

Method for Estimating Instantaneous Structural Intensity on Curved Structures Based on Moving Least Squares

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Structural intensity (SI) is an effective indicator for visualizing the flow of vibration energy and identifying transmission paths of structure-borne noise. In steady state, time-averaged SI may make transmission paths difficult to identify in lightly damped systems. To address this limitation, the authors proposed evaluating energy flow using the instantaneous SI of the first wave immediately after excitation and established a method for approximately estimating instantaneous SI from measured velocities in flat structures. Practical structures such as vehicle bodies often contain curved thin-walled components. To evaluate SI on curved structures, spatial derivatives of displacements and velocities must be obtained in a local coordinate system defined on the curved surface. Although methods for calculating time-averaged SI from measured vibration data based on shell theory have been proposed, stable estimation of derivative quantities from noisy measurement data remains a challenge.

This study proposes a measurement method for instantaneous SI in curved structures based on moving least squares (MLS). Based on Kirchhoff-Love shell theory, the internal forces are expressed in terms of the displacement derivatives in a local coordinate system, and the α -component of the instantaneous SI is given by

$$I_{\alpha}(t) = -(N_{\alpha}v_{\alpha} + N_{\alpha\beta}v_{\beta} + M_{\alpha}\omega_{\alpha} - M_{\alpha\beta}\omega_{\beta} + Q_{\alpha}v_{\gamma})$$

where N_{α} , $N_{\alpha\beta}$, M_{α} , $M_{\alpha\beta}$, and Q_{α} denote the membrane force, in-plane shear force, bending moment, twisting moment, and transverse shear force, respectively, while v and ω denote the translational and rotational velocities. The β -component is obtained analogously. At each evaluation point, a local tangent plane is defined and the neighboring points are projected onto it (Fig.1). The coefficients $c(t)$ of the polynomial basis $p(\alpha, \beta)$ are determined by minimizing the weighted residual,

$$c(t) = \arg \min_c \sum_{j \in \Omega_i} w(r_{ij}) [p^T(\alpha_{ij}, \beta_{ij}) c(t) - f_j(t)]^2$$

where Ω_i denotes the set of neighboring points of evaluation point i , $w(r_{ij})$ denotes a distance-based weighting function, and $f_j(t)$ denotes the measured value at neighboring point j . The required spatial derivatives are then obtained by differentiating the approximated field, allowing the instantaneous SI to be evaluated without a mesh.

The proposed method was validated using a steel panel (620 × 520 mm, 1.0 mm thick) with a spherical dome of 380 mm diameter and 120 mm height. Three-dimensional vibration velocities were measured on a 10 mm grid non-invasively with a three-dimensional Laser Doppler Vibrometer (LDV) under impact excitation. The displacements were obtained by trapezoidal time integration of the measured velocities. A finite element (FEM) model of the same specimen was built with quadratic triangular shell elements, and the measured excitation force was applied as the input. MLS employed a third-order polynomial basis with Gaussian distance weighting, using at least 150 neighboring points at each evaluation point.

The instantaneous SI distributions obtained from the measured velocities were compared with a FEM reference solution (Fig. 2). At 0.45 ms after excitation, all approaches reproduced the outwardly propagating first wave, and the contour separating high-SI and low-SI regions showed good agreement. During first-wave propagation, the Spearman correlation coefficients ranged from 0.806 to 0.927 and the Pearson correlation coefficients ranged from 0.815 to 0.891. These results demonstrate that the proposed method can reproduce the magnitude distribution of first-wave instantaneous SI on curved structures from measured three-dimensional velocity data.

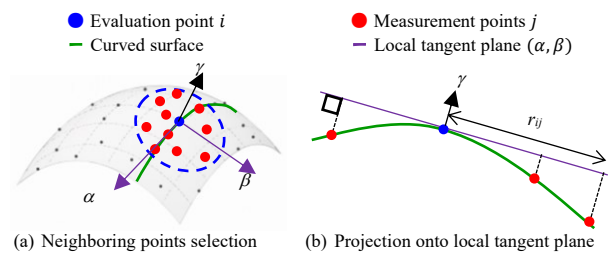


Fig.1 Local coordinate system and projection onto tangent plane

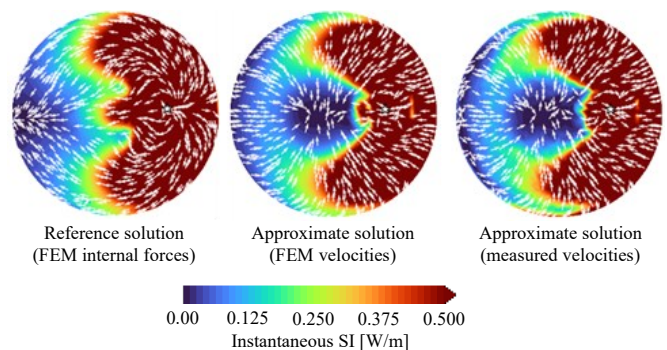


Fig.2 Comparison of instantaneous SI distributions at 0.45 ms