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VIBRATION ENERGY FLOW IN WELDED CONNECTION OF PLATES

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The presented results are concerned with energy transmission in two dimensional plate-like structures, which undergo the different frequency force excitation. The method for structural intensity computation is illustrated and formulas of structural intensity for plates and their relationship with internal force and strain are given in works [1–4]. The formulas were used in the program algorithm for structural intensity calculations. The calculations were done with use the FE method to obtain harmonic response solution. Numerical examples are presented – the welded connection of two flat rectangular plates. The model included the force excitation and dampers formed in lines parallel to the one side of plate and the welded connection. The relationship between structural intensity and structural mode shapes as well as the changes of energy flow in plate for the excitation frequency change are discussed.

Key words: vibration energy flow, structural intensity.

1. Introduction

The structures of vehicles are subjected to external dynamic loading with various excitation frequencies, from slowly varying wave loads to high frequency interaction of engines, road and suspension induced forces. When the frequencies of the external forces are close to one of the natural frequencies of the structural components, the permissible vibration levels may be exceeded, which results in fatigue failure in the structure, or very high noise level inside. Since plates are most commonly used built-up structural elements in vehicles, the damage of plates or their connections will result in disintegration of overall body of the vehicle.

The quantity of the structural intensity is the power flow due to structural vibration per unit cross-sectional area in elastic medium. The interest on investigation of structural intensity arises for practical reasons. Structural intensity field indicates the magnitude and direction of vibration energy flow at any point of a structure. Energy flow distribution offers information of energy transmission paths of mechanical energy. Dissipative elements, mechanical modification and active vibration control can be used for an alteration of energy flow paths within the structure. Of practical concerns are complex built-up structures, which can be successfully treated only by numerical computation when prediction of structural behaviour in various operating conditions is needed. For these reasons, the investigation of energy flow paths in plate connections is important to the damage detection for vehicles.

The work presents formulations on structural intensity calculations. The method for structural intensity computation is illustrated and formulas of structural intensity for plates and their relationship with internal force and strain. The modelling and computation is done for one and two dimensional structures: plates and shells considered here as constructional elements. The numerical method of intensity evaluation was based on complex modal analysis and superposition of modes with use of finite elements method. There are presented results of the calculations which lead to the assessment of distribution of structural intensity (vector field) on the surface of simply supported rectangular steel plates connected by the welded type joints. The models included the source of vibrations (linear force excitation) and sink of energy in form of linear configuration of damping elements. The changes of finite elements grid density enabled detailed analysis of total vibration energy flow in analysed plates through the place of joint. Solved problem was intended to show the usability of structure surface intensity method in diagnostics of joints and role of stiffeners in mechanical constructions specially those typical for the vehicles as means of personal transport.

2. Assessment of energy flow

For linear flexural vibration in thin plates, the total active structural intensity vectors consist of components due to shear waves, bending waves and twisting waves. Following the conventions of references [1, 2] the orthogonal components of structural intensity, in W/m^2, for thin-walled two dimensional structures may be written as:

$$\overline{I} = I_x \, \hat{\imath} + I_y \, \hat{\jmath}. \tag{1}$$

The components I_x and I_y are computed from the internal shears and moments, which for thin plates are proportional to the spatial derivatives of the transverse plate velocity [2–4]:

$$I_x = \frac{\langle Q_x \, \dot{w} \rangle_t + \langle M_y \, \dot{\theta}_y \rangle - \langle M_{xy} \, \dot{\theta}_x \rangle}{h}, \tag{2}$$

$$I_y = \frac{\langle Q_y \, \dot{w} \rangle_t - \langle M_y \, \dot{\theta}_x \rangle + \langle M_{xy} \, \dot{\theta}_y \rangle}{h}. \tag{3}$$

The spatial derivatives can be calculated analytically with the assumptions of plate theory or computed through finite differencing. Equations (2) and (3) are used to form formulas for structural intensity components [2, 3].

3. Model of welded connection of plates

The main target of the analysis of the rectangular plate was the testing the structural intensity fields for different frequency force excitation. In the process of modelling and analysis was applied elaborated program for calculations of complex modal model, allowing the consideration of additional localised damping in the system.

Each intensity component was computed at all points of the mesh grid at first 100 resonance frequencies of thin, rectangular plate, simply supported on two shorter sides. The plate dimensions were $1\ \mathrm{m} \times 3.3\ \mathrm{m} \times 0.01\ \mathrm{m}$. It was composed of two plates connected at the shorter side. Model of line welding included the stiff connection of plates along the one row of finite elements and at the distance equal to the thickness of one plate. The length of composing plates are $1\ \mathrm{m} \times 1.5\ \mathrm{m} \times 0.01\ \mathrm{m}$. The material of plates was the constructional steel. The material properties of steel were following: Young's modulus, $E = 2.11 \times 10^{11}$ Pa, Poissons ratio, $\nu = 0.3$ and density, $\rho = 7860$ kg/m^3. The plate was excited by harmonic forces perpendicular to the plate. They form a line parallel to the shorter plate's side, marked as line of stars in figures. The amplitude of the excitation was set to 10^3 N. The frequency of excitation was changed in the range from 5 to 100 Hz. The viscous damping forces were applied to the plate in the purpose of vibration energy absorption. They form a line parallel to the shorter plate's side, marked as line of triangles on Figures. The FEM model was arranged using the NASTRAN software and consisted of equal square elements of QUAD4 type.

Figures 1, 2, 3, 4 and 5 show the predicted structural intensity patterns. Each plot contains a set of structural intensity values shown in form of vector field. The vector lengths are proportional to the magnitude of the intensity at the location of vector's tail. Vectors are proportional to the intensity magnitude and shown in grey scale (left side of plot). Each plot shows clearly energy flow from the excitation forces on left part of the plate toward the dampers placed on the right part of the second plate. Beyond the damper positions the intensity vectors show lower magnitudes, indicating energy dissipation at the damper. The plots of vectors go to zero at the shorter plate edges (supported edges) due to the increased stiffness. The highest values of structural intensity at the edges of plates are the results of highest values of stresses at the edges in the place of welded connection. Figure 6 shows the predicted maximum values of structural intensity magnitude for each vector field versus excitation frequency.

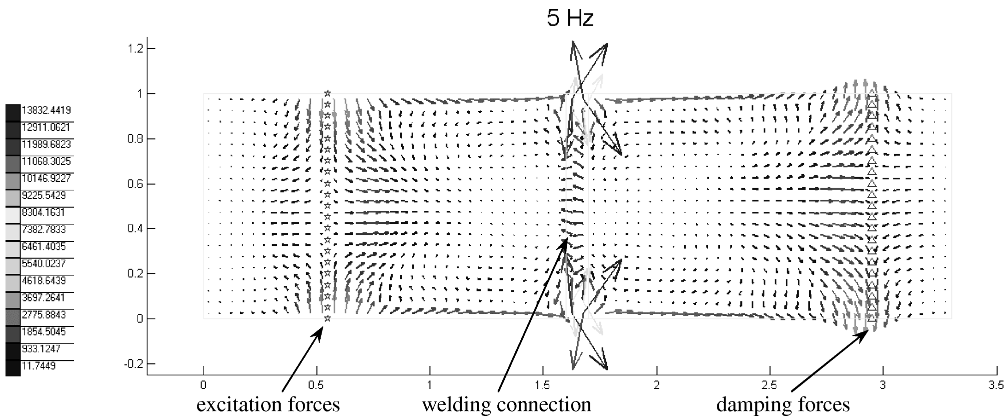

Fig. 1. Structural intensity field for two simply supported welded rectangular plates. Excitation force frequency 5 Hz.

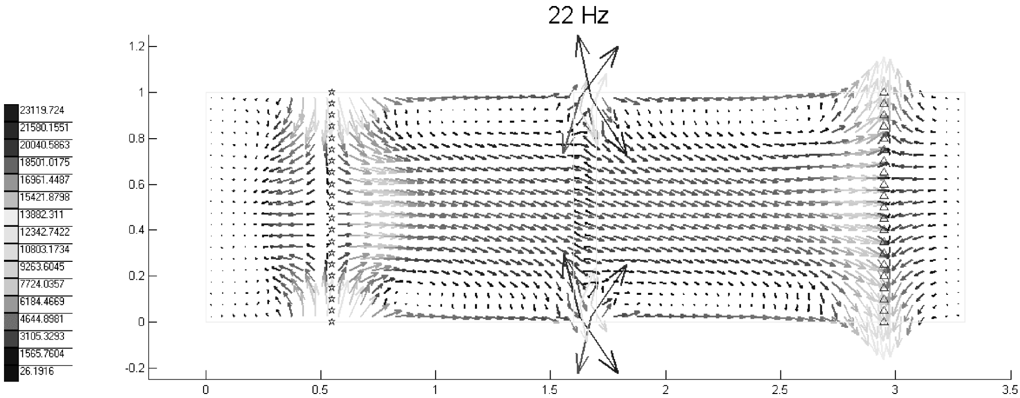

Fig. 2. Structural intensity field for two simply supported welded rectangular plates. Excitation force frequency 22 Hz.

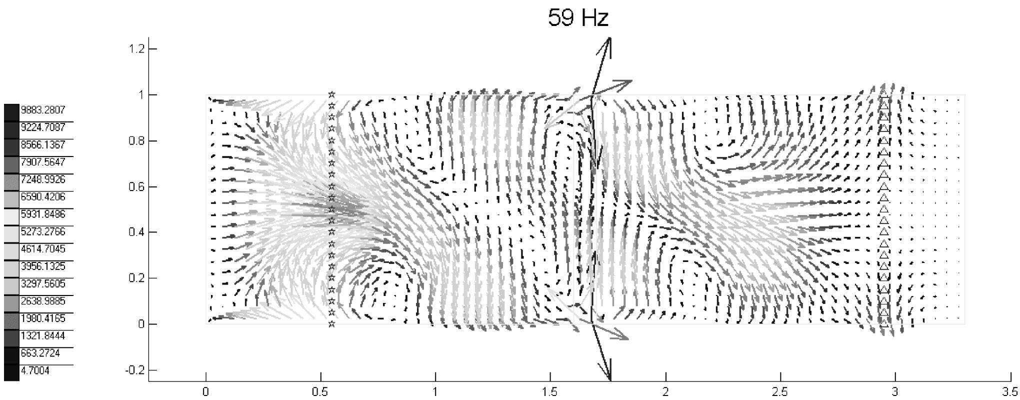

Fig. 3. Structural intensity field for two simply supported welded rectangular plates. Excitation force frequency 59 Hz.

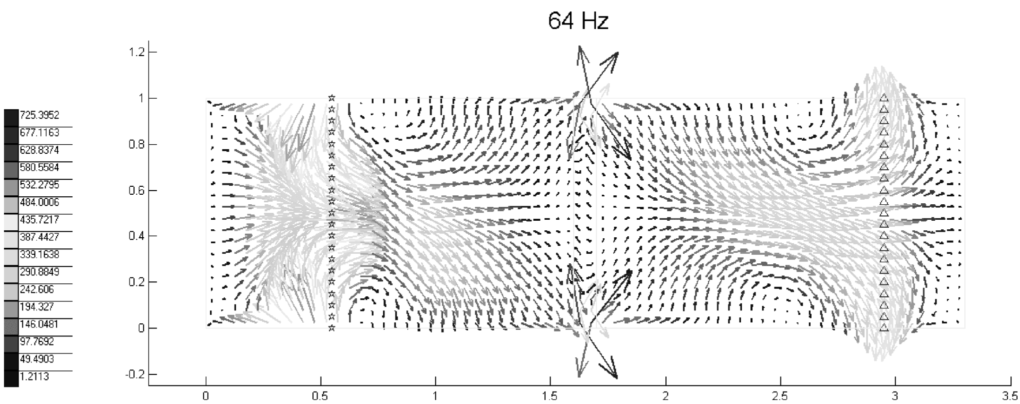

Fig. 4. Structural intensity field for two simply supported welded rectangular plates. Excitation force frequency 64 Hz.

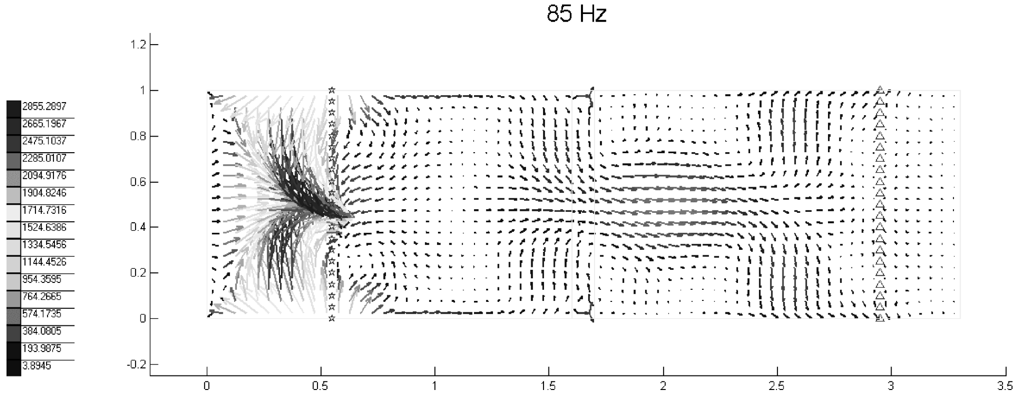

Fig. 5. Structural intensity field for two simply supported welded rectangular plates. Excitation force frequency 85 Hz.

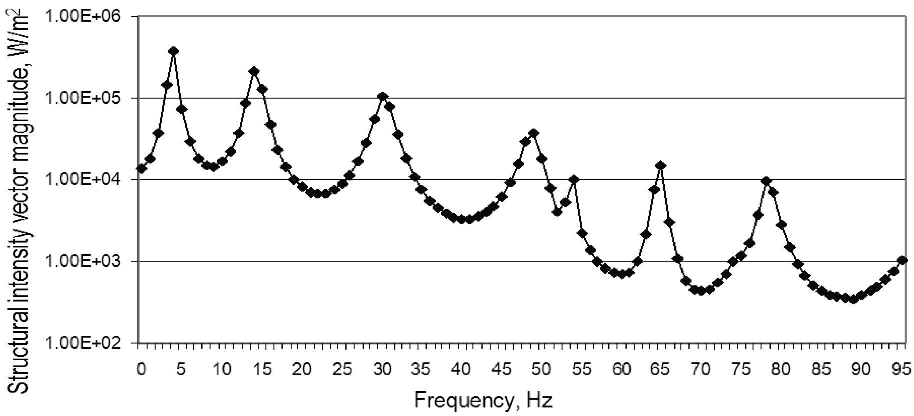

Fig. 6. Maximum values of structural intensity magnitude for each vector field versus excitation frequency.

The calculation has been done for 100 first mode shapes. In cases of low number of mode shapes there were observed significant changes in distribution of vectors for the same density of net of elements. For the some frequencies there were observed abrupt changes of vectors distribution and what is more significant the maximum value of vectors magnitude.

The change in value of vectors magnitude was of 4 orders varying from 10^2 till 2.0×10^6 W/m^2. The magnitude of structural intensity vectors decrease with increase of excitation frequency. In energy flow analysis it is not sufficient to observe only the intensity vectors. The better measure of energy flow is the total energy flow through the closed area around the places of excitation and damping or through the whole width of the plate.

4. Conclusions

The distribution of structural intensity vectors gives the qualitative characteristic of vibration energy transportation in mechanical systems. Introduction of an additional measure in form of integral of magnitude structural intensity vector component perpendicular to the certain closed surface enables the quantitative assessment of energy transfer paths and its balance in the structure. The method of analysis of structural intensity distribution enables the investigation in the regions of high concentration of vibration energy flow which consequently is exposed to the risk of damage or is propagating the sound waves to the environment. It can be also considered as the identification of the regions for application of additional damping elements in purpose of lowering of vibration level and resulting noise radiation. The structural intensity pattern can be used to identify power transfer paths as it presents a vectorial nature of vibration energy flow in structures. Presented method of structural intensity vector calculation enables its evaluation for chosen frequency range and mode shapes [3]. The calculations are done with the application of complex modal parameters – modal analysis based on finite element method.

From the calculated results, we can find that despite the change of the excitation force frequency acting on the plate, the structural intensity fields can 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 plate will be changed with many factors, such as loading characteristics, mode shapes of coupled structures, number and geometry shape of stiffeners attached to the plate, and many others. Analysed case of welded connection has shown the influence the connection stiffness upon the field distribution and magnitude of structural intensity vectors. High values of structural intensity at the edges of plates at the welded connection is due to the over estimated stress values. The nature of structural intensity distribution is highly frequency dependent. It has been proved by the numerical experiment that it is very sensitive in the range close to the mode frequency. It can be observed the abrupt changes of vector field distribution but not similar in shape to the suitable mode shape.

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