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SHAKER-EXCITED LDV MEASUREMENTS OF ETFE MEMBRANES AND CUSHIONS: ACOUSTIC RESPONSE TO RAINDROP IMPACTS

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ABSTRACT

The elastic properties of ethylene tetrafluoroethylene (ETFE) membranes are of importance for the features of their distinct drum-like acoustic response when subjected to rainfall, which in turn can affect acoustic comfort, speech intelligibility, and cognitive task performance. The spectrum and loudness of the sound caused by rain impact is dependent on the elastic parameters of the membrane, on the membrane tension, and on the geometry. This study addresses the elastic behavior of single-layer ETFE membranes and multi-layer ETFE cushions, using shaker-excited, scanning laser Doppler vibrometry (LDV)-detected guided wave measurements. The dispersion relation of bending waves running along ETFE membranes was determined, enabling the extraction of the applied tension. The findings contribute to a deeper understanding of the acoustic behavior of ETFE systems during rainfall and their implications for architectural design.

Keywords: *ETFE, Rain noise, Tension, Stress, LDV*

1. INTRODUCTION

Ethylene tetrafluoroethylene (ETFE) membranes are widely used in contemporary architecture due to their lightweight properties, durability, and optical transparency. They are commonly implemented in large-span roofs, façades, and stadium enclosures, where their mechanical and acoustic behavior plays a crucial role in overall performance. One of the significant acoustic challenges associated with ETFE structures is the sound generated by impacting raindrops [1,2]. Depending on factors such as membrane tension, material stiffness, and structural configuration, rain-induced noise can range from subtle background sound to disruptive levels that affect acoustic comfort in enclosed spaces. Accurately predicting this noise requires a precise understanding of ETFE's mechanical properties, particularly the in-plane tension, bending stiffness, and Young's modulus.

The in-plane tension of an ETFE membrane directly influences the propagation of bending waves, which in turn affects how vibrations and sound waves are generated upon raindrop impact. However, the exact tension in mounted ETFE membranes is not always well known, leading to uncertainties in acoustic modeling. A more accurate estimation of these mechanical properties allows for better predictions of rain-induced noise and improved numerical simulations of droplet impacts.

To address this, this study investigates the mechanical properties of single-layer ETFE membranes and multi-layer ETFE cushions through wave propagation analysis. The findings will contribute to improving the modeling of the

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acoustic response of ETFE membranes under raindrop impact, enhancing the accuracy of predictions for architectural applications.

2. METHODOLOGY

The measurement of ETFE membranes' vibrational properties was achieved through Laser Doppler Vibrometry (LDV), by recording the vibrational response of the membranes under excitation. This setup allows for a detailed analysis of the material's dynamic behavior at various frequencies and distances from the shaker. Figure 1 presents an image of the experimental setup. The measurements were conducted in a semi-anechoic chamber. The sample was placed on a damping material to minimize the transmission of vibrations from the sample through floor to the laser measurement device.

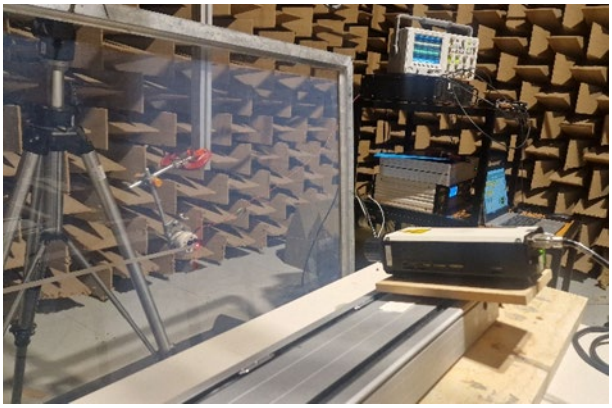

Figure 1. Picture of the measurement setup

A schematic representation of the measurement setup is provided in Figure 2.

The key steps were as follows:

- A swept-frequency signal is generated by a computer and transmitted to the shaker via a sound card, with amplification applied during transmission. The shaker's cylindrical moving element made gentle contact with the membrane, with its circular end (approximately 2 mm in diameter) touching the surface. The sweep covers a frequency range from 10 Hz to 10 kHz. To prevent overloading at low frequencies, the amplitude was fading in from low to high values till 1000 Hz and constant above. The total sweep duration was 20 seconds, which is more than twice of measured structural reverberation time of the sample. Figures 3 and 4 show the waveform and spectrogram of the sweep, respectively.

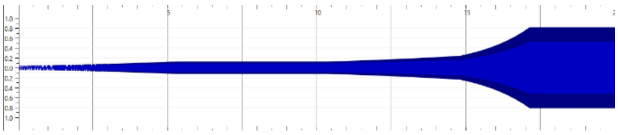

Figure 3. Waveform of the 20 second sweep

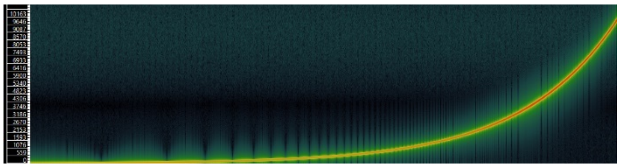

Figure 4. Spectrogram of the sweep

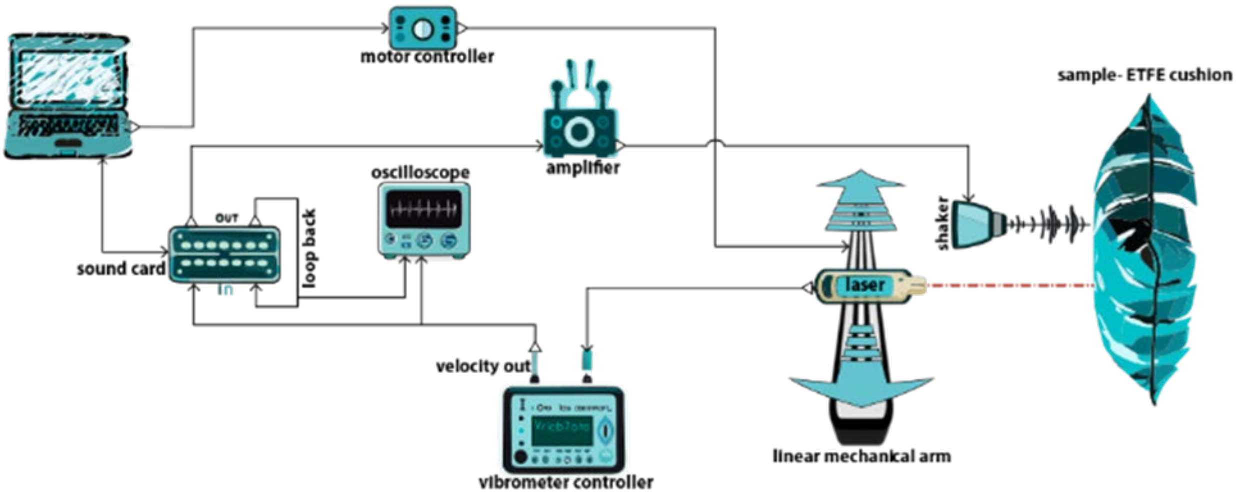

Figure 2. Schematic representation of the Laser Doppler Vibrometry (LDV) setup.

- The vibrational response was recorded with a sampling rate of 44.1kHz . In addition to the normal displacement component of the vibration response with a Laser Doppler Vibrometer (LDV), also the sent signal was looped back to a second recording channel, to serve as reference.
- The vibrations were recorded at different distances from the shaker contact point along a line starting from the excitation point using a linear mechanical arm. For each sample, over 600 recordings were taken along a distance exceeding 60 cm, with a spatial step size of 1 mm, thus obtaining the spatiotemporal dependence of the normal vibration velocities $v_z(r,t)$. The overall measurement range was sufficient to capture the longest wavelengths, while the spatial step size was fine enough to resolve the shortest wavelengths. Table 1 provides detailed specifications of the equipment used in this measurement setup.
- From the sweep recordings, for each detection distance, the spectrum $v_z(r,f)$ was determined. By making use of the sent spectrum, the transfer spectrum was determined and Fourier transformed to get the impulse response for each distance r.
- The impulse responses were windowed in order to select only the direct wave arrivals, and then Fourier transformed back to frequency domain. Finally, the direct signals $v_{z,direct}(f,r)$ were spatially Fourier transformed to obtain the waveumber-frequency dispersion relation $v_{z,direct}(f,k_b)$.
- From the maximum amplitudes in wavenumber-frequency domain, the velocity dispersion was determined.

$$c(f) = \frac{\omega}{k} \qquad (1)$$

Table 1. Equipment details

Equipment	Model/Specification	Details
Sound Card	Roland Quad-Capture	24-bit, 192 kHz
Amplifier	EHQ Power VPA2350MB	
Shaker	LDS V100 series	Diameter of moving circular end: 2mm
Velocity Controller(LDV Decoder)	Polytec OFV 3001 Vibrometer Controller	Velocity Range: 1000 mm/s/V
Retroreflective Tape		Thickness: 0.5 mm

Two types of samples were measured: a membrane and a cushion. Both consisted of similar membranes, as shown in Table 1, but differed in structure. The first sample was a single-layer membrane, while the second was a three-layer cushion with an air pressure of approximately 250 Pa in both cavities. The outer layers had a thickness of 250 µm, while the inner layer's thickness is uncertain but is estimated to be between 80 and 120 µm based on the company's production specifications.

3. THEORETICAL MODEL

3.1 Wave propagation in uniaxially stressed membrane

The material properties, specifically Young's modulus and tension, were determined by fitting the obtained c(f) to a theoretical model for Lamb wave propagation in a membrane under stress: for uniaxial stress, the governing dispersion relation for wave propagation is given by [3]:

$$\omega = \sqrt{\frac{\frac{B}{h} * k_b^2 + \sigma_{xx}}{\rho}}\, k_b \qquad (\mathrm{rad.s^{-1}}) \qquad (2)$$

where ω is angular frequency(rad/s), h is the membrane thickness (m), k_b is the wavenumber (1/m), σ_{xx} is in-plane tension(Pa), ρ is the material density(Kg/m^3), and B is the bending stiffness(N·m), given by:

$$B = \frac{Eh^3}{12(1-\nu^2)} \qquad (\mathrm{N.m}) \qquad (3)$$

E is Young's modulus (Pa) and ν is Poisson's ratio (dimensionless).

Eq. (2) can be rewritten to determine the phase velocity of the propagating bending wave:

$$c_b = \pm\sqrt{\frac{\sigma_{xx} \pm \sqrt{\sigma_{xx}{}^2 + 4\omega^2 \rho B/h}}{2\rho}} \qquad (\mathrm{m.s^{-1}}) \qquad (4)$$

where c_b represents the phase velocity. Equation (4) shows that the bending wave velocity is dependent on the in-plane tension of the material, as demonstrated in Figure 5 for an ETFE membrane-the sample used in this experiment, for literature values for the material properties listed in Table 2 and varying values of the tension.

Table 2. Known physical properties of the ETFE sample

Abbreviation	Name	Value	Unit
E	Young's modulus	0.52×10^9	Pa
H	Thickness	250×10^{-6}	m
μ	Poisson's Ratio	0.45	-
ρ	Density	1750	kg/m3
η	Loss Factor	0	-

4. RESULTS

4.1 Impulse response(time vs distance plot)

The impulse responses from all measurement positions were combined into a spectrogram, where the color represents the amplitude of the impulse response. The recordings were normalized to ensure that the impulse responses from further positions could be adequately visualized without excessive amplitude variation. Additionally, to mitigate the effects of high-frequency noise and improve signal clarity, low-pass filter was applied to the recordings.

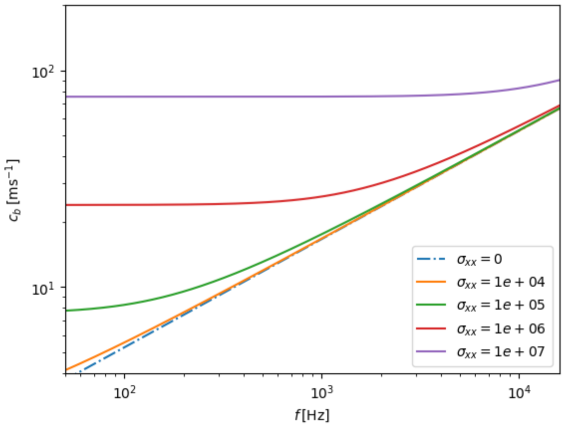

Figure 5. Theoretical relation between bending wave velocity and frequency for different values of the in-plane tension of an ETFE membrane.

The results are plotted as a function of position and time in Figure 6 (single-layer membrane) and Figure 7 (cushion). The signal magnitude is color-coded. The slope of the bright color regions corresponds to the bending wave velocity, with steeper slopes indicating a higher wave velocity. Also reflected waves, particularly in the cushion sample, can be observed, with the 722 mm position marking the edge of the sample.

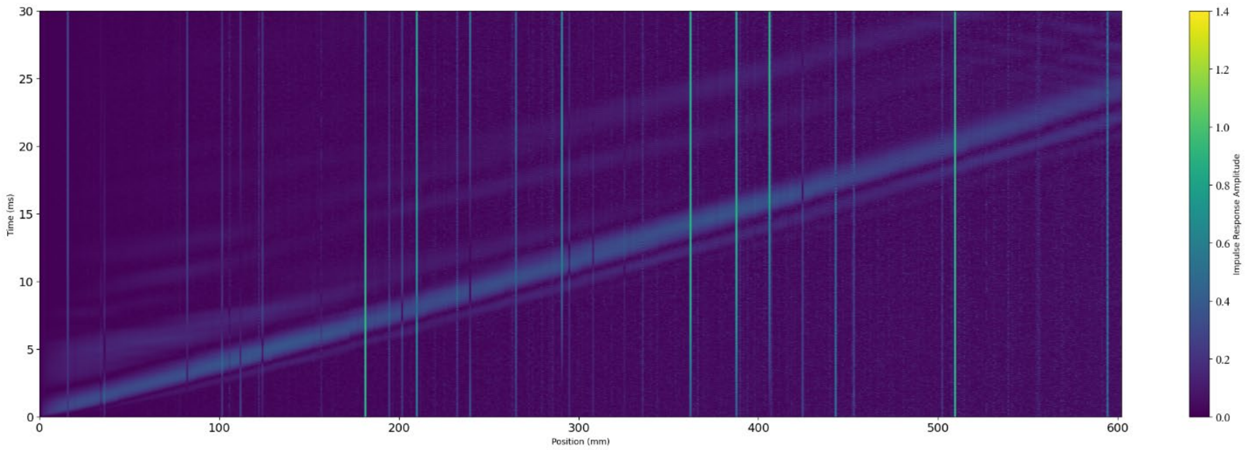

Figure 6. Time-distance plot of the arriving waves of the single-layer membrane.

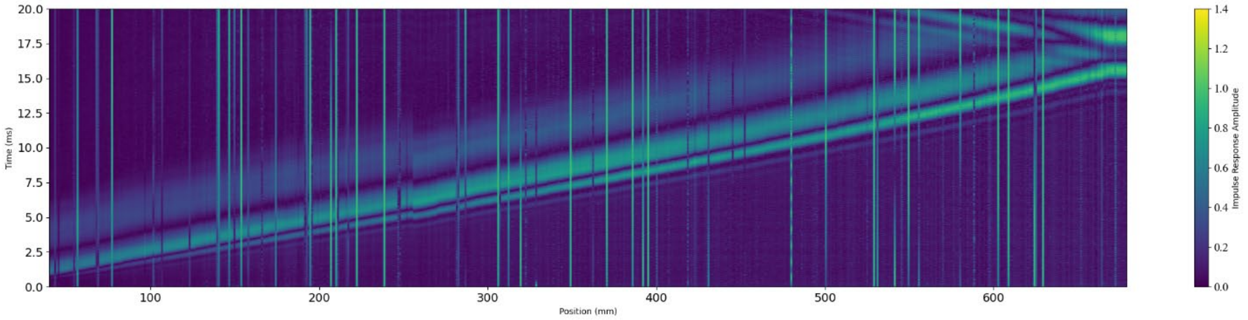

Figure 7. Time-distance plot of the arriving wave of the 3 layers cushion.

4.2 Wavenumber–frequency dispersion curve

After windowing the direct sound from the impulse responses, a 2D Fourier transform was applied, resulting in the wavenumber-frequency spectrum $S(k_b,f)$ in Figures 8 and 9, for the membrane and the cushion, respectively.

4.3 Tension estimation

Eq. (2), the relationship between wavenumber and frequency was used to fit the experimental k-f plot, enabling the estimation of the corresponding in-plane tension. The value of Young's modulus and Poisson' ratio were taken from literature (Table 1). The tension was found to be 1.95±0.03 MPa in the single membrane and 3.30±0.02MPa in the cushion.

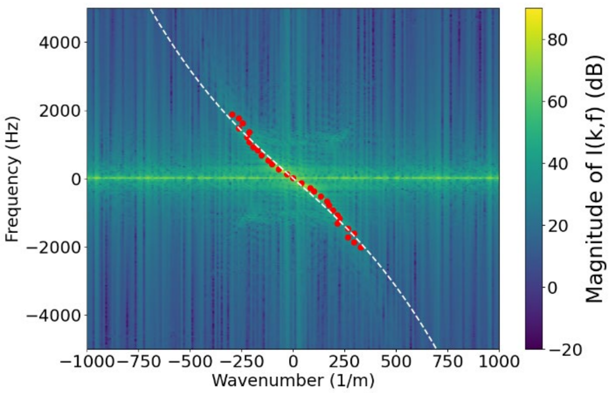

Figure 8. Fitted frequency-velocity plot of the bending wave along the membrane. The white dashed line represents the theoretical dispersion curve fitted using a tension value of 1.95 MPa.

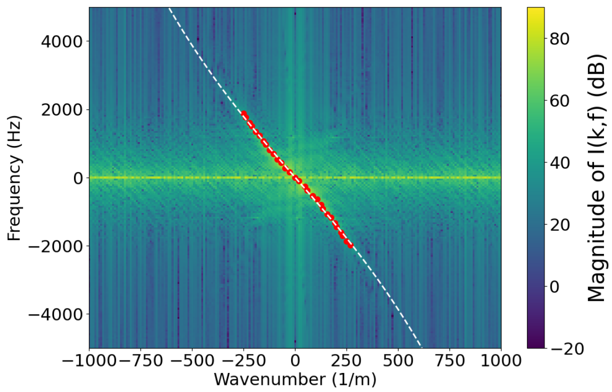

Figure 9. Fitted frequency-velocity plot of the bending wave along the 3 layer-cushion. The white dashed line represents the theoretical dispersion curve fitted using a tension value of 3.30 MPa.

5. CONCLUSION

This study has demonstrated the effectiveness of using shaker-excited Laser Doppler Vibrometry (LDV) to characterize the dynamic behavior and estimate the in-plane tension of ETFE membranes and cushions. We characterized a single-layer membrane with a thickness of 250 microns and a multi-layer cushion, which had an outer layer thickness of 250 microns, with an estimated internal air pressure of approximately 250 Pa. The results reveal a clear and significant difference in mechanical tension between the single-layer membrane (1.95±0.03 MPa) and the multi-layer cushion (3.30±0.02 MPa). These large tension values strongly affect the dispersion and therefore also the acoustic impedance[4] and radiation efficiency when rain drop impact generated bending waves are running along the surface.

This indicates that the applied tension can be used as a parameter to control or mitigate the loudness and spectral features of rain noise, which can be exploited in architectural design of membrane and cushion based building structures.

6. ACKNOWLEDGMENTS

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