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MEASUREMENTS OF FLEXURAL WAVE PROPERTIES ON VISCOELASTIC PANELS USING A LASER DOPPLER VIBROMETER

Ning Xiang[1*] **Jack Taylor**[1] **Max Miller, III**[1]
[1] Graduate Program in Architectural Acoustics, Rensselaer Polytechnic Institute, USA

ABSTRACT

Sandwiched wall-board systems that incorporate viscoelastic panels as constrained damping layers efficiently enhance sound transmission losses. For a better understanding of the damping mechanism of the constrained damping layers, propagation of the bending wave in these building devices is of central importance. The damping properties of constrained damping layers made of viscoelastic materials need to be characterized by bending wave excitations. The dispersive nature of the bending waves makes the experimental characterization extremely challenging in reliable dynamic material testing. An experimental methodology based on the theory of the bending wave has been explored to characterize the properties of the flexural wave, including the bending stiffness and the loss factor of highly viscous panels. The transfer function between two locations radially away from a flexural wave exciter on the viscoelastic panel are experimentally measured. This measurement method experimentally determines the broadband bending phase speed, the bending stiffness, and the bending loss factor. This paper further investigates the experimental method for characterizing the bending-wave properties using a laser Doppler vibrometer. The investigation also addresses experimental challenges as well as an approach to mitigate disturbing effects and improve measurement accuracy.

Keywords: *Laser Doppler vibrometry, bending waves flexural waves, viscoelastic panel properties, bending stiffness, loss factor*

****Corresponding author***: *xiangn@rpi.edu.*

1. INTRODUCTION

It has been considered challenging to characterize dynamic mechanical properties over broad frequency ranges with high enough resolution, particularly when devices / materials in plates are viscoelastic in nature. Classical methods [1] would be less effective due to the fundamental limitations relying on modal analysis. This work investigates a measurement method for experimentally characterizing bending wave properties of viscoelastic plates. The method has not been documented in major acoustics literature, but conference presentations [2, 3]. The method employs a laser Doppler vibrometer (LDV) to measure the bending wave (transversal) velocity in a non-contacting manner, while exciting the bending waves on the thin plate under test using a light-weight piezo disk as a bending wave source. This paper discusses further investigations from that of previously accomplished by Miller III *et al.* [2, 3].

2. EXPERIMENTAL METHOD

The laser beam of the LDV senses the surface velocities when shinning perpendicularly at two surface points of known separation in response to the bending wave exciter, building a transfer function between the two surface points positioned radially away from the exciter.

2.1 Theoretical Background

In thin, viscoelastic panels, plate mass m'' per unit area and the bending stiffness B' per unit length play a decisive role in bending wave propagation [4]. For viscoelastic materials, the viscous loss can be accounted for by a complex-valued bending stiffness $\underline{B}'$ through a complex-valued Young's modulus $\underline{E}$ [5]

$$\underline{B}' = \frac{\underline{E}\,h^3}{12(1-\nu^2)}, \quad \underline{E} = E' + \mathrm{j}E'', \tag{1}$$

with plate thickness h, Passion's ratio ν. E' represents the storage modulus while E'' the loss modulus, a ratio of them defines the loss factor $\eta = E''/E'$ [6].

The phase speed c_b of the bending waves is derived from a four-order partial differential equation [4]

$$c_\mathrm{b} = \frac{\omega}{\underline{k}_\mathrm{b}} = \sqrt[4]{\frac{\underline{E}}{m''(1-\nu^2)}}\sqrt{\omega}\,, \tag{2}$$

where $\underline{k}_\mathrm{b}$ is complex-valued propagation coefficient of the bending waves. Equation (2) indicates that the bending wave speed c_b plays a central role in determining the bending stiffness $\underline{B}'$, Young's modulus $\underline{E}$ when the loss factor η is independently measurable.

Under condition $|\underline{k}_\mathrm{b}|\,r \gg 1$ with $\underline{k}_\mathrm{b}$ being the complex-valued propagation coefficient of the bending waves, and the loss factor η is often small, decomposing the complex-valued propagation coefficient

$$\underline{k}_\mathrm{b} = k'_\mathrm{b} - \mathrm{j}\,k''_\mathrm{b} = \sqrt[4]{\frac{\omega^2 m''(1-\nu^2)}{E'\,(1+\mathrm{j}\,\eta)}}. \tag{3}$$

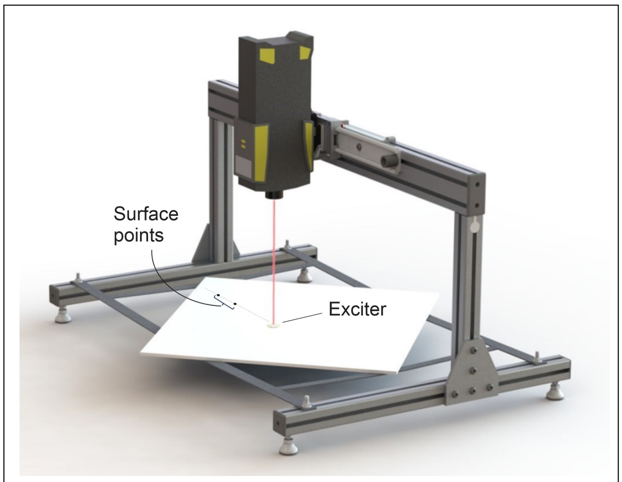

Figure 1. Laser Doppler vibrometer-based measurement setup. The laser beam senses the transverse velocity of bending waves at surface points radially away from the source.

2.2 Bending wave properties

At two radial distances r_1, r_2 with $r_2 > r_1$ and separation $r_\Delta = r_2 - r_1$, the bending wave velocities in frequency domain build a transfer function,

$$\underline{H}_\mathrm{V}(\omega) = \frac{\underline{V}_\mathrm{b}(\underline{k}_\mathrm{b}\,r_2)}{\underline{V}_\mathrm{b}(\underline{k}_\mathrm{b}\,r_1)} = |\underline{H}_\mathrm{V}(\omega)|\,\mathrm{e}^{-\mathrm{j}\varphi(\omega)}, \tag{4}$$

where $\varphi(\omega)$ is (unwrapped) phase function for the known separation r_Δ. These two quantities determine the phase speed of the bending wave. The phase speed is decisive using Eq. (1) to determine the complex-valued Young's modulus $\underline{E}$ and teh loss factor η.

2.3 Laser Doppler vibrometer measurements

Figure 1 illustrates the measurement setup based on laser Doppler vibrometer. A light-weight piezo thin disk as a exciter of the bending wave is attached on the viscoelastic panel under test. The laser beam perpendicularly senses the velocity of the bending wave $v_\mathrm{b}(t)$. From the exciter to the two points at r_1, r_2 radially away from the exciter, two impulse responses $h_\mathrm{b}^{(1)}(t)$, and $h_\mathrm{b}^{(2)}(t)$ are measured using the advanced correlation technique [7]. The LDV system is inevitably contaminated by speckle noise that manifests itself as random impulsive disturbance, and it is beneficial to use maximum-length sequences to mitigate this effect.

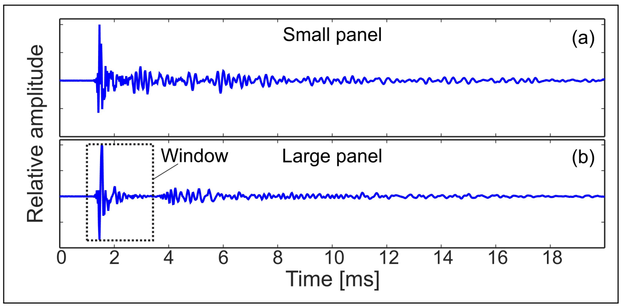

Figure 2. Comparison of bending wave impulse responses between small and large panels of 6.4 mm thickness. (a) Small panel. (b) Large panel. A window can be applied to the direct vibration signal.

3. RESULTS / DISCUSSIONS

Figure 2 illustrates examples of LDV-measured impulse responses on thin panels of different sizes. Figure 2 (a) shows a segment of the experimentally measured impulse response in the time domain on a square viscoelastic panel of 61 cm x 61 cm in size and 6.4 mm in thickness. The panel is made of XPS foam resiliently supported by elastic bands, as conceptually illustrated in Fig. 1. In the small panel as shown in Fig. 2 (a), boundary reflections are inevitably entangled with the direct vibration component.

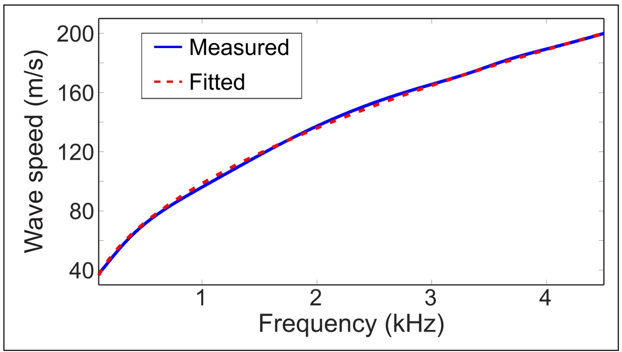

Figure 3. Phase speed of the bending wave experimentally measured in comparison with a curve fitting by a model of the square-root of frequency.

Figure 2 (b) shows a segment of impulse response experimentally measured on a large-sized panel (121 cm x 122 cm). The direct signal is temporally separated from the other reflections. The clear separation facilitates the application of a suitable window technique. The transfer function is then calculated from the windowed impulse responses $h_{\mathrm{b}}^{(\mathrm{W}_1)}, h_{\mathrm{b}}^{(\mathrm{W}_2)}$ at two radial points (r_1, r_2) followed by the fast *Fourier* transforms (FFT)

$$\underline{H}_{\mathrm{V}}(\omega) = \frac{\mathrm{FFT}[h_{\mathrm{b}}^{(\mathrm{W}_2)}]}{\mathrm{FFT}[h_{\mathrm{b}}^{(\mathrm{W}_1)}]} = |\underline{H}_{\mathrm{V}}(\omega)|\, \mathrm{e}^{-\mathrm{j}\varphi(\omega)}. \quad (5)$$

Its phase function results in the phase speed of the bending wave at the given separation of r_{Δ}. Figure 3 illustrates the experimentally measured phase speed of the XPS foam panel. As Eq. (2) indicates that the bending (phase) speed follows a course in square-root of frequency. Figure 3 also compares the experimental curve with that of the square-root of frequency, reflecting the viable measurement procedure for the bending wave speed. Figure 4 illustrates preliminary results of Young's modulus E' and the loss factor experimentally measured on the XPS foam panel. Further effort is expected in the near future to validate the method in systematic manner.

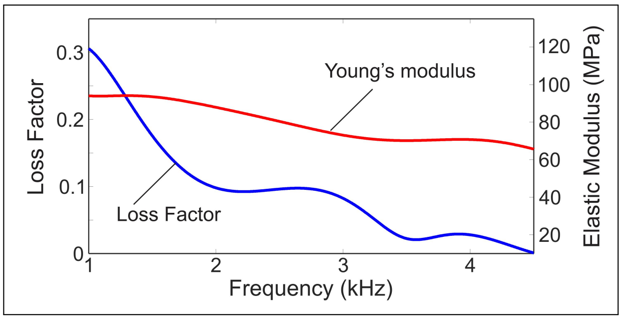

Figure 4. Young's modulus and the loss factor of the XPS foam panel experimentally measured by the transfer function method.

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