A FLOATING STRUCTURE," *Journal of Marine Science and Technology*: Vol. 20: Iss. 2, Article 11.
DOI: 10.51400/2709-6998.1839
Available at: https://jmstt.ntou.edu.tw/journal/vol20/iss2/11

Journal of Marine Science and Technology, Vol. 20, No. 2, pp. 201-209 (2012)

SLAMMING INDUCED DYNAMIC RESPONSE OF A FLOATING STRUCTURE

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Key words: floating structure, modal analysis, slamming, finite element method.

ABSTRACT

Study of the slamming phenomenon is one of the most important branches of the floating structure dynamics. Experimental study of the floating structure dynamics can be very expensive because it requires a long wave flume and a moving model. Hence, numerical methods are considered to be very useful and efficient tools for modeling and dynamic analysis of floating structures. In the present paper, slamming induced impulsive loads are investigated firstly. Afterwards, dynamic response of a barge under the slamming excitation is studied, and the natural frequencies and mode shapes are determined, using the FE software package, ANSYS. Critical cross sections of the structure corresponding to the maximum stresses are determined and the effect of the float speed and the hull stiffness on the shearing force and bending moment along the longitudinal axis of the structure are investigated.

I. INTRODUCTION

In order to understand the behavior of floating structures under various environmental conditions, study of dynamic responses of the structure subjected to different types of environmental excitations such as wind, waves, and currents can be very useful. Several methods are available for studying the floating structure dynamics. Experimental techniques are useful but also are normally very expensive because they require a long wave flume and a moving model. An alternative method is deriving the closed-form solution for the dynamic equations of motion which is a time consuming and sometimes impractical process. Hence, the use of numerical methods such as the finite elements seems inevitable.

In general, the motion of a floating structure due to the sea waves has six degrees of freedom. The vertical transition and the rotation around the transverse axis are called the heave and pitch motions, respectively. Combination of these motions and the water surface fluctuations can lead to the occurrence of slamming phenomenon which is one of the most destructive phenomena for ships. Designers and constructors of floating structures are always trying to decrease the slamming induced damages [12]. Wave slam results form the sudden immersion of a structure in the water during the passage of the wave. When a horizontal member in a structure is placed near the mean water level, there will be occasions when it will be alternately in water and air as the waves pass it. If the axis of the member is parallel to the wave crest the member will experience sudden impact or slamming loads as the wave comes up underneath it. This sudden load will often sufficient to excite the member at its natural frequency and the fatigue life of its joints will be significantly affected [6]. In the case of floating structures, this phenomenon occurs when a part of the structure which is outside the water due to severe water surface fluctuations, return towards the water and immersed again. The period and the height of the waves which can produce the slamming are varied for different structures. For example, short waves are not able to produce slamming in long structures [9]. The magnitude of the slamming induced loads is difficult to calculate, but experimental evidence suggests that it is of the order of 2-3 times the wave induced drag force. It is the function of the wave amplitude [12]. There are usually two types of barge motion due to storm waves. These simultaneous motions are the heave which is vertical transition of the barge and the pitch which is the rotation of the barge around its transverse axis. These oscillations are amplified when particular waves hit the barge. The characteristics of these specific waves depend on the barge length [1]. In the structural design of ship hulls, an estimation of slamming loads is important to avoid substantial damage on the fore body. For instance, the probability of slamming on the fore part of high-speed vessels in rougher seas is significantly high and therefore, wave impacts can damage the bow [3].

In the present paper, slamming induced impulsive loads are investigated firstly. Afterwards, dynamic response of a floating structure under the slamming excitation is studied and the natural mode shapes and frequencies are obtained, using the FE software package, ANSYS. Critical cross sections of the structure corresponding to the maximum stresses are determined and the effect of the float speed and the hull stiffness on the shearing force and bending moment along the longitudinal

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Paper submitted 06/10/09; revised 11/02/10; accepted 12/23/10. Author for correspondence: Mohammad Ali Lotfollahi-Yaghin (e-mail: lotfollahi@tabrizu.ac.ir).

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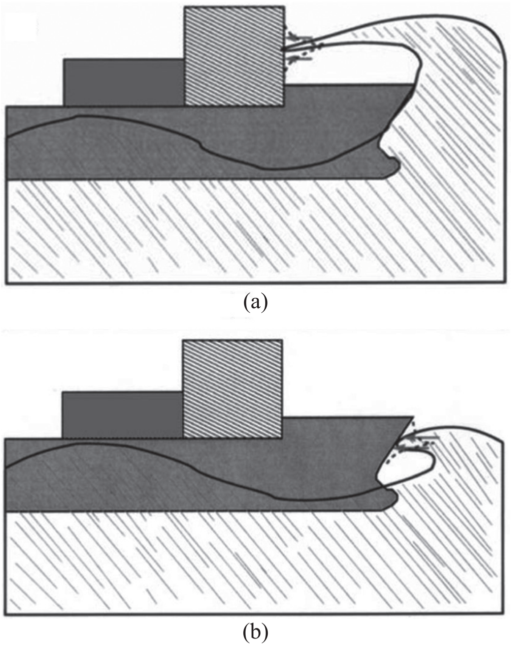


(a)

(b)

Fig. 1. (a) Green water slamming, (b) Bow-stem slamming [4].

axis of the structure are investigated.

II. LITERATURE REVIEW

Because of the practical importance of the slamming study in shipbuilding engineering, several investigations have been carried out. The former work is due to Von Karman [13] who developed an asymptotic theory for flat impact problems with linearized free surface and body boundary conditions. The impact load on a sea plane during landing was estimated by the force on a two dimensional wedge upon entry into calm water, neglecting the water surface elevation.

Slamming on ships is often categorized as bottom, bow-flare, bow-stem and wet-deck slamming [4]. Green-water impact on deck structures and bow-stem slamming are of concern for Floating Production Storage and Offloading (FPSO) units, as sketched in Fig. 1 [5].

Morris [10] carried out a three-dimensional finite element model structural analysis, using NASTRAN finite element package, of the entire hull and superstructure of a large aluminum alloy wave-piercing catamaran. Quasi-dynamic analysis was used to identify field and concentrated stresses within suitable global and local structural models. Loading patterns were applied according to Lloyd's.

Case studies on the state-of-the-art computer simulation and modeling techniques, using I-DEAS Master Series mechanical aided engineering software, applied on the design of INCAT's large wave piercing aluminum catamarans was presented by Yakimoff [14]. The author highlights the importance of the use of sophisticated computer techniques to prove new concepts, improving safety and to quickly optimize structures of this kind of vessels.

Hughes [7] presented a strategy for achieving first principles optimum structural design of a ship, using MAESTRO finite element software. The author highlighted the dramatic structural weight saving that can be achieved by using composite materials (13% of the total displacement of a 100 m length mono-hull fast ferry).

Ojeda *et al*. [11] created a full, 3-D shell element, model of a small composite catamaran using ANSYS 6.0. The SHELL99 3-D and MASS21 are used for modeling. The applications of two quasi-static slamming load cases according to the DNV HSLC rules, hollow landing and crest landing, were studied. Both load cases were solved under a static linear approach using ANSYS 6.0. Deflection and stresses along the hull are studied to check the integrity of the vessel structure.

III. CALCULATION OF SLAMMING INDUCED PRESSURE

Following equations have been proposed by Bishop [1] for the calculation of slamming induced pressure exerted on a floating structure:

$$P_{SL} = 162\sqrt{L}.C_1.C_{SL}.C_A\left(\frac{1-C_{RW}}{2}\right) \quad L \le 150\ m \qquad (1)$$

$$P_{SL} = 1984\,(1.3-0.002L).\,C_1.C_{SL}.C_A\left(\frac{1-C_{RW}}{2}\right) \quad L > 150\ m \qquad (2)$$

where L is the length of the float and the unit is KN/m^2. The coefficient C_{RW} is the range of service which has a maximum value of 1.0 and C_I is calculated by the following equation:

$$C_1 = 3.6 - 6.5\left(\frac{T_b}{L}\right)^{0.2} \qquad (3)$$

where T_b is the maximum ballast in meters. The coefficient C_A is defined as:

$$C_A = \frac{10}{A} \qquad 0.3 \le C_A \le 1 \qquad (4)$$

where A is the area of the loaded surface in m^2. Slamming induced pressure distribution factor C_{SL} is determined as follows:

$$C_{SL} = 0 \qquad x/L \le 0.5 \qquad (5)$$

$$C_{SL} = \frac{(x/L)-0.5}{C_2} \qquad 0.5 < x/L \le 0.5 + C_2 \qquad (6)$$

$$C_{SL} = 1 \qquad 0.5 + C_2 < x/L \le 0.65 + C_2 \qquad (7)$$

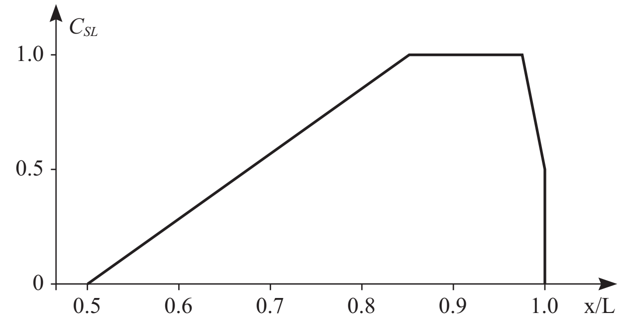


Fig. 2. Useful chart for calculation of pressure distribution factor C_{SL}.

$$C_{SL} = 0.5\left(1+\frac{1-(x/L)}{0.35-C_2}\right) \qquad x/L > 0.65+C_2 \tag{8}$$

The coefficient C_2 is:

$$C_2 = 0.33C_B + \frac{L}{2500} \le 0.35 \tag{9}$$

where C_B is the blockage factor and its maximum value is 0.6. Fig. 2 can be used to determine the distribution factor C_{SL}.

The forces exerted on the float resulting from the slamming induced pressures are impulsive in nature and have high frequencies. Theoretical pattern of these impulsive loads can be considered triangular. Exertion of these triangular impulses on the floating structure leads to producing large flexural moments and shearing forces along the longitudinal axis of the structure.

IV. NUMERICAL SIMULATION

1. Theoretical Aspects and General Considerations

A floating structure such as a barge can be considered as a free beam lying on the surface of the water and its reactions are the functions of water surface fluctuations. In the other words, the water can be modeled as an elastic bed for the barge. In the present research, a barge with box shaped cross section is studied. Mechanical and geometrical properties of the considered barge are presented in Table 1.

Table 1. Mechanical and geometrical properties of the studied barge.

Length	50 *m*
Width	10 *m*
Height	5 *m*
Wall thickness	5 *cm*
Modulus of elasticity	2100000 kgf/cm^2
Poison's ratio	0.3
Mass density	0.0078 kg/cm^3

The equilibrium of the barge is established providing that the buoyant force balances the weight of the barge. Since the buoyant force is equal to the weight of the displaced water, hence the barge draft can be easily calculated using equilibrium equations. In the present study, the sea water is replaced by a system of springs lying under the barge. The stiffness of these springs depends on the shape of the barge's cross section. The stiffness of springs can be assumed to be constant for the barges with rectangular cross sections. In the other words, the springs are considered to be linear. Initial calculations are presented in Table 2.

Table 2. Initial calculations.

Area of the cross section	14900 cm^2
Moment of inertia	710624167 cm^4
Mass of the barge	581100 *kg*
Barge draft	116 *cm*
Buoyant force	5689800 *N*
Total stiffness of the spring system	4905000 *N/m*
Stiffness of an individual middle spring	49050 *N/m*
Stiffness of the first and the last springs	24525 *N/m*

Total stiffness of the spring system can be determined through dividing the buoyant force by the draft of the barge. One hundred springs have been used to simulate the elastic bed replacing the sea water. Since the barge length is 50 meters, the distance between the elements becomes 50 centimeters. The stiffness of an individual middle spring can be obtained through dividing the total stiffness of spring system by 100. The stiffness of edge springs is half of the middle ones'.

2. Finite Element Modeling and Analysis of the Floating Structure

Finite elements based software package ANSYS is used for the numerical simulation of the barge. The utilized elements are *Beam 2D* and *Combin 40*. The element *Combin 40* consists of a linear spring including the gap property and a dashpot. When the barge moves upward, no considerable tensile force is exerted by water on the structure. Hence, the springs must not be under the tension during the upward movement of the barge. The gap property of the *Combin 40* element leads to detachment of the springs from the barge in such conditions.

The weight of the structure is a permanent load and plays an effective role in establishing the equilibrium of the barge. Hence, at the beginning of any analysis and before simulating the slamming conditions, sufficient time must be consumed until the oscillations of the springs are decayed and the barge becomes equilibrated. This initial equilibrium time is considered 50 seconds for all analyses. When the equilibrium is completely established and the barge displacement becomes equal to 116 centimeters, the slamming phenomenon must be simulated.

To simulate the slamming induced triangular impulses and the resulting displacements on the barge, two powerful loops of ANSYS, **Do…*End do* and **If…*Then…*End if*, are used.

Table 3. Natural frequencies and periods of the considered model.

Mode No.	Period (sec)	Frequency (Hz)
1	2.164	0.462
2	2.16	0.463
3	2	0.503
4	1.387	0.721
5	0.853	1.172
6	0.61	1.641

After defining the physical and geometrical characteristics of the model, the loop **Do* starts generating the time history of the exerted force at all nodes while the **If* loop controls the impulsive loads to be triangular. The analysis process is finished when the force in the middle node equals to zero. After this moment, the barge oscillates freely and the oscillations are gradually decayed due to the damping of the system which consequently leads to stable equilibrium of the barge. After running the simulation, *Post 26* processor of ANSYS is used to create the charts showing the change of the responses by the time at different sections along the barge. The studied responses are the flexural moment and the shearing force.

V. RESULTS AND DISCUSSION

1. Results of Modal Analysis

Determination of the natural frequencies and mode shapes are very useful to investigate the dynamic behavior of the structure. Floating structures such as ships and barges experience numerous dynamic loadings. Results of the modal analysis performed on the considered barge including the natural frequencies and mode shapes are presented in Table 3 and Fig. 3, respectively.

The first natural mode is the pitch motion which is the rotation of the barge around the transverse axis. The second natural mode is the heave motion which is the vertical transition of the barge. It can be seen that the frequencies of these two modes are very close. The third natural mode is the first flexural mode. This mode is excited when either the hogging or the sagging occurs. The fourth natural mode is the second flexural mode. This mode is usually excited when the slamming occurs. The fifth natural mode is the third flexural mode. This mode is excited if at least one of the following conditions exists [2]: (a) The frequency of the incident wave is high; (b) The floating strucutre is long; (c) The sagging and hogging occur at two symmetric points on the floating structure. The sixth natural mode is the first longitudinal deformation mode which is the result of horizontal wave component.

2. Time History and the Spectral Density of the Internal Forces

Six degrees of freedom can be generally defined for the motion of a barge due to the incidence of sea waves. The heave

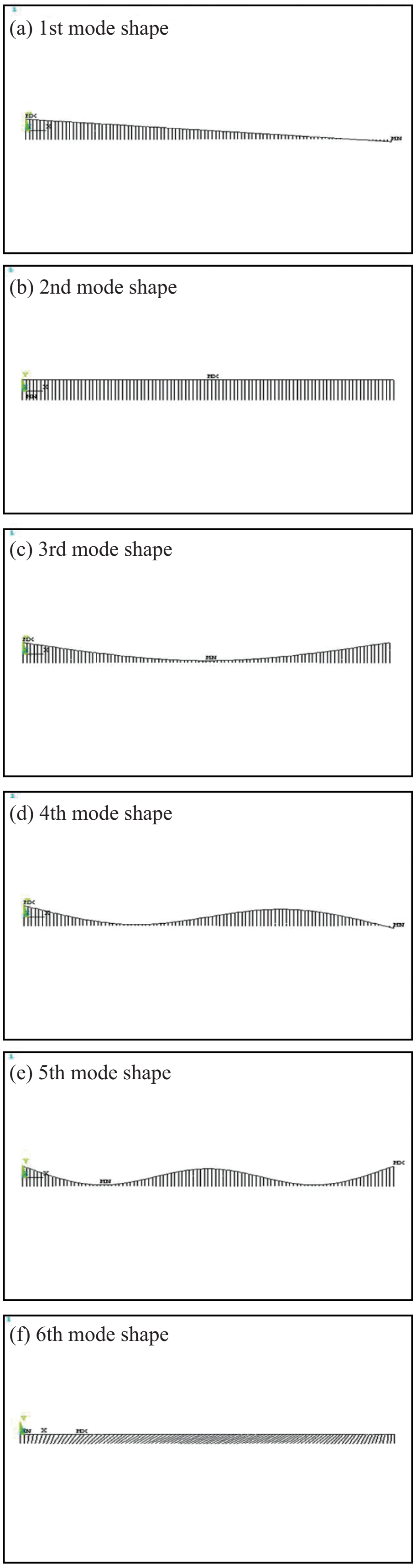
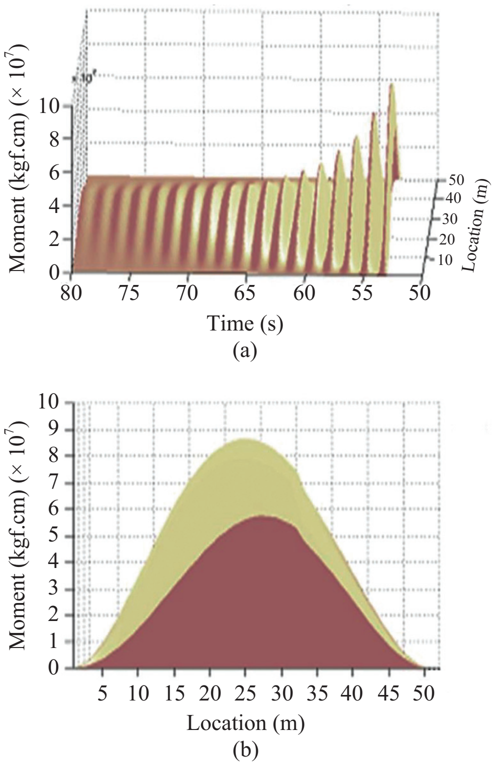


Fig. 3. First six mode shapes of natural vibration.



(a)

(b)

Fig. 4. Diagram of the flexural moment along the axis of the barge: (a) 3D moment-location-time diagram, (b) 2D moment-location diagram at two different times.

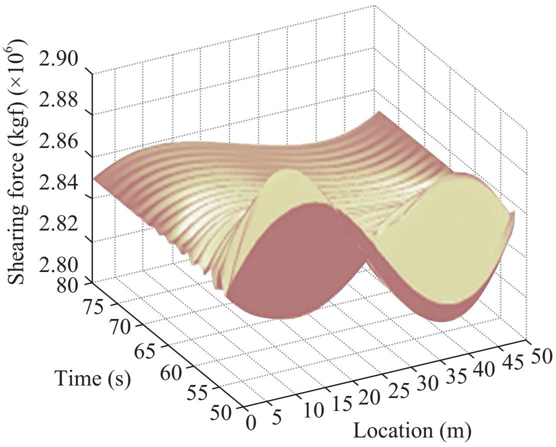


Fig. 5. 3D Diagram of the shearing force along the axis of the barge.

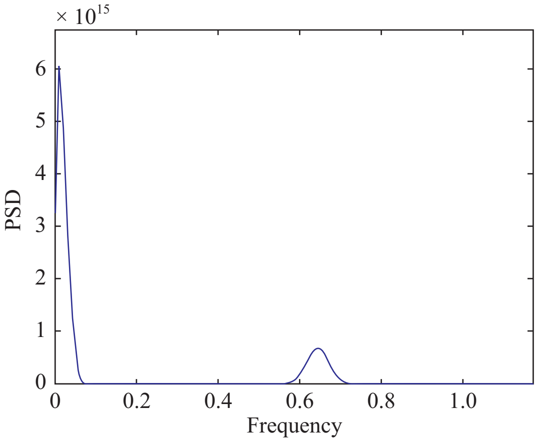


Fig. 6. The power spectral density (PSD) of the flexural moment.

and pitch motions are two dominant degrees of freedom. The combination of these two types of motion with the fluctuations of the barge on the water surface leads to the occurrence of slamming which can cause major structural damages in a floating strucutre. Designers and constructors of ships and barges are always trying to control this phenomenon and reduce the induced damages.

In the present research, the locations of maximum slamming induced internal forces have been determined. Two charts are presented in Fig. 4 showing the time history of the produced flexural moment at different sections along the longitudinal axis of the barge. Similar charts are presented in Fig. 5 for the internal shearing force.

It can be concluded from Fig. 4 that the maximum flexural moment is produced at the middle cross section of the barge and maximum shearing forces are produced at the cross sections located in one-fourth of the barge length.

The power spectral density (PSD) of the flexural moment is extracted using MATLAB (see Krauss [8]) and presented in Fig. 6. It can be seen that when the slamming occurs, the fourth natural mode shape is excited which is the second flexural mode of the barge's oscillation.

3. Effect of the Barge Speed on the Produced Internal Forces

One of the most important parameters affecting the intensity of slamming induced impulsive forces is the barge speed. The slamming induced damages can be reduced through restricting the speed of the barge to a specific range. To study the effect of the barge speed on the maximum flexural moment, different values are assigned to the barge speed from 10 m/s to 100 m/s in increments of 10 m/s.

Three examples for the time history of the maximum flexural moment are presented in Fig. 7 for different values of the barge speed. In the proceeding sub-section, it was indicated that the maximum flexural moment is produced at the middle cross section of the barge. According to Fig. 7, it can be concluded that the maximum flexural moment is ascending at the barge speeds up to 50 m/s and if the speed becomes higher than 50 m/s, the maximum flexural moment is reduced again.

Similar time histories are presented in Fig. 8 for the maximum shearing force. In the proceeding sub-section, it was indicated that the maximum shearing forces are produced at the cross sections located in one-fourth of the barge length. It can be concluded from Fig. 8 that the maximum shearing force is ascending at the barge velocities up to 30 m/s and if the speed becomes higher than 30 m/s, the maximum shearing force is reduced again.

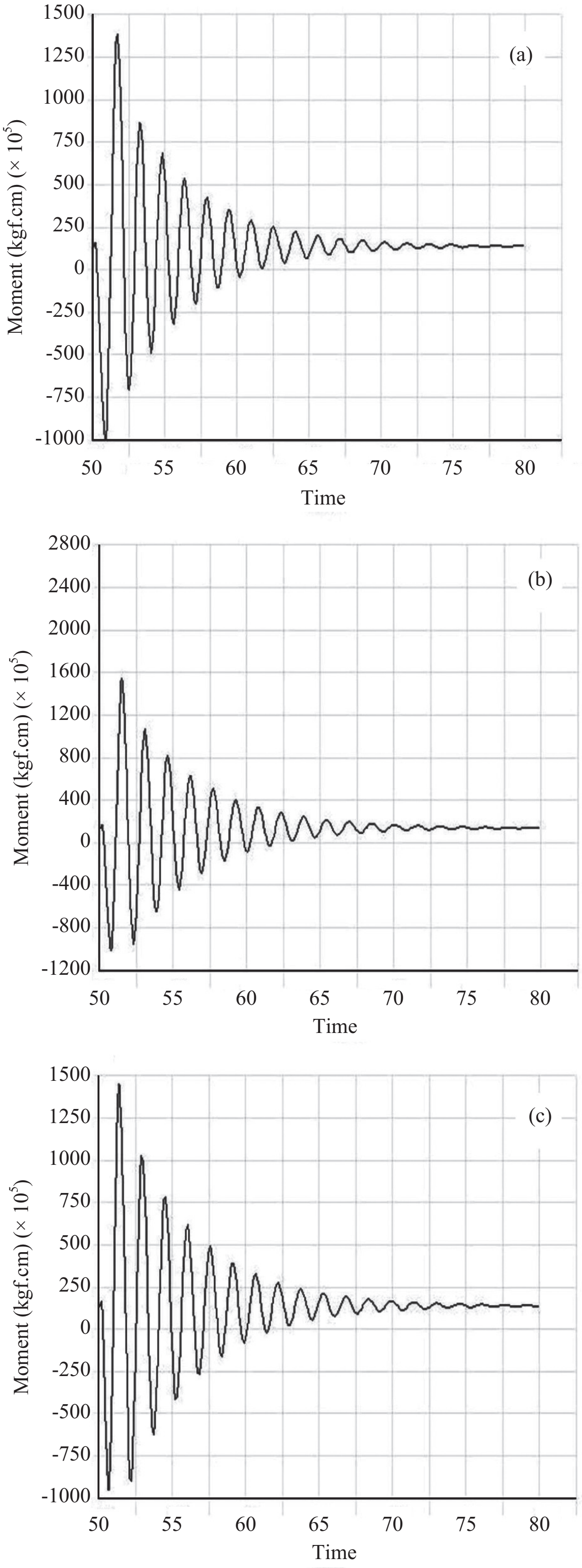


Fig. 7. Temporal change of the maximum flexural moment for different barge speeds: (a) 40 m/s, (b) 50 m/s and (c) 60 m/s.

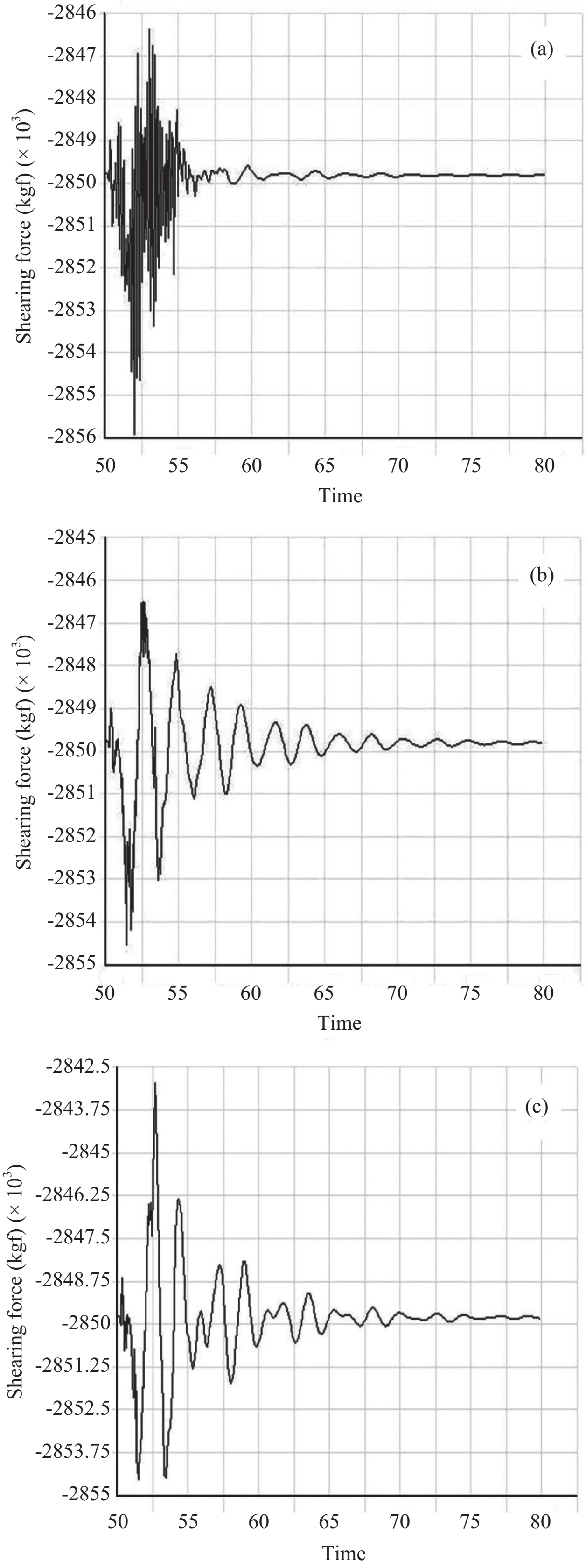


Fig. 8. Temporal change of the maximum shearing force for different barge speeds: (a) 20 m/s, (b) 30 m/s and (c) 40 m/s.

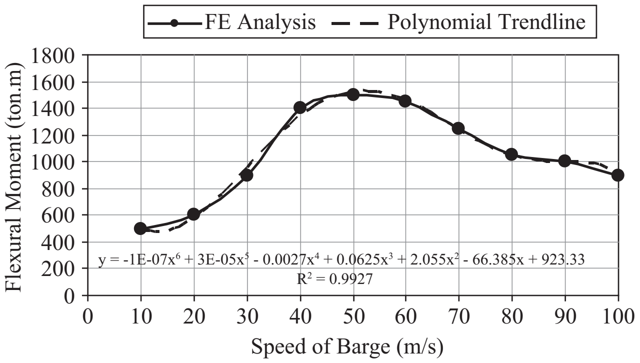


Fig. 9. The relationship between the maximum flexural moment and the speed of the barge.

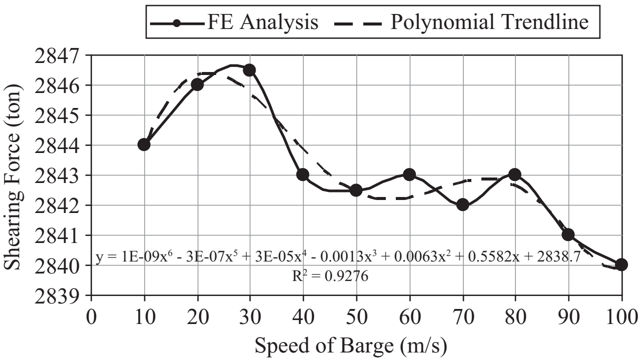


Fig. 10. The relationship between the maximum shearing force and the speed of the barge.

The relationship between the barge speed and the maximum produced internal forces are shown in Figs. 9 and 10. Fig. 9 shows the relationship between the maximum flexural moment and the barge speed and Fig. 10 shows the relationship between the maximum shearing force and the barge speed. It can be concluded from Figs. 9 and 10 that when the barge speed is 50 m/s, the highest maximum flexural moment is produced, and in the higher speeds, the flexural moment is reduced again. When the barge speed is 30 m/s, the highest maximum shearing force is produced, and it is reduced when the speed is increased. Hence, in order to reduce the slamming induced damages, the barge speed must be reduced in storm conditions. Since the speeds higher than 50 m/s are usually out of reach, hence increasing the speed in order to reduce the internal forces is impractical.

4. Effect of the Barge's Hull Stiffness on the Produced Internal Forces

The stiffness of the barge's hull is the function of the barge's length, the geometric shape of the cross section and the mechanical properties of the construction materials. It is clear that the amount of the produced internal forces in iso-static structures is independent from the stiffness of the structure. However in hyper-static structures, the stiffness of the structure affects the produced internal forces.

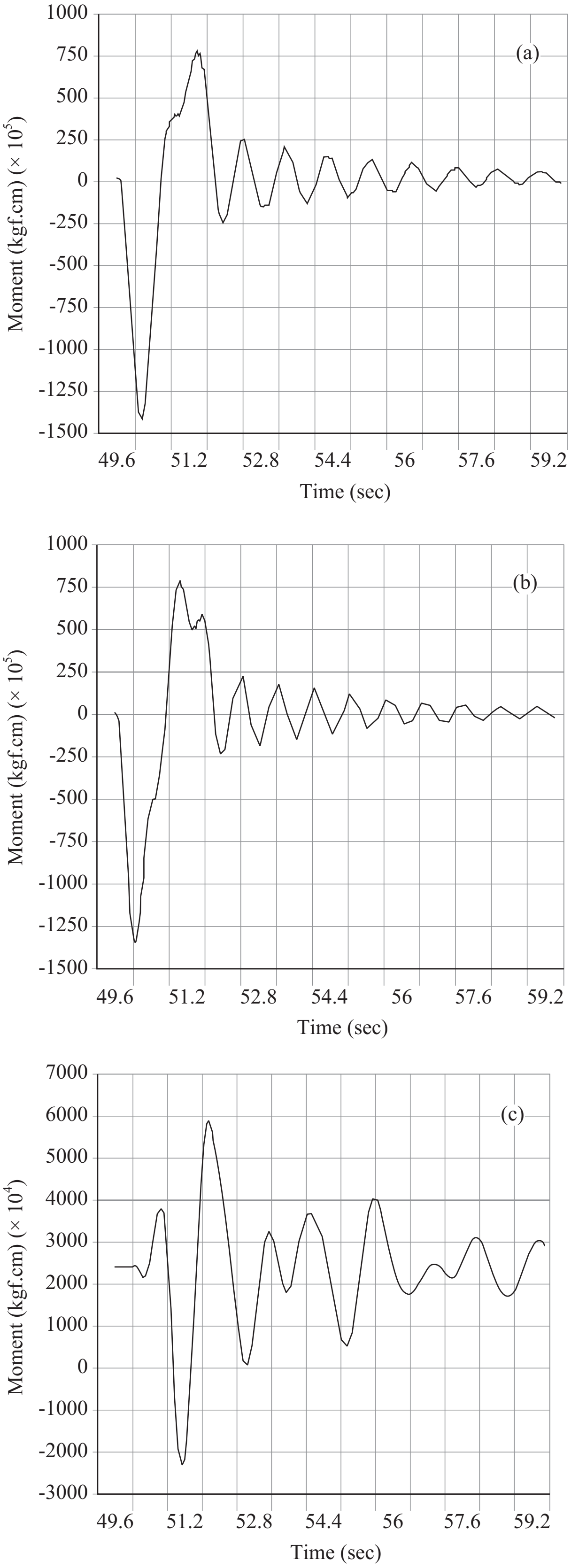


Fig. 11. Temporal change of the maximum flexural moment for different stiffness multiplication factors (MFs): (a) MF = 0.1, (b) MF = 10 and (c) MF = 100.

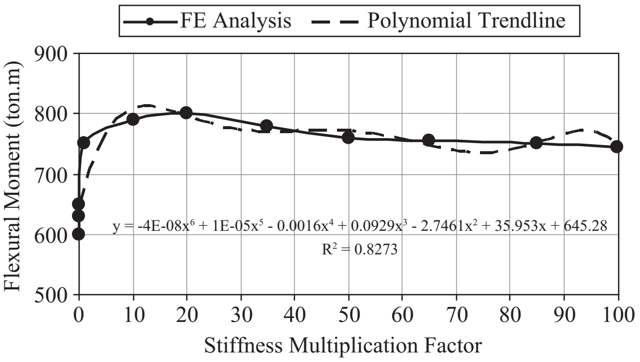


Fig. 12. The relationship between the maximum flexural moment and the stiffness of the barge.

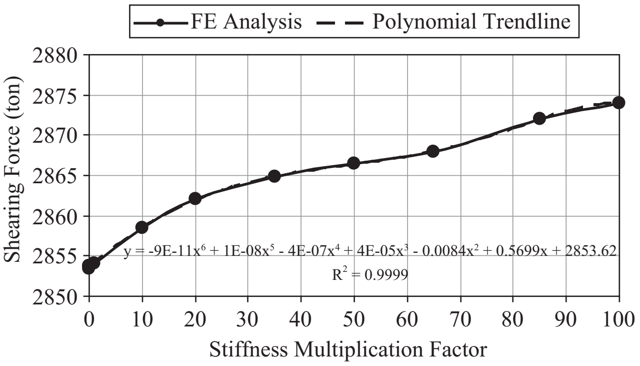


Fig. 13. The relationship between the maximum shearing force and the stiffness of the barge.

In this sub-section, in order to study the effect of the stiffness of barge's hull, the temporal changes of the maximum flexural moment and the shearing force for different values of stiffness are investigated. In order to change the stiffness of the barge's hull, the moment of inertia has been changed from 1% to 100 times of the existing value (710624166 cm^4). Some examples are presented in Fig. 11.

The relationship between the barge stiffness and the maximum produced internal forces are shown in Figs. 12 and 13. Fig. 12 shows the relationship between the maximum flexural moment and the barge stiffness and Fig. 13 shows the relationship between the maximum shearing force and the barge stiffness. Through curve fitting and eliminating the higher order terms which are quite small, it can be seen that the relationship between the stiffness and the maximum shearing force is approximately linear. Also there is a third order relationship between the stiffness and the maximum flexural moment. If the relationships between the stiffness and the response forces are given, the design of suitable stiffener to reinforce the critical sections will be convenient.

VI. CONCLUSIONS

In the present paper, dynamic response of a barge subjected to the slamming excitation was studied and the natural mode shapes and frequencies were obtained, using the FE software package, ANSYS. Critical cross sections of the structure corresponding to the maximum stresses were determined and the effect of the barge speed and the hull stiffness on the shearing force and bending moment along the structure's longitudinal axis were investigated. The concluding remarks regarding the considered model can be summarized as follows:

1. When the slamming occurs, the maximum flexural moment is produced at the cross section located in 0.5*L* and the maximum shearing force is produced at the cross sections located in 0.25*L* and 0.75*L*, where *L* is the barge length.
2. The slamming excites the fourth natural mode shape of the barge's vibration which is the second flexural mode.
3. One of the most important parameters affecting the intensity of slamming induced impulsive forces is the barge speed. In the studied barge, when the speed is 50 m/s, the highest maximum flexural moment is produced, and in the higher speeds, the flexural moment is reduced again. When the barge speed is 30 m/s, the highest maximum shearing force is produced, and it is reduced when the speed is increased. Hence, in order to reduce the slamming induced damages, the barge speed must be reduced in storm conditions. Since the speeds higher than 50 m/s are usually out of reach, increasing the speed to reduce the internal forces is impractical.
4. For the studied barge, the relationship between the stiffness of the hull and the maximum shearing force is approximately linear. Also there is a third order relationship between the stiffness and the maximum flexural moment. If the relationships between the stiffness and the response forces are given, the design of suitable stiffener to reinforce the critical sections will be convenient.

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