EXPERIMENTAL STUDY OF PACKAGING MATERIALS BASED ON ACOUSTIC MEASUREMENTS COMBINED WITH TENSILE TESTS

Kai Yang, Etienne Mfoumou, Sharon Kao-Walter, Yilin Chi

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KAIYANG1,2; ETIENNEMFOUMOU1,3; SHARON KAO-WALTER1; YILINCHI2

Abstract. In this report, we investigated the variation between tension and fundamental frequency with respect to time, and at a constant strain rate. This was done for rectangular thin sheets under uniaxial tensile test and transverse vibration. Thin Paper (PPR), Low Density Polyethylene (LDPE) and laminate (PPR/LDPE/Al-foil) sheets were analyzed both within the elastic and plastic (which was investigated in this work) regions. The emphasis is on the linear relationship between the resonance frequency (in square) and the load.

Keywords: Acoustic Measurement; Thin Sheet; Resonance; Tension; Strain.

Introduction

Amongst many diagnostic methods for assessing dynamic properties, vibration testing is one of the most used. Vibration generated by acoustic waves has the advantage of being non-destructive, and therefore does not introduce any alteration in the material being tested.

Sound waves can be used to remotely excite thin materials because it is a non-contact method. This was illustrated with the concept of Shear Wave Elasticity Imaging (SWEI) [1]. In this work, a low frequency sound will be used for its good ability to remotely excite bending modes of thin sheets, and the dynamic property of the specimens was studied at a continuously increasing strain. The basic principles of the method were established in [2], and were based on the idea that a variation in tensile stiffness of a packaging related material causes detectable changes in the modal properties, specifically in the resonance frequency. In the present work a series of experiments on PPR, LDPE and laminate were performed. The measurements were conducted while the materials were in the elastic region but also extended to the plastic region until rupture occurred.

1. Theoretical analysis

1.1. Specimen geometry and assumptions.

The geometry of the specimen is a rectangular strip with length \( b \), width \( a \) and thickness \( w \), as shown in figure (1). The upper and lower ends are fixed and the surface of the membrane is subjected to transversal vibrations. Figure (1)-right shows the profile view of the specimen when vibrating at its fundamental mode.

Our investigation assumes the material to be a true membrane, with the following conditions:

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Figure 1. Specimen Model

1. The boundaries are free from transverse shear forces and moments in planes tangent to the middle surface.
2. The left and right edges of the specimen can be displaced freely in the direction normal to the surface of the membrane.
3. The material surface has a smoothly varying, continuous surface.
4. The components of the surface and edge loads must be smooth and continuous functions of the coordinates.
5. The material is assumed homogeneous and isotropic.

1.2. Vibration analysis. The specimen under vibration, as shown in figure (1), consists of a stretched membrane, allowing free transversal vibrations. The tensile force slowly increases continuously during small vibration excitation. The governing equation of a vibrating membrane having intrinsic elasticity was established in [4] as follows:

\[
\frac{\partial^2 \xi}{\partial t^2} - c^2 \left( \frac{\partial^2 \xi}{\partial x^2} + \frac{\partial^2 \xi}{\partial y^2} \right) + d^2 \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right)^2 \xi = \frac{p(x, y, t)}{\rho h}
\]

Here \( \xi \) is the displacement of membrane along the z-axis from its equilibrium position \( z = 0 \); \( c = \sqrt{F/(\rho ah)} \) is the velocity of propagation of bending wave which is determined by the tensile force \( F \) on boundary of the membrane, \( \rho \) is the density and \( h \) is the thickness of the membrane. The external pressure \( p(x, y, t) \) is a function of time and spatial coordinates. \( d^2 = \frac{Eh^3}{12\rho(1-\nu^2)} \), where \( E \) is the elastic modulus and \( \nu \) is the Poisson’s ratio.

The previous equation was used in [2] to derive the equation describing the natural frequencies of our rectangular strips as given below:

\[
w_{mn} = c_1 \sqrt{\left( \frac{\pi m}{a} \right)^2 + \left( \frac{\pi n}{b} \right)^2}
\]

\( m = 0, 1, 2, 3, \ldots; n = 1, 2, 3, \ldots \)

\( a, b \) are the dimensions of the membrane in figure (1); \( m, n \) are the mode numbers along the width and length directions respectively.

Materials, setup and experimental method
Two material compositions were tested in this work: a single layer paper sheet (PPR) and a single layer Low Density Polyethylene (LDPE). Tensile tests have been performed and the load-extension curves are shown in the Appendix A. The material physical properties and the specimen geometries are shown in table (1).

<table>
<thead>
<tr>
<th>Material</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPR</td>
<td>250</td>
<td>15</td>
<td>100</td>
</tr>
<tr>
<td>LDPE</td>
<td>250</td>
<td>15</td>
<td>25</td>
</tr>
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<td>15</td>
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</tbody>
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In this experiment, only the machining direction of the material is considered. For each specimen, the width and thickness were measured at a minimum of 10 different locations using a micrometer to the nearest thousandth of a millimeter. The values were averaged (values in table 1) in order to be used as input parameters in the TestWorks software of the MTS machine. The specimens were conditioned under room temperature of 23°C and an atmospheric humidity of 50% during three days prior to testing.
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![Figure 2. Experimental Setup](image)

The Experimental setup shown in Figure (2) consists of the following:
The specimen is vertically positioned between upper and lower clamps of the MTS Universal Testing Machine and is loaded at a constant strain rate by pulling the upper edge of the specimen. This allows for the record of the load and extension data. Simultaneously, a 10 V sine sweep signal with certain frequency range and sweep time depending on each material was generated to remotely excite the specimen through the loudspeaker. The vibration response of the material was measured by the LDV connected to a data acquisition card controlled by LabVIEW. The data processing setup was adjusted to acquire 20 kilosamples at a rate of 40 kilosamples/s. In the frequency domain, fast Fourier transform (FFT) was estimated in LabVIEW software, and the resonance frequencies were extracted from the response.

![Load vs extension curves for PPR](image)

**Figure 3.** Load vs extension curves for PPR

3. Experimental Results and Analysis

3.1. Experiment on PPR. The PPR material was loaded until it ruptured. The load extension curves for three specimens are shown in figure (3) in the appendix. The loading speed was 1.5 mm/min, and the swept excitation signal was ranging from 10 Hz to 600 Hz with a sweep time of 0.5 s. In setting up the LabVIEW, 20kHz was recorded at 40kHz sampling rate, and the fundamental frequency was monitored at increasing load. Figure (4) shows the variation of the fundamental
frequency, strain and tension versus time for five specimens with less variation, indicating a stable measurement.

Figures (5 and 6) show the plots of the square of the resonance frequency with respect to the strain and the applied load respectively. For the latter, the experimental result shows a curve with nearly the same slope from the start to the breaking point. This result complements the one obtained by Mfoumou et al. [3], which demonstrated the linearity of square of the frequency versus strain in the elastic region. The results show that equation (4) may also be suitable in the plastic region. Further investigation and analysis are required in order to support the observation made in the plastic region in this report.
3.2. Experiment on LDPE. A similar procedure was applied to LDPE. The material was extended to plastic region with a loading speed of 2.5 mm/min. The wave generator was set with a sine-swept frequency range of 10 Hz to 500 Hz and swept time of 0.5 s. All the other settings remained the same as with PPR.
The results obtained are shown in figures (7), (8), (9) and (10). Similar trends are observed leading to similar conclusions as shown below.

Figure 7. Load vs extension curves for LDPE

Figure 8. LDPE: Resonance, strain and tension vs. time
The settings in LabVIEW were the same as in PPR. The variation of the fundamental frequency, strain and tension versus time for five test specimens are shown in Figure (12).

The relationships between the square of the resonance frequency and both the strain and the applied load are shown in Figures (13) and (14).

3.3. **Experiment on Laminate.** Here laminates were loaded until rupture like the PPR. The load extension curves for three specimens are shown in figure (11). The materials were loaded until they break at a speed of 1.5 mm/min. The swept excitation signal ranged from 10 Hz to 600 Hz with the same swept time of 0.5 s.
The settings in LabVIEW were the same as in PPR. The variation of the fundamental frequency, strain and tension versus time for five test specimens are shown in Figure (12).

The relationships between the square of the resonance frequency and both the strain and the applied load are shown in Figures (13) and (14).

**Figure 11.** Load vs extension curves for Laminate

**Figure 12.** Laminate: Resonance, strain and tension vs. time
4. Conclusion

A series of experiments were performed in this work for investigating the relationship between resonance frequency and tension on thin sheet materials considered as membranes. The resonance frequency was continuously recorded at increasing
extension. It was found that the square of the resonance frequency is proportional to the applied load both in the elastic and plastic regions. This work used the method implemented in [2] for elastic region, and the observation from the figures indicates that there are new opportunities of further analytical investigation into the plastic region and correlation with elastic region.

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