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The energy flow analysis in stiffened plates of marine structures

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Abstract

The transmission of vibrational energy flow in stiffened plates is analyzed by the structural intensity method. Three typical cases for ship and marine structures are selected as examples: a plate with one longitudinal stiffener under lateral area pressure excitation, a longitudinally stiffened plate under point force excitation, and a cross-stiffened plate under inplane pressure excitation. The relationships between structural intensity and structural mode shapes and the effects of stiffeners on the changes of energy flow in plate are discussed. Finally, the potential application of structural intensity technique towards the design for stiffened plates of marine structures is explored and presented.

Keywords: Energy flow; Stiffened plate; Structural intensity; Finite element method

1. Introduction

Marine vehicles are always subjected to external dynamic loading with various excitation frequencies, from slowly varying wave loads to relatively high frequency main engines and propeller induced forces. Generally speaking, when the frequencies of the external forces are close to one of the natural frequencies of the structural components in ship hull, the permissible vibration levels may be exceeded, which may result in fatigue failure in the structure, destruction of electronic and mechanical equipment or very high noise level. Since stiffened plates are most commonly used built-up structural elements in marine vehicles, which form the

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backbone of ships, appearing in decks, bottoms, bulkheads, and side shell, the damage of stiffened plates will result in the collapse of overall system structures. An increasingly popular approach to undertake ship hull ultimate strength analysis is to consider the failure of the individual stiffened plates and combine these to determine the failure load of the entire hull cross-section.

Structural intensity is the power flow due to structural vibration per unit cross-sectional area in elastic medium and it is analogous to acoustic intensity in a fluid medium. The interest on investigation of structural intensity arises for practical reasons, because structural intensity field indicates the magnitude and direction of vibrational energy flow at any point of a structure, and energy flow distribution offers information of energy transmission paths and positions of sources and sinks of mechanical energy. Dissipative elements, mechanical modification and active vibration control can be used for an alteration of energy flow paths within the structure and the amount of mechanical energy injected into the structure. Of primary practical concerns are complex built-up structures, which can be successfully treated only by measurements or by numerical computation when prediction of structural behavior in various operating conditions is needed. For these reasons, the investigation of energy flow paths in stiffened plates is very important to the response and damage detection for overall ship hull structures.

The present paper is concerned with energy transmission in a plate, which is stiffened by a series of parallel and crossed stiffeners with different spacing and geometry. This situation can be likened to vibration transmission along a section of a ship hull. Using structural intensity techniques, the detailed description of the transmission pattern of vibrational energy flow from the source of excitation to the sink through structures as well as the energy exchanges between plates and stiffeners can be obtained. The computational method for structural intensity is illustrated and formulas of structural intensity for beams and plates and their relationship of force and strain are given in Section 2. These formulas will be used in the post-processing for structural intensity calculations for stiffened plates in using the finite element full method for obtaining harmonic response solution. A number of numerical examples which are linked to those on ship and marine structures are presented in Section 3, where the comparisons are made with different calculation conditions and the effects of stiffeners on structural intensity are analyzed. The relationship between structural intensity and structural mode shapes as well as the changes of energy flow in plate for the existence of stiffeners are discussed. Finally, the potential application of structural intensity technique in ship and marine engineering is explored and presented.

2. Theoretical background

2.1. Instantaneous and net structural intensity

Vibrational power flow per unit cross-sectional area of a dynamically loaded structure is defined as the structural intensity. The net energy flow through the structure is the time average of the instantaneous intensity and the intensity at point in the ith-direction can be defined as [1]:

$$I_i = \langle I_i(t) \rangle = \langle -\sigma_{ij}(t) v_j(t) \rangle, \quad i,j = 1,2,3 \tag{1}$$

where $\sigma_{ij}(t)$ and $v_j(t)$ are the stress and velocity in the jth-direction at time t.

For a steady state vibration, the ith-direction of active structural intensity inside an elastic body in a frequency domain is given by

$$I_i(\omega) = -\frac{1}{2}\mathrm{Re}(\tilde{\sigma}_{ij}(\omega)\tilde{v}_j^*(\omega)), \quad i,j = 1,2,3 \tag{2}$$

where $\tilde{\sigma}_{ij}(\omega)$ is the complex amplitude of the Fourier transform of stress $\sigma_{ij}(t)$ and $\tilde{v}_j^*(\omega)$ is the complex conjugate of the Fourier transform of the velocity $v_j(t)$.

2.2. Formulation for beams and plates

Integration of the structural intensity over the cross-section of a beam gives the total net energy flow in the beam. Since a beam is a one-dimensional element, the energy flows along the centerline of the beam. In a single case, the velocities can be replaced by displacements by using the commonly adopted complex algebra. The formulation of structural intensity in beams can be expressed as follows [1]:

$$I_x = -(\omega/2)\,\mathrm{Im}[\tilde{N}\tilde{u}^* + \tilde{Q}_y\tilde{v}^* + \tilde{Q}_z\tilde{w}^* + \tilde{T}\tilde{\theta}_x^* + \tilde{M}_y\tilde{\theta}_y^* + \tilde{M}_z\tilde{\theta}_z^*] \tag{3}$$

where $\tilde{N}$ is complex axial force, $\tilde{Q}_y$ and $\tilde{Q}_z$ are complex transverse shear force, $\tilde{T}$ is complex torque, $\tilde{M}_y$ and $\tilde{M}_z$ are complex bending moments, $\tilde{u}^*$, $\tilde{v}^*$ and $\tilde{w}^*$ are complex conjugate of translational displacements, $\tilde{\theta}_x^*$, $\tilde{\theta}_y^*$ and $\tilde{\theta}_z^*$ are complex conjugate of rotational displacement along x, y and z directions (see Fig. 1). Im denotes an imaginary part.

An analogous approach can be used for plate and shell elements. Since stresses and displacements are usually determined as stress results and movements of the mid-surface and the integration is carried out over the thickness, the structural intensity in the plates and shells can be expressed in the form of power flow per unit width. Besides flexural deformations of the plate, the membrane effect is also considered in the formulation of structural intensity. As the plate and shell elements are two-dimensional, the energy may flow in the local x and y directions.

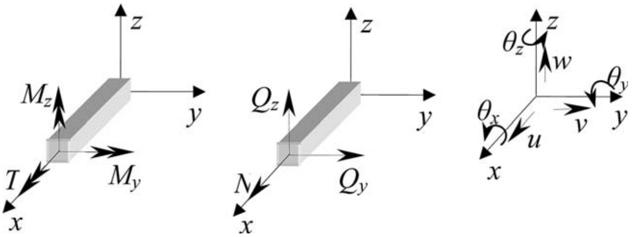

Fig. 1. Forces and displacement for beam element.

The x and y components of the structural intensity for a vibrating flat plate can be expressed as

$$I_x = -(\omega/2)\,\mathrm{Im}[\tilde{N}_x\tilde{u}^* + \tilde{N}_{xy}\tilde{v}^* + \tilde{Q}_x\tilde{w}^* + \tilde{M}_x\tilde{\theta}_y^* - \tilde{M}_{xy}\tilde{\theta}_x^*] \tag{4}$$

$$I_y = -(\omega/2)\,\mathrm{Im}[\tilde{N}_y\tilde{v}^* + \tilde{N}_{yx}\tilde{u}^* + \tilde{Q}_y\tilde{w}^* - \tilde{M}_y\tilde{\theta}_x^* + \tilde{M}_{yx}\tilde{\theta}_y^*] \tag{5}$$

where $\tilde{N}_x$, $\tilde{N}_y$ and $\tilde{N}_{xy} = \tilde{N}_{yx}$ are complex membrane forces per unit width of plate, $\tilde{M}_x$, $\tilde{M}_y$ and $\tilde{M}_{xy} = \tilde{M}_{yx}$ are complex bending and twisting moments per unit width of plate, $\tilde{Q}_x$ and $\tilde{Q}_y$ are complex transverse shear forces per unit width of plate, $\tilde{u}^*$, $\tilde{v}^*$ and $\tilde{w}^*$ are complex conjugate of translational displacements in x, y and z directions, $\tilde{\theta}_x^*$ and $\tilde{\theta}_y^*$ are complex conjugate of rotational displacement about x and y directions. The positive orientations of forces and displacements are shown in Fig. 2.

2.3. Force–displacement relationship for stiffened plate

For the stiffened plate with identical and equally spaced stiffeners, the relationship between resultant forces and moments and strains and curvatures can be expressed as [2]:

$$\begin{Bmatrix} \{N\} \\ \{M\} \end{Bmatrix} = \begin{bmatrix} [A] & [B] \\ [B] & [D] \end{bmatrix} \begin{Bmatrix} \{\varepsilon\} \\ \{\kappa\} \end{Bmatrix} \tag{6}$$

Where

$$\{N\}^{\mathrm{T}} = \{ N_x \quad N_y \quad N_{xy} \}; \qquad \{M\}^{\mathrm{T}} = \{ M_x \quad M_y \quad M_{xy} \}$$

$$\{\varepsilon\}^{\mathrm{T}} = \left\{ \frac{\partial u}{\partial x} \quad \frac{\partial v}{\partial y} \quad \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) \right\}; \qquad \{\kappa\}^{\mathrm{T}} = \left\{ \frac{\partial^2 w}{\partial x^2} \quad \frac{\partial^2 w}{\partial y^2} \quad \frac{\partial^2 w}{\partial x \partial y} \right\}$$

$$[A] = \begin{bmatrix} \left(A_{\mathrm{p}} + \dfrac{E_{\mathrm{st}}}{E_{\mathrm{p}}} A^{xi}\delta(\eta - \eta_i)\right) & vA_{\mathrm{p}} & 0 \\ vA_{\mathrm{p}} & \left(A_{\mathrm{p}} + \dfrac{E_{\mathrm{st}}}{E_{\mathrm{p}}} A^{yi}\delta(\xi - \xi_i)\right) & 0 \\ 0 & 0 & \dfrac{1}{2}(1 - v)A_{\mathrm{p}} \end{bmatrix}$$

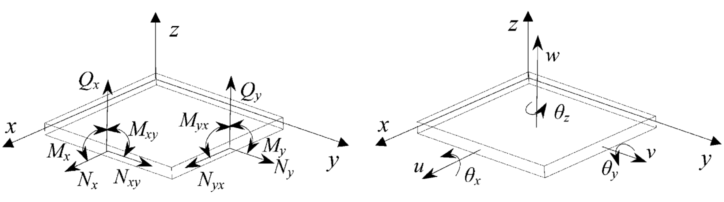

Fig. 2. Forces (moments) and displacements for plate element.

$$[B] = \begin{bmatrix} -\dfrac{E_{st}}{E_p} Q^{xi} \delta(\eta - \eta_i) & 0 & 0 \\ 0 & -\dfrac{E_{st}}{E_p} Q^{yi} \delta(\xi - \xi_i) & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$[D] = \begin{bmatrix} \left(I_p + \dfrac{E_{st}}{E_p} I_y^{xi} \delta(\eta - \eta_i) \right) & vI_p & 0 \\ vI_p & \left(I_p + \dfrac{E_{st}}{E_p} I_x^{yi} \delta(\xi - \xi_i) \right) & 0 \\ 0 & 0 & \begin{array}{l} \dfrac{1}{2}(1-v)I_p + \dfrac{G_{st}}{2E_p} \cdot (J^{xi}\delta(\eta - \eta_i) \\ + J^{yi}\delta(\xi - \xi_i)) \end{array} \end{bmatrix}$$

where N_x, N_y, N_{xy} and M_x, M_y, M_{xy} are resultant force and moment components, u, v and w are in-plane and out-of-plane displacements, ξ and η are non-dimensional parameters which equal x/a and y/b respectively, A_p is the area of the plate per unit width, $A_p = t_p/(1 - v^2)$, t_p is thickness of the plate. A^{xi} and A^{yi} are areas of ith stiffener along x- and y-axes, E_p and E_{st} are Young's moduli for the plate and the stiffeners, Q^{xi} and Q^{yi} are first moment of inertia of typical x- and y-stiffener, I_p is plate flexural rigidity per unit width, $I_p = t_p^3/12(1 - v^2)$, I_y^{xi} and I_x^{yi} are second moment of inertia about the major axis of typical x- and y- stiffener, J^{xi} and J^{yi} are torsional rigidity of typical x- and y-stiffener.

The transformation delta functions, $\delta(\eta - \eta_i)$ and $\delta(\xi - \xi_i)$, are used to evaluate the displacement function at the location of the stiffener. For example, when this transformation function is used with the out-of-plane displacement function, then

$$w(\xi, \eta)\delta(\eta - \eta_i) = w(\xi, \eta_i) \tag{7}$$

where η_i is the location of the stiffener spanning along x- or ξ-axis, as shown in Fig. 3.

2.4. Computational method

The investigation of structural intensity started in the early 1970s [3,4] which aimed to develop measurement techniques of structural intensity for simple structural elements. The computation of the structural intensity in simple structures such as beam and plate was later developed since 1990 [1,5,6], for instance, Gavric and Pavic [1] and Pavic [5] analyzed the intensity for a conservative simply supported plate with discrete viscous dampers at particular point. Most of the calculation methods were based on mode superposition methods with the use of finite element analysis techniques. The emphasis was on various aspects of accuracy of the results and the efficiency of the numerical procedures used.

In this study, the full method for harmonic response solution has been used for the calculation of the structural intensity to predict the energy flow in relatively complex stiffened plate coupled structures. Unlike the mode superposition, full

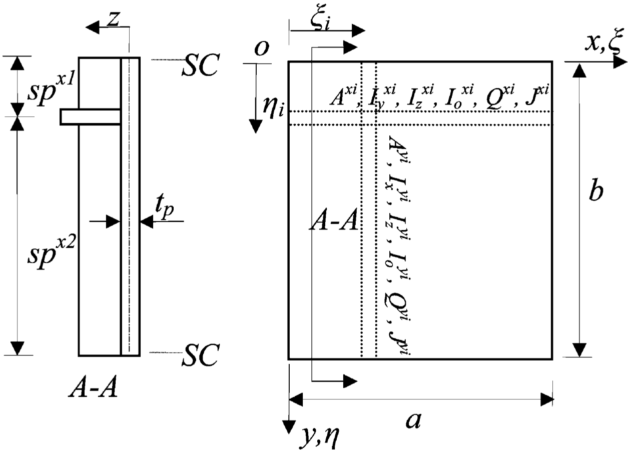

Fig. 3. Orthogonally stiffened plate.

matrices of the system are used for finding the solution in the full method without simplifications. It is directly computed from the mass, damping and stiffness matrices of the model. Though it is more expensive in terms of computation, it can give more accurate results since it does not include modal truncations. The commercial finite element analysis code ANSYS [7] was used for all the calculations in this study.

3. Examples and discussions

3.1. Structural intensity due to lateral area pressure excitation

When a ship is sailing in waves of sea, the structural components of the ship, i.e. stiffened plates, will be subjected to many kinds of lateral pressure excitation. For instance, the stiffened plates of side hull will be subjected to periodical actions from lateral sea wave pressure; the ship will undergo a severe hydrodynamic impact, i.e. bottom slamming or bow slamming, if the forward part of the ship hits the water surface with a sufficient high relative velocity after a bow emergence; the green water may be shipped on deck if the relative motion with respect to the water surface exceeds the local freeboard. Among these typical lateral pressures on stiffened plates, the excitation frequencies will be changed very much from slowly varying load to rapidly varying load, the problem of calculating the load effects can be solved in the frequency domain, because almost any irregular dynamic loading can be represented as a combination of regularly varying loads if the force–displacement relation is linear.

The model used in this study is a rectangular plate with length $a = 2640$ mm, width $b = 900$ mm, and thickness $t_p = 21$ mm which is attached with one central longitudinal flat-stiffener with stiffener height $h_w = 250$ mm and thickness

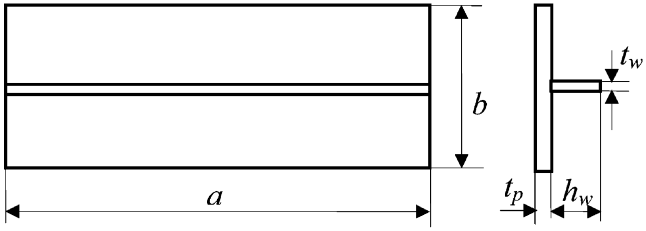

Fig. 4. Structural model.

$t_w = 12$ mm, as shown in Fig. 4. The material properties of this model are: elastic modulus $E = 205.8$ GPa, Poisson's ratio $\nu = 0.3$ and mass density $\rho = 7800\,\mathrm{kg/m^3}$. The stiffened plate is simply supported along two transverse sides of the plate (including end sides of stiffener) while the two longitudinal sides of the plate are applied with symmetrical boundary conditions. A uniform unit lateral pressure is employed on the plate towards the stiffener with an excitation frequency of 68 Hz which is near the structural fundamental frequency, and the structural damping with a constant damping ratio of 0.07 is considered herein.

Fig. 5(a) and (b) shows the pattern of structural intensity vectors in plate and stiffener respectively. From the figures, we can clearly see how the vibrational energy flows in the stiffened plate and energy exchanges between plate and stiffener for this loading case.

3.2. Structural intensity due to point force excitation

For marine vehicles, there are always some machines on board which are generally mounted on stiffened plates of decks or bottoms of ships, and those stiffened plates are supported by stronger structures, such as pillars or bulkheads, near its

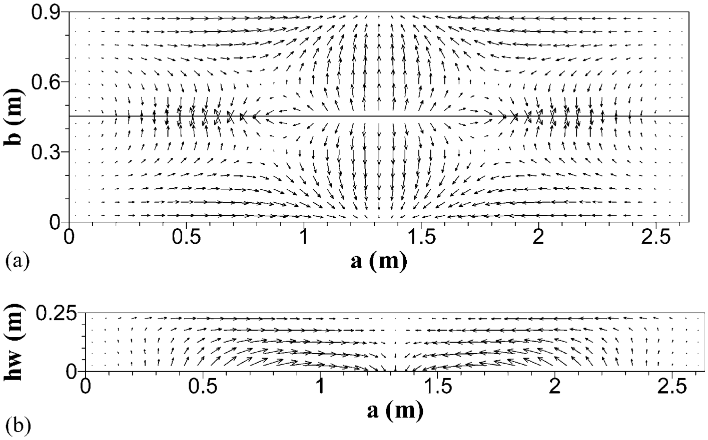

Fig. 5. Structural intensity vectors in (a) plate, (b) stiffener.

loading and boundary area. Inevitably, the stiffened plate will be one of the transmission medium for the vibrations originated from the machines. In practice, the contact area dimension of the machines may be relatively small compared with the dimension of stiffened plate, so that a point force excitation can be used to simulate the machine as the structural vibration source. In order to investigate the vibratory energy flows in the stiffened plates, a corresponding viscous dashpot will be attached on the other side of the plate. The additional damper represents the presence of the dissipative element which can be used to simulate some particular structures such as the loosed bolt on board.

In this study, the emphasis is on the influence of the existence of stiffeners to the structural intensity in plate. Although the energy flows in stiffeners are very important, only the structural intensity in plate will be plotted and compared to analyze the effect of different parameters of stiffeners on the structural intensity.

The first model is selected as a reduced scale experimental model of longitudinally stiffened plate of real ship structures. The material properties of this model are same as before and the dimension are: overall width of plate $B = 1440$ mm, length of plate (or stiffener) $a = 1080$ mm, thickness of plate $t = 6$ mm; the cross-section of stiffener is flat bar with height $h_w = 110$ mm and thickness $t_w = 10$ mm. The stiffened plate is simply supported at its all edges. In order to account for the effect of changes of the number of stiffeners on the structural intensity in stiffened plate, four cases are considered, namely (1) un-stiffened plate, (2) one longitudinal stiffener, (3) two longitudinal stiffeners with different spacing, (4) three longitudinal stiffeners with uniform spacing. An excitation force with a magnitude of 1 N is applied at $x = 270$ mm and $y = 1260$ mm along the z direction on the plate and a viscous damper with a damping rate of 2000 Ns/m is attached to the plate at $x = 810$ mm and $y = 180$ mm for all the cases. The excitation frequencies are close to the fundamental structural vibration frequencies for each of these cases, which are illustrated in Table 1. The patterns of structural intensity vectors for each of these cases are shown in Fig. 6.

In the following examples, all of the stiffened plates have three longitudinal stiffeners with uniform spacing but with different cross-sectional geometrical shapes. The dimensions of the model are corresponding to be typical of the bottom stiffened plates in large merchant vessel structures. The values used are $B = 3600$ mm, $a = 2640$ mm, $t_p = 21$ mm. Three kinds of typical cross-section types for stiffeners of ship structures, namely (1) flat bar, (2) angle bar, and (3) tee bar are employed in the study. The geometrical shapes of different stiffeners are shown in Fig. 7. The dimensions of these stiffeners are as follows respectively:

Table 1
Natural frequencies for all cases

Stiffener Num.	0	1	2	3
N. F. (Hz)	19.58	43.54	56.94	126.33

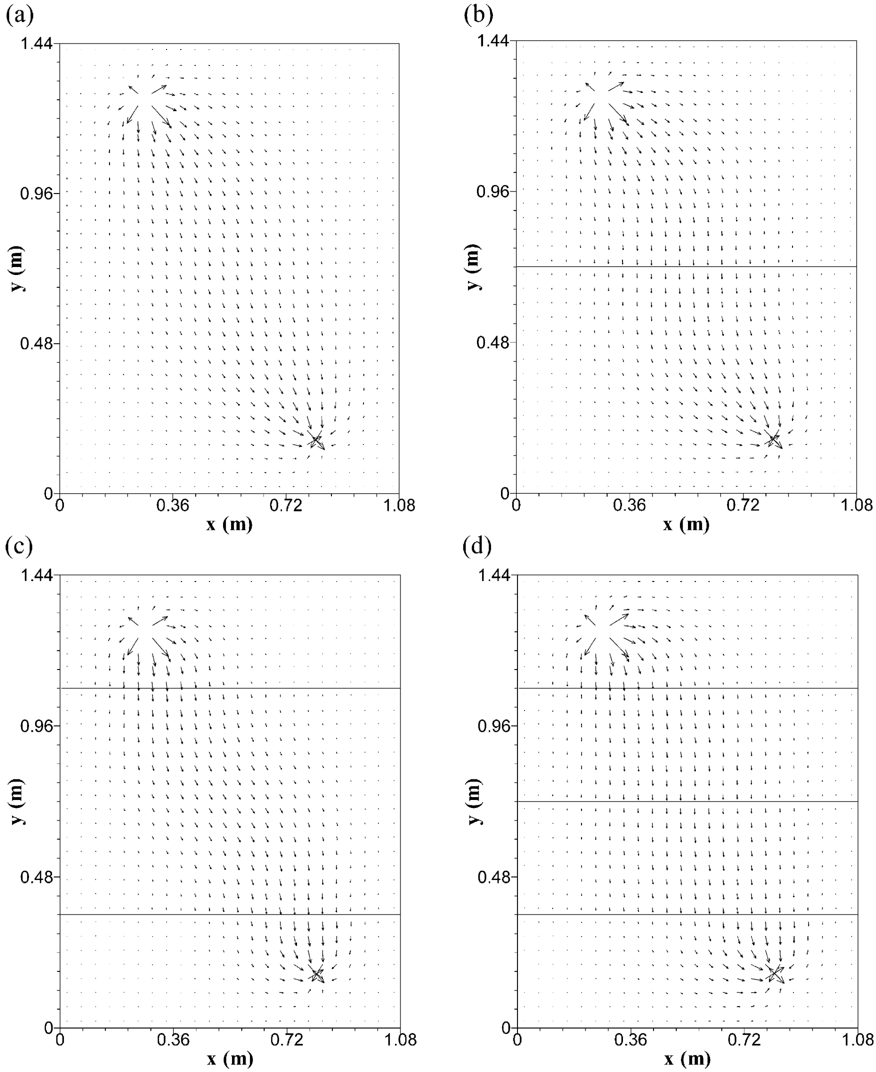

Fig. 6. Structural intensity vectors in a stiffened plate at an excitation near their fundamental frequency with four edges simply supported. (a) bare plate, (b) plate with one central stiffener, (c) plate with two stiffeners, (d) plate with three stiffeners.

(1) Flat bar: $h_w = 250$ mm; $t_w = 12$ mm.
(2) Angle bar: $h_w = 250$ mm; $t_w = 12$ mm; $b_f = 90$ mm; $t_f = 16$ mm.
(3) Tee bar: $h_w = 250$ mm; $t_w = 12$ mm; $b_f = 100$ mm; $t_f = 15$ mm.

The same magnitude of excitation force and viscous damper are employed on the similar position as the above examples. However, the boundary condition is

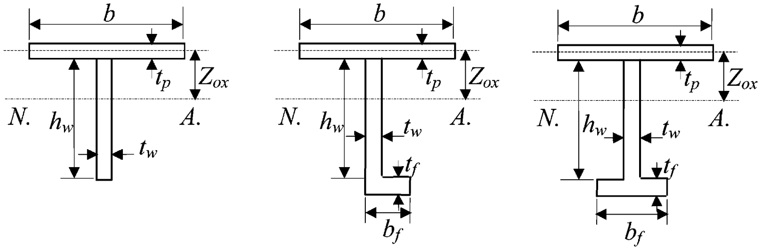

Fig. 7. Typical cross-section of stiffener in ship structures.

changed in order to account for the effect of stiffener geometry on structural intensity in plate, that is, four sides of the plate are simply supported while the end sides of the stiffeners are free. Meanwhile, a certain excitation frequency of 53 Hz is employed for all the calculation cases. Table 2 illustrates the natural frequencies for all calculation models, and their structural intensity vectors in plate are shown in Fig. 8.

3.3. Structural intensity due to in-plane pressure excitation

In this example, the excitation force is taken as the pressure acting on one edge of the plate along the longitudinal and transverse direction, respectively. These pressures can be seen as coming from the vertical and horizontal wave-induced bending moment by which the ship encounters periodically when it navigates in the sea. In this calculation example, a certain magnitude of line pressure and its excitation frequency are taken as 1 N/m and 2 Hz, respectively. This excitation frequency is close to the common two-node vibration frequency of ships as well as the shorter period components of encountered waves. The structural damping is considered with a constant damping ratio of 0.07.

The model used is a relatively complicated full scale steel grillage (cross-stiffened plate) representing typical warship bottom structure shown in Fig. 9. The grillage model has identical T-type longitudinal stiffeners and identical T-type transverse frames. The overall dimensions of the grillage are $L = 6096$ mm long and $B = 3048$ mm wide, and the thickness of the plate is 7 mm. The dimensions of longitudinal stiffeners are: height of web $h_{wx} = 115$ mm, thickness of web $t_{wx} = 5.4$ mm, height of flange $b_{fx} = 45.5$ mm, thickness of flange $t_{fx} = 9.5$ mm. The dimensions of transverse stiffeners are: height of web $h_{wy} = 204$ mm, thickness of web $t_{wy} = 8.3$ mm, height of flange $b_{fy} = 102$ mm, thickness of flange $t_{fy} = 16$ mm.

Table 2
Natural frequencies for all cases

Stiffener shape	Flat bar	Angle bar	Tee bar
N. F. (Hz)	55.387	62.308	62.943

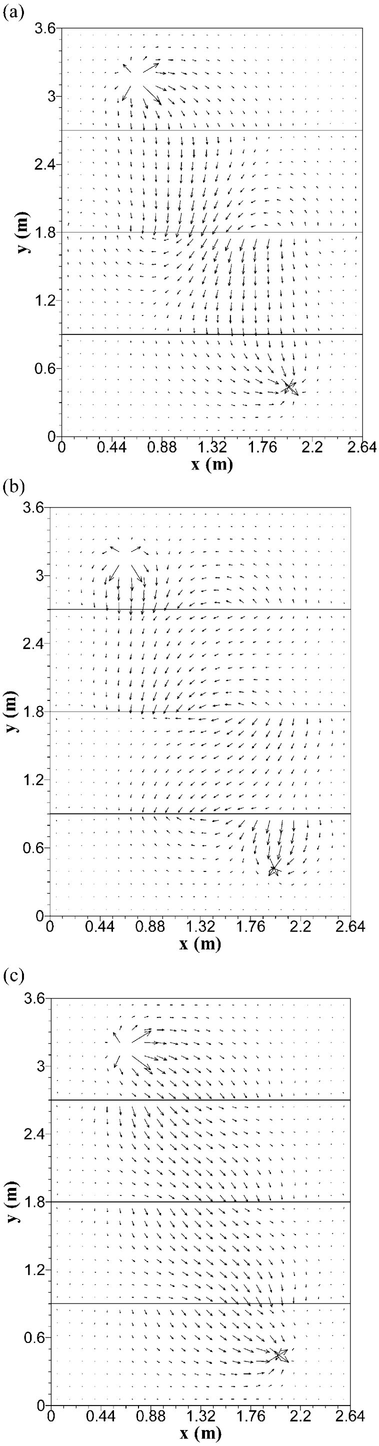

Fig. 8. Structural intensity vectors with same excitation frequency. (a) Flat-bar stiffener, (b) Angle-bar stiffener, (c) Tee-bar stiffener.

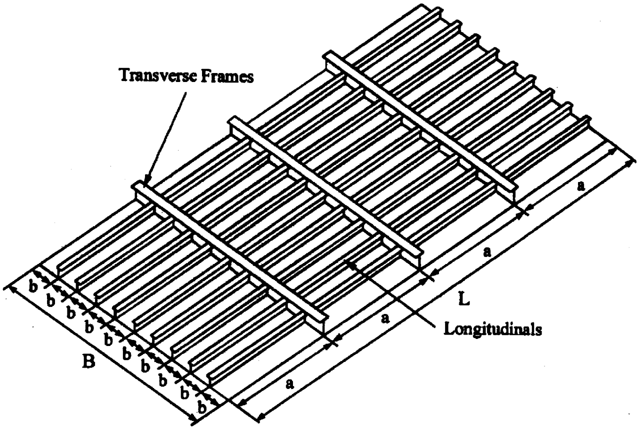

Fig. 9. The cross-stiffened plate model.

Fig. 10 shows the structural intensity in a cross-stiffened plate under the excitation of longitudinal in-plane pressure with all edges simply supported and Fig. 11(a) shows that under transverse in-plane pressure excitation. In order to reveal the influence of stiffeners on the energy flow in plate, the structural intensity vectors in plates with only longitudinal stiffeners and without any stiffeners are illustrated in Fig. 11(b) and (c) respectively.

3.4. *Influence of plate/stiffener proportions*

The objectives in this section are to study the influence of plate/stiffener proportions on the structural intensity of the assembled structures. Considering the future application of the structural intensity technique in marine structures, the emphasis of the current analysis is toward the optimization design for stiffened plate in terms

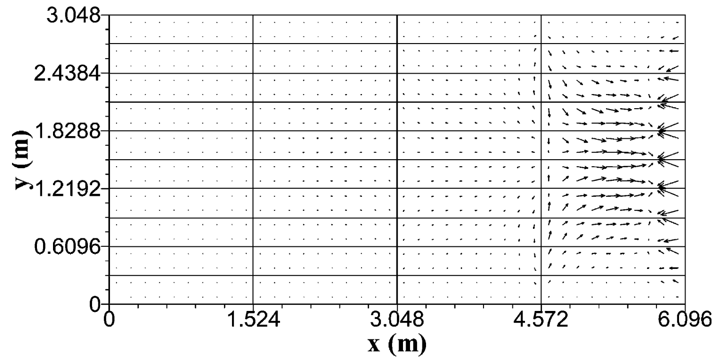

Fig. 10. Structural intensity vectors in cross-stiffened plate with all edges simply supported under the excitation of uniform longitudinal in-plane pressure with the frequency of 2 Hz.

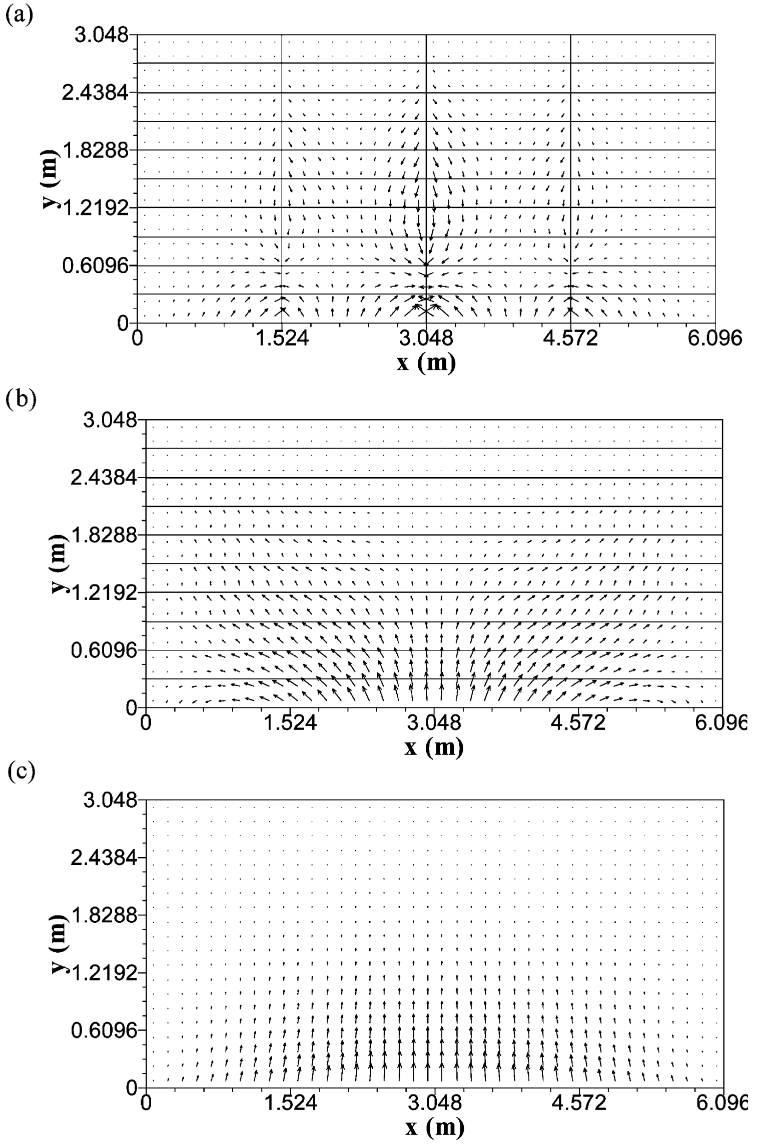

Fig. 11. Structural intensity vectors in plate with all edges simply supported under the excitation of uniform transverse in-plane pressure with the frequency of 2 Hz. (a) Cross-stiffened plate, (b) plate with longitudinal stiffeners, (c) bare plate.

of minimization of structural intensity under the external harmonic loading actions. The models and calculation conditions are the same as in the first example, where the thickness of plate t_p and height of stiffener h_w are selected as the variables. However, the overall structural weight remains constant during the process

Table 3
Comparison of results (excitation frequency of 68 Hz, damping ratio of 0.07)

Case	h_w (mm)	t_p (mm)	N. F. (Hz)	Max. SI (W/m^2)	Max. Stress (Pa)	Max. Dis. (m)
1	0	24.333	8.5237	0.202×10^{-5}	1058	0.681×10^{-7}
2	50	23.666	18.559	0.220×10^{-5}	2201	0.518×10^{-7}
3	100	23.000	35.526	0.234×10^{-5}	2826	0.575×10^{-7}
4	150	22.333	56.646	0.718×10^{-5}	6769	0.126×10^{-6}
5	200	21.666	71.635	0.422×10^{-5}	5923	0.113×10^{-6}
6	250	21.000	67.952	0.336×10^{-6}	2313	0.497×10^{-7}
7	300	20.333	63.178	0.883×10^{-7}	1549	0.348×10^{-7}
8	350	19.666	56.906	0.364×10^{-7}	1510	0.299×10^{-7}
9	400	19.000	49.488	0.194×10^{-7}	1551	0.286×10^{-7}
10	450	18.333	42.163	0.177×10^{-7}	1639	0.291×10^{-7}
11	500	17.666	35.844	0.195×10^{-7}	1766	0.309×10^{-7}
12	550	17.000	30.677	0.228×10^{-7}	1932	0.339×10^{-7}
⋮	↓Increase	↓Decrease	↓Decrease	↓Increase	↓Increase	↓Increase
N	1000	11.000	18.559	0.173×10^{-5}	9870	0.249×10^{-6}

of increasing h_w and decreasing t_p. The calculated results for all models are illustrated in Table 3.

In Table 3, the stress represents Von-Mises resultant stress which excludes the influence of boundary conditions. From the calculated results and their comparison, we can find that under dynamic loading actions, the maximum value of stress does not imply the maximum magnitude of structural intensity as the latter is the vector product of stress and velocity. Increasing h_w/t_p, the location of maximum structural intensity moves from the stiffener to central parts of the plate, the location of maximum stress moves from top side of the stiffener to bottom side (intersected line with plate) of the stiffener, the location of maximum deflection is almost unchanged.

If we use three kinds of criteria, namely structural intensity criteria, dynamic stress criteria, and dynamic deflection criteria, into the design for stiffened plates of marine structures, here we can see that Case 4 is the most dangerous design scheme whichever design criteria is based on, Case 10 is the best design scheme according to structural intensity design criteria, Case 8 is the best one according to stress design criteria for stiffened plates (although stress in un-stiffened plate is smaller), and Case 9 is the best one according to deflection design criteria.

3.5. Discussions for calculated results

The structural intensity pattern can be used to determine how energy is injected by mechanical excitations and to identify power transfer paths as it presents a vectorial nature of vibrational energy flow in structures. From the calculated results, we can find that despite the existence of stiffeners within the plate, the structural intensity fields can still clearly indicate the source, the sink and the transmission of energy flow from source of excitation to the sink through plate. The patterns of structural intensity in stiffened plate will be changed with many factors, such as loading characteristics, mode shapes of coupled structures, number of stiffeners attached to the plate, geometry shape of stiffeners, and many others.

Comparing Fig. 6(a–c) and (d), we can find that the patterns of energy flow are different with the variation of stiffener numbers, that is, because the number of stiffeners attached to plate will affect the vibration modes of stiffened panels. The mode shapes changed from one-half sine wave to four-half sine waves along the transverse direction for each structure model with increased number of stiffeners. This means that the nature of structural intensity is frequency dependent. When the excitation frequency is of the same order with structural fundamental frequencies, the magnitude (or pattern) of structural intensity mainly depends on the relationship between structural mode shape and external loading characteristics. This can be explained by comparing Cases 4, 6 and 8 in the above examples for designs. Although the natural frequency of Case 6 is closer to the excitation frequency than Case 4, the magnitude of structural intensity for Case 4 is larger than that for Case 6, this is because the mode shape of Case 4 is consistent to the external loading pattern. Although the mode shape of Case 6 is similar with that of Case 8, the magnitude of structural intensity for Case 6 is larger than that for Case 8 because of different structural natural frequencies. However, for Case 11 and latter models, their fundamental mode shapes change again, Fig. 12 illustrates the model shape of stiffened plate for Case 4 and Case 6 respectively.

At the same time, the patterns of energy flow in those stiffened panels will be changed with different types of stiffeners employed, which can be seen by comparing Fig. 8(a), (b) and (c). These patterns illuminate the effect of stiffness of stiffeners on the energy flow in plate. From the stiffness relationship for stiffened plate, we can see that for un-stiffened plate, the coupling stiffness [B] becomes zero and the components of in-plane loads and moments decoupled. For the plate with different directional stiffeners, the in-plane compression or tension stiffness and bending stiffness along the orientation of the stiffeners will be changed (increased), so that the energy flow in the stiffened plate will be changed thereafter. This phenomenon can also be shown clearly by comparing between Fig. 11(b) and (c).

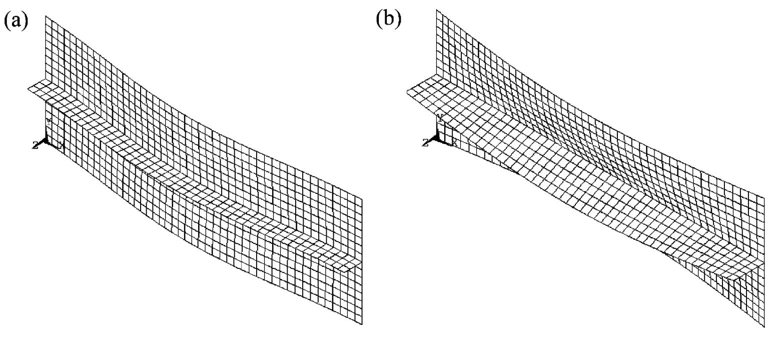

Fig. 12. Mode shapes for stiffened plates. (a) Case 4, (b) Case 6.

For the cross-stiffened plates in a ship, the plate takes most of the in-plane compressive load. The stiffeners carry most of the lateral load and bending moment, meanwhile stiffen and stabilize the plate so that it can carry the in-plane load. From Fig. 10 and Fig. 11 (a), we can see that the distribution of energy flow is very complicated in the cross-stiffened plate under such loading and boundary conditions. Despite the in-plane compressive pressure is applied on the edge of plate, the bending of stiffener results in tension stress in the attached plate, so that the directions of structural intensity in plate are oppositely changed. However, the vectors of structural intensity in the flange of stiffeners have the same direction, and the values of structural intensity in the flange of stiffeners are much larger than that in the plate.

4. Conclusions

In this study, the structural intensity analysis method has been developed to predict the information of energy flow for the stiffened plates of marine structures. Three typical cases in marine structures have been selected as calculation examples, that is, a plate with one longitudinal stiffener under lateral area pressure excitation, a longitudinally stiffened plate under point force excitation, and a cross-stiffened plate under in-plane pressure excitation. The calculation results showed that, despite the existence of stiffeners within the plate, the structural intensity fields can still clearly indicate the source, the sink and the direction of energy flow from the source to the sink. Meanwhile, the existence of stiffeners will change the energy flow in plate. The nature of structural intensity is frequency dependent, the interchange of energy flow between stiffeners and plates will depend on the mode shapes that are dominant for a given frequency range. It has been shown that the structural intensity analysis can act as a new (maybe more reliable) criteria for marine structural design. It can also be an effective tool of vibration control for marine structures provided the power flow pattern and energy density in stiffened plates can be controlled by properly arranging stiffeners.

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