Acoustic Measurements of the Slow Dynamics of Thin Sheets

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Abstract:
Based on the relationship between resonance and tension on thin sheets, an experimental approach was adopted to test the slow dynamic behaviour of Paper, Low Density Polyethylene (LDPE), the laminate of both and same laminate with Aluminium inclusive. We used a non contact acoustic excitation and non contact laser sensing. We chose to use a non contact acoustic excitation for its efficiency. A mixed dynamic extension was applied to the specimens including periods of dynamic extension and a long time of constant extension (conditioning).

The modal parameters were extracted via a laser vibrometer using the LabVIEW software. The results enabled us to show the slow dynamic characteristics of the thin sheets.

Keywords:
Slow Dynamics, Relaxation, Recovery, LabVIEW.
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Notation

\[ a \quad Width \ of \ the \ membrane \ [mm] \]
\[ b \quad Length \ of \ the \ membrane \ [mm] \]
\[ c \quad Velocity \ of \ propagation \ of \ the \ bending \ wave \ [ms^{-1}] \]
\[ d \quad Force \ specific \ volume \ [Nm^3kg^{-1}] \]
\[ E \quad Young's \ modulus \ [Nm^{-2}] \]
\[ f \quad Frequency \ [Hz] \]
\[ h \quad Thickness \ of \ the \ membrane \ [m] \]
\[ p \quad External \ Pressure \ [Nm^{-2}] \]
\[ T \quad Tension \ on \ the \ membrane \ [N] \]
\[ t \quad Time \ [s] \]
\[ x \quad Position \ in \ x-axis \ direction \ [m] \]
\[ y \quad Position \ in \ y-axis \ direction \ [m] \]
\[ z \quad Position \ in \ z-axis \ direction \ [m] \]
\[ \xi \quad Displacement \ to \ the \ membrane \ [m] \]
\[ \rho \quad Density \ [kgm^{-3}] \]

Abbreviations

PPR \quad Paper
LDPE \quad Low \ Density \ Polyethylene
DAQ \quad Data \ Acquisition
FFT \quad Fast \ Fourier \ Transform
DFT \quad Discrete \ Fourier \ Transform
DTFT \quad Discrete \ Time \ Fourier \ Transform
FRF \quad Frequency \ Response \ Function
Chapter 1

Introduction

1.1 Background

This thesis work deals with the properties of thin sheets. Thin Sheets (thickness \( \leq 100 \mu m \)) exhibit certain changes in their material properties when subjected to dynamic loading. Moreover, they are assumed to have no bending stiffness. For this reason, we decided to carry out an experimental investigation of this phenomenon. The method to be used is acoustic excitation which is a non-contact process. There are many diagnostic methods applied nowadays in structural testing and detection. However, amongst them, the acoustic diagnostic method is one of the most important. The reason for this is that it involves the use of non-destructive testing approach where the test material is actually not adversely affected by the test source. It has an obvious advantage to be used in non-destructive measurement in engineering fields, such as the material science and medical field.

In this report, we have used a vibration-based technique. A low frequency sound was used for its good propagation through materials and for that reason; sound waves can excite vibrations remotely as well. Based on remote excitation, the properties of specimens vibrated by sound waves were studied.

The measuring principle of the materials was based on the physical property that is subjected to non-equilibrium dynamics which changes the modal properties of the thin sheet.

Thin films were given as the specimens to be measured. The loading applied on the thin film would affect its modal properties as it is excited by the swept sine wave sound. In this work, we will study how the resonance frequency shifts obtained from experimental measurements is affected. It is also interesting to know how the relaxation and recovery of the material happens and try to forecast if the materials go back to their original form.
1.2 Aim and Scope

1.2.1 Aim

What we need to obtain is the slow dynamic behaviour of thin membranes which are subjected to dynamic strain or extension. Here, slow dynamics refers to the fast decrease in elastic modulus in response to symmetric stress cycling or temperature change of either sign, thus violating the symmetry of the inducing source [1], and the slow subsequent recovery.

1.2.2 Scope

The main purpose of our work is to determine the slow dynamic characteristics of Thin Sheets via experimental results. This will involve applying cycles of constant low and high extension strains, and then measuring the resonance shift. The observation of how the acoustic resonance shifts, in the dynamic and static state due to the changing of the material properties, is crucial in this experiment.

1.3 Method

To perform the experiment, we needed to apply a non-destructive testing method owing to the fact the material is very light and thin, making it more sensitive to impact and the environment.

There are many non-destructive methods among which are:-

1) radiographic testing
2) ultrasonic testing
3) acoustic testing
4) liquid penetrant testing
5) magnetic testing
6) eddy current testing

We preferred to use acoustic testing for the reason that we are required to make the material vibrate so that we extract its modal properties. Low frequency acoustic wave within the range of 10 – 450 Hz was considered. The wave type of choice was a sine-sweep because it contains more energy at low frequencies as an excitation signal. We just needed to enter the start
frequency, end frequency and the sweep time in the MATLAB script developed to run simultaneously with the LabVIEW software.

In this thesis work, we will test paper sheet, low density polymers and two laminate sheets, one made of the previous two and the other made of aluminium inclusive.

1.3.1 Similar Work and its Method

While the creep test (as in rigid objects such as rocks) is carried out at prolonged constant tension and compression at constant elevated temperatures [2], our test involves prolonged conditioning (low and high extensions) strains at constant room temperature. Also in the determination of the stress relaxation, we use a safe extension (within the elastic region) instead, when measuring the decrease in stress over a prolonged period of time at constant strain.

According to Mfoumou Etienne [3], the stress relaxation curves were obtained from the data recorded by the TestWorks software (bundled with the MTS machine). His work was quite similar to ours based on the general method used, but there is a great difference in the approach used in analysis of the data obtained, which is what is particularly interesting. The frequency shifts obtained via the LabVIEW software was used instead. Owing to the extracted modal parameters of the vibrating membrane, we were able to show that the recorded frequency shifts were enough if not more convenient to describe the behaviour of these materials in terms of the relaxation. This method produced similar results as in [3], but with different characterization of the materials.

1.3.2 Method in this topic

For testing the membrane materials, we would apply an outer dynamic extension on specimens and simultaneously excite the thin sheets with a swept sine sound wave from one side normal to the surface of the specimen. The vibrating frequency (velocity) of the membrane will be measured with a non-contact laser vibrometer. The data is obtained via the labVIEW software and the recorded resonances are analyzed. With the acquired data, we have to solve for the FFT (Fast Fourier Transform) and FRFs (Frequency Response Functions) which aids us in describing the slow
dynamic properties of thin sheets over time. The block diagram of the method is shown in figure (3.2).
Chapter 2

Theoretical Model

2.1 Physical Model

The geometry of the specimen is a rectangular strip with length $b$, width $a$ and thickness $w$, as shown in figure (2.1 a). The upper and lower ends are fixed as the surface of the membrane is subjected to transversal vibrations. Figure (2.1 b) - right shows the profile view of the specimen when vibrating at its fundamental mode. The image to the right in figure 2.1 shows the profile view of the specimen when vibrating at its fundamental mode.

We already know from Mfoumou et al. [3] that bending resonance can be used to extract the Young’s modulus of thin sheets.

Figure 2.1 Specimen Model.
2.2 Assumptions

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

1. The boundaries are free from transverse shear forces and moments in planes tangent to the middle of the 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 smooth continuous surface.
4. The components of the surface and edge loads must be smooth and continuous functions of the coordinates.
5. Vibrating displacements are assumed to be sufficiently small so that the response to dynamic excitation is always in the elastic region.
6. The material is assumed homogeneous and isotropic, and following Hooke's law.

So, the ideal model is one that has no bending stiffness. And the material can only sustain tensile loads, which is the most principle condition to the derivation of wave speed from the resonance frequencies.

2.3 Mathematical Model

The specimen under vibration, as shown in figure (2.1 b), 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 [3] as follows:

\[
\frac{\partial^2 \xi}{\partial t^2} - c^2 \left( \frac{\partial^2 \xi}{\partial x^2} + \frac{\partial^2 \xi}{\partial y^2} \right) + a^2 \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right)^2 \xi = \frac{p(x, y, t)}{\rho h} \tag{2.1}
\]

Where \( \xi \) is the displacement of membrane along the \( z \)-axis from its equilibrium position \( z = 0 \), \( c = \sqrt{\frac{T}{\rho h}} \) is the velocity of propagation of the bending wave which is determined by the tensile force \( T \) per unit length of boundary of 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 of
spatial coordinates. \( d^2 = \frac{Eh^2}{12\rho(1-v^2)} \), Where \( E \) is the elastic modulus and \( v \) is the Poisson’s ratio.

### 2.4 Simplification to Case

Solution to equation (2.1) is a form of summary of each mode. In our case, we need just the first mode that is vibrating across the length direction, and without the other modes. The solution that we need for equation (2.1) is expressed as:

\[
\omega_n^2 = \frac{T}{4\rho ab^2 h}, \quad \text{or} \quad f_n = \sqrt{\frac{T}{4\rho ab^2 h}} \quad (2.2)
\]

Note that equation (2.2) only holds for the case where the membrane is vibrating in the first mode as shown in figure (2.1 b).
Chapter 3

Materials Selection and Experimental Setup

3.1 Material Selection

The first material that will be used in the experiment is paper sheet (PPR). Except for the general usage, such as to write or print on, to represent a value as money etc, it has a huge usage in the industry such as for packaging use. Thus, the paper sheet is chosen as one of the materials due to its important usage.

Low-density polyethylene (LDPE) is another material that we will use in the experiment. It is a thermoplastic made from oil. It has a good unreactive property, quite flexible and even almost unbreakable. It is widely used to manufacture various containers, computer components, laboratory equipment etc. The understanding of its characteristics under cyclic load is of great importance in this experiment.

In industry, sometimes we have a need to combine some properties to satisfy a production condition. People combine two or more layers of materials together to obtain some special properties.

In our experiment, we would use a kind of laminate that is made up of three layers, which includes PPR, LDPE and aluminum. We would also test the laminate that is made up of only PPR and LDPE. Laminates of these materials is very interesting to study because they are widely used in the food packaging industry. Usually the combined property of these materials is more important than that of the individual material. For an instance, a liquid content could be wrapped using a laminate of LDPE and PPR. While the LDPE protects the liquid from soaking the PPR, the PPR protects the LDPE as well as the liquid from rough surfaces which would have led to a leakage.
3.1.1 Material Parameters

The materials that were used are as follows:

(1) PPR (100 µm)
(2) LDPE (25 µm)
(3) Laminate (two layers), LDPE (25 µm)/ PPR (100 µm)
(4) Laminate (three layers), LDPE (25 µm)/ PPR (100 µm)/ Al (20 µm)

The dimensions and the material parameters are shown in the table (3.1):

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPR</td>
<td>684</td>
<td>250</td>
<td>15</td>
<td>100</td>
</tr>
<tr>
<td>LDPE</td>
<td>910</td>
<td>250</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Laminate (2 layers)</td>
<td>729</td>
<td>250</td>
<td>15</td>
<td>125</td>
</tr>
<tr>
<td>Laminate (3 layers)</td>
<td>1063</td>
<td>250</td>
<td>15</td>
<td>145</td>
</tr>
</tbody>
</table>

Here, all the length directions of materials are in the machine direction (MD) because it has a better property rather than cross direction of the thin membrane.

3.1.2 Material Storage Condition

The temperature and the humidity are two important conditions that would affect the experiment very much. In our experiment, the mentioned materials are stored in the laboratory at a constant temperature of 20°C and 40% constant humidity.

Additionally, the materials are stored in the above condition for more than one week. And the experimental condition is the same as the storage condition.
3.2 Experimental Setup

3.2.1 Equipment

In this experiment, there are four modules introduced to carry out the task.

(1) Apply the outer extension or strain on the membranes holding them at a constant position. Then record the parameters that are time, extension, stress, force and even strain using the software TestWorks controlling the MTS machine.

(2) Generate the sound wave that is suitable for the experiment and send the signal through the loudspeaker. This in turn excites the membrane.

(3) Measure the response of the membrane using the laser vibrometer, and save the data with the LabVIEW software for further analysis.

(4) Analyze the saved data to get the modal parameters as the result that would be used. Both the FFT and FRFs are generated.

The equipment and software that were used in the experiment are:

(1) MTS QTest/100 system with its supporting software TestWorks 4.0,
(2) LabVIEW with hardware NI BNC-2100 data acquisition (DAQ),
(3) MATLAB,
(4) Laser Doppler vibrometer (Ometron VS 100),
(5) Amplifier (Vincent SP331) and
(6) Loudspeaker.
3.2.2 Equipment Setup

The equipment setup is as shown in figure (3.1):

Figure 3.1 Equipment Setting.

A. Monitors for LabVIEW and TestWorks (MTS machine).
B. NI BNC 2110 (Data acquisition card).
C. Laser Doppler vibrometer.
D. The Specimen.
E. Loudspeaker.
F. Oscillograph (test the frequency range before the former experiment)
G. Amplifier.
H. MTS QTest/100 system.
3.2.3 Equipment’s Working Principles

Firstly, let us see the experimental block diagram for this test setup as shown in figure (3.2).

![Experimental block diagram]

**Figure 3.2** Experimental block diagram.

For the excitation part, we generated a swept sine wave codec using MATLAB which was added to the LabVIEW software protocol to generate the sound via an A/D converter; NI BNC 2110. Through the amplifier, the signal was magnified to excite the membrane via the loudspeaker.

The response of the membrane was measured with a laser vibrometer, which generates an analog signal which is later converted to a digital signal.

Both the signal from the wave generator and the laser vibrometer are introduced into LabVIEW by NI data acquisition card (DAQ). They are considered as input and output signals of the excited membrane, which are to be processed. For each data block from the DAQ, we derive a resonance and record it together with the related time. The data would be used for analysis in the following chapters.
3.2.3.1 Sound Generation

In order to vibrate (excite) the membrane over a range of frequency, we need a swept sine acoustic wave. Since we have decided to use a low frequency acoustic wave, the range of the swept sine frequency was discretionally chosen to be from 10 Hz to 300 Hz for a test. The sweep time was taken to be 5 seconds. We also made use of digital filters which is better than the traditional analog filters in many ways.

The distance between the membrane and the loudspeaker was maintained at about 200 mm (0.2 m) giving a sharp focus by the vibrometer.

\[ y(i) = A \sin \left( \frac{a \cdot i^2}{2} + b \cdot i \right) \] (3.1)

Where \( y \) = Amplitude, \( i \) = an integer, 
\( A \) = Peak Voltage Amplitude 
\( a \) and \( b \) are variables. 
\[
\begin{align*}
a &= \frac{2\pi(f_2 - f_1)}{n} \\
b &= 2\pi f_1
\end{align*}
\]

Where \( n \) = number of samples 
\( f_1 \) and \( f_2 \) are the normalized frequencies at the start and stop respectively. Both are in the units; cycles per samples.

\[
\begin{align*}
f_1 &= \frac{\text{start frequency}}{\text{sampling frequency}} \\
f_2 &= \frac{\text{end frequency}}{\text{sampling frequency}}
\end{align*}
\]

We need a sample rate that will produce a reasonable representation of a sine wave at the stop frequency. We used at least 10 samples/cycle at stop frequency i.e. 10 multiplied by the end frequency equals the sampling frequency, or at least 10 multiplied by the start frequency equals the
sampling frequency. This is done to ensure that we avoid aliasing in the generated signal.

For the index, we used 0 to (n-1) samples. The index is used for the regulation of the voltage sent to the loudspeaker via the amplifier.

A MATLAB script was used to implement the swept sine in connection with LabVIEW’s Virtual instrument. The plot of the wave is shown in the figure 3.3 below.

![Figure 3.3 Sine sweep wave as the exciting sound wave.](image-url)
Chapter 4

Experimental Basis

4.1 Existing Experiments

The content of this chapter refers to the work in [4]. The thin membranes are to be extended from 0mm to the state which is the critical rupture point (5mm – 10mm); however the LDPE is extended to 40mm because it can't be broken in the MTS working range. The tensile speed for PPR and Laminate is 1.5mm/min, but for LDPE it is 2.5mm/min, with 20 kilosamples and 40 kHz sampling frequency in the LabVIEW setup. The remote sound is sweeping from 10Hz to about 600Hz within 0.5 s.

Data acquisition system used was the NI BNC 2110 from National Instruments instead of the traditional wave generator.

4.2 Existing Results

From the equation (2.2) in chapter 2, the square of the resonance of the thin membrane is proportional to the tension applied on it. Because the other parameters, density $\rho$, width $a$, length $b$ and thickness $h$, are considered to be constant. It means that, the square of the resonance is in linear relationship with the tension.

The three trial materials were paper sheet, low density polyethylene (LDPE) and the laminate made from paper sheet (PPR), LDPE and aluminum. The dimensions are the same as in the previous chapter.
The figure (4.1) shows five specimen-tests, which is the relationship between the square of the resonance and tension of PPR. The black straight line is the analytical curve from equation (2.2), while the five colorful lines refer to the five tests respectively.

It is clear that the square of the resonance is proportional to the tension of PPR, though the theoretical curve is not the same with the experimental results but they are quite close. However, what we need to understand is that the two parameters (square of the frequency and tension) are in proportion.

**Figure 4.1** PPR: Resonance vs. Tension.
Figure 4.2 *LDPE: Resonance vs. Tension.*

Figure (4.2) shows three specimens' tests for the LDPE material. The line colors and line type represents similar meaning as it is in PPR figure. For LDPE, it is thinner than PPR, and it was extended much more than the previous ones, so this induces more error than the PPR.

Nonetheless, the relationship between the square of the resonance and the tension in the experimental results is proportional, which satisfies our expectation.

What we need to explain here is about the fluctuation of the experimental results in figure 4.2. For LDPE, it is very soft resulting to the small tensile strength of the material, ranging from 0N to 3N. Due to the later reason, little force causes big displacement which makes the membrane seem to be fluctuating more than in the PPR. And the resonance is according to the tension value, so it is also fluctuating simultaneously.

Now we go to the case for the laminate that is including three layers (PPR, LDPE and Aluminum). See figure (4.3). The lines represent similar
meaning as in the previous two. The analytical curve is exactly consistent with the experimental results. So, the square of the resonance is proportional to tension both for analytical solution and experimental results.

![Graph showing resonance in square vs. Tension](image)

**Figure 4.3** Laminate: Resonance in square vs. Tension.

### 4.3 Conclusion

The experimental tests for the three materials indicate that there is a linear relationship between the square of the resonance and the tension on the membranes, which is in the first mode without bending stiffness. And it reveals the relationship between the mechanical characteristics and the modal parameters. It provides us with the basic understanding of this thesis topic.

With the force or modal parameter of the known materials as we have tested above, we can differentiate one from the other by the theoretical or experimental relationships.
Furthermore, it provides another indirect approach for the research of relaxation or reverse-relaxation because they are the stress changes under constant strain.

In the following chapters, we would apply the dynamic relaxation and reverse-relaxation on membranes to study the trends of their behaviour.
Chapter 5

Slow Dynamics Experiment

In this chapter, we will discuss the slow dynamics tests on the mentioned membrane materials. The dimensions are shown in chapter 2. We applied dynamic extension on the membrane. See the figure (5.1) which shows one dynamic cycle that includes ten periods of high extension and low extension. The low extension lasts as long as the ten periods. Here, in each period, the hold time $t_1$ of high extension is the same as that of low extension $t_2$. In our experiment, we set $t_1$ and $t_2$ to be 200 seconds each. So that for one period, including the high extension and the low extension, we have (200 * 2) seconds. Then for the whole dynamic cycle, which includes both the ten periods and the hold time in the low extension, we would have (2 * 10 * 400) seconds. We would apply three dynamic cycles on the membranes to obtain the slow dynamic characteristics. One set of experiment lasts for about 7 hours.

Figure 5.1 Dynamic extensions for one dynamic cycle (from MTS m/c).
5.1 PPR: Slow Dynamics Experiment

5.1.1 Initial Result

Firstly, we test the PPR material. The setting in MTS machine is shown in table (5.1).

Table 5.1 PPR_MTS settings.

<table>
<thead>
<tr>
<th>Name</th>
<th>Setup Parameters</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preload</td>
<td>0.45</td>
<td>N</td>
</tr>
<tr>
<td>Preload speed</td>
<td>25.4</td>
<td>mm/min</td>
</tr>
<tr>
<td>Data acquisition rate</td>
<td>100</td>
<td>Hz</td>
</tr>
<tr>
<td>High extension</td>
<td>1</td>
<td>mm</td>
</tr>
<tr>
<td>Low extension</td>
<td>0.6</td>
<td>mm</td>
</tr>
<tr>
<td>Hold time t1</td>
<td>200</td>
<td>s</td>
</tr>
<tr>
<td>Hold time t2</td>
<td>200</td>
<td>s</td>
</tr>
<tr>
<td>Cycles</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Test speed</td>
<td>10</td>
<td>mm/min</td>
</tr>
</tbody>
</table>

In LabVIEW, we set the number of samples to 100,000 for the data acquisition card and the sampling frequency to 10 kHz. The frequency accuracy is enough for this experiment, because there are many factors that affect the experiment, such as the wind from air conditioning, the working of the other equipment, and the reverberation of the sound by the walls.

After the testing is done on the PPR, we obtain the frequency-time figure through MATLAB data processing. We get two data, one is the FRF, and the other one is FFT as shown in the figure (5.2).
The trend shows that, for the three dynamic cycles, the resonance frequency decreases with time. In each dynamic cycle, the peaks of the ten periods are also decreasing individually. However, for each period, the trend is decreasing in the high extension, and increasing in the low extension. This is according to the relaxation and the reverse-relaxation of the material when tensioned on the MTS machine as mentioned in the previous chapter. In the long time reverse-relaxation that last for the same time as the preceding ten periods, the frequency increases according to the increasing tension under the recovery stage.

**Figure 5.2** PPR: Frequency-time figure in dynamic extension.
5.1.2 Trends for Each Cycle

The three dynamic cycles are constructed from the ten relaxations and ten reverse-relaxations without the recovery trend. And they are similar in each cycle, however the distributions are different. Let us check the distribution in one figure for each dynamic cycle. Here, the long time recovery is left out for later discussion.

![Figure 5.3](image-url) 

**Figure 5.3** PPR: (Reverse) Relaxation and their 4th polynomial curve fitting (first dynamic cycle).
Figure 5.4 PPR: (Reverse) Relaxation and their 4th polynomial curve fitting (second dynamic cycle).

Figure 5.5 PPR: (Reverse) Relaxation and their 4th polynomial curve fitting (third dynamic cycle).
In the figures (5.3, 5.4, and 5.5), the upper curves are for the relaxations and the lower ones are for the reverse relaxations. And the red curves represent the experimental curves, while the green curves represent the relative fourth order polynomial curve fitting.

Here the fourth order polynomial curve fitting is in the form of

\[ F^2 = At^4 + Bt^3 + Ct^2 + Dt + E \]  \hspace{1cm} (5.1)

Where F is frequency, t is time, and A, B, C, D, E are the constants according to the experimental curve.

From the three figures, it is obvious that the upper relaxation curves decreases successively. It is the same case for the lower reverse-relaxations. Among the three figures, figure (5.3) decreases faster than the later two figures (5.4 and 5.5).

What is more interesting is that each of the lower reverse relaxation curves is increasing with time although they decrease successively.

In addition, if we check the values of the starting point of each major cycle, we would observe that the peak of the first cycle of the dynamic frequencies in square is at 1.3 * 10^5 Hz^2, the second is at 1.1 * 10^5 Hz^2, while the third is at 1.07 * 10^5 Hz^2. The differences between the neighbors are not equal or equivalent. The first difference is greater than the second. Thus, the rate of decrease in the peaks slows down in time advance if not disappear entirely.

5.1.3 Trends for Similar Points

The previous curves show the general trend of the slow dynamics of PPR. We need more particular trends that are clear and can be defined by values. In order to define the kind of trends, we should pick the points with values from the figure (5.2). For example, for one period in a dynamic cycle, we chose four points in it. The sketch map is shown in figure (5.6 a and b). We decided to name the start point of the relaxation curves as up1 and the end point as up2. In the same manner, the start point of reverse-relaxation curves was named as low1 and the end point as low2.
Figure 5.6a Sketch map used in picking points for slow dynamic trends.

Figure 5.6b Illustration of how the points were picked.

- Upper start point → the beginning of each relaxation period
- Upper end point → the end of each relaxation period
- Lower start point → the beginning of each reverse relaxation (i.e. recovery) period
Lower end point → the end of each reverse relaxation (i.e. recovery) period
First dynamic curve → the first big period during Conditioning ON (i.e. the ten cycles)
Second dynamic curve → the second big period during Conditioning ON (i.e. same ten cycles)

We picked the points from each period of the ten cycles and note them as up1x; up1y; up2x; up2y; and low1x; low1y; low2x; low2y, here up represents the upper line, while low represents the lower line, 1 and 2 represents the start point and the end point respectively, while x and y represents the x and y coordinates. Then we obtain three tables (5.2, 5.3, and 5.4) for the three major cycles:

Table 5.2: PPR: The start and end values of the first dynamic cycle (Units x[s] and y[Hz]).

<table>
<thead>
<tr>
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<th>Second</th>
<th>Third</th>
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Table 5.3: PPR: The start and end values of the second dynamic cycle  
(Units x[s] and y[Hz]).

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Table 5.4: PPR: The start and end values of the third dynamic cycle  
(Units x[s] and y[Hz]).

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</table>
We connected the four different points (that is the start and end points of the relaxation and reverse-relaxation curves) to produce four lines having ten points each. These four lines are plotted in one figure for each of the three major dynamic cycles. The figures are shown in Fig. 5.7, 5.8 and 5.9.

Figure 5.7 PPR: Curves of up1, up2, low1 and low2 in the first cycle.
Figure 5.8 PPR: Curves of up1, up2, low1 and low2 in the second cycle.

Figure 5.9 PPR: Curves of up1, up2, low1 and low2 in the third cycle.
The above figures (5.7, 5.8, and 5.9) reveal the relationship between the four types of lines in each major cycle joining the up and low points. The red line represents the start point of upper extension (up1), the green line represents the end point of upper extension (up2), the blue line represents the start point of the lower extension (low1), and the black one represents the end point of the lower extension (low2).

For these curves, the curve connecting the up1 is greater than that of up2 in each major cycle, while the low1 curve is less than that of the low2 curve. We can say that for the up curves, relaxation is taking place, thus the later points should be less than the previous ones. This is not the case for the low curves because it is the reverse relaxation instead.

Next we plot the curves for up1, up2, low1 and low2 of the individual major cycles but this time, superimposing the plots for the three major dynamic cycles on one plot. This means that the plots for up1 alone for the three major cycles are plotted in the same plot so that the scaling is much near to the line type, then it is easy to distinguish between them. See figure (5.10, 5.11, 5.12, and 5.13).

![Figure 5.10](image)

**Figure 5.10** PPR: Comparison of start points (up1) of high extension for three major cycles.

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Figure 5.11 PPR: Comparison of end points (up2) of high extension for three major cycles.

Figure 5.12 PPR: Comparison of start points (low1) of low extension for three major cycles.
Figure 5.13 PPR: Comparison of end points (low2) of low extension for three major cycles.

The above four figures shows the slow dynamics trends of the PPR membrane in the start point and the end point of up and low extensions. Blue circular points represent the measurements from the first major cycle, green right triangular points represent those from the second cycle, and the red triangular (with horizontal base) points represent the third.

What we get from the above curves is that, in the beginning of the dynamics (that is the start point of high extension), the frequency decreases sharply then slowly. It is the same case as the start points of the reverse relaxation curve but in the opposite direction.

Another phenomenon that is obvious in the figure is that the difference between the first and the second curve is greater than that between the second and the third and so on.

We can now say that the trend reveals the rule that slow dynamics starts with a frequency which decreases speedily at the beginning followed by a slow decrease towards the end of the cycle. We suggest that it might stabilize (recover completely), if the time is long enough (maybe days).
5.1.4 Exponential Curve Fitting

5.1.5 Recovery Curve

For the long time reverse-relaxation, we plot the three figures and make the exponential curve fitting for the experimental results. See figures (5.14, 5.15, and 5.16). However, the interesting thing is that each of the lower reverse relaxation curves (recovery curve) is increasing even in the period without dynamics. But looking at the three major cycles, they are decreasing one after the other.

SECOND DYNAMIC

\[ T_{\text{Max}}(f_q = ) = 44.198 \]
\[ T_{\text{Min}}(f_q = ) = 0.176 \]

Figure 5.14 PPR: Long time reverse-relaxation and its curve fitting in the first major cycle.
Figure 5.15 PPR: Long time reverse relaxation and its curve fitting in the second major cycle.

Figure 5.16 PPR: Long time reverse relaxation and its curve fitting in the third major cycle.
It is similar as in the relaxation curves; the beginning part of the reverse relaxation increases sharply followed by a much slower increase towards the end.

Comparing the three curves; it is also obvious that the first curve increases the fastest, while the third one is the slowest.

5.2 LDPE: Slow Dynamics Experiment

5.2.1 Initial Result

Taking a close look at figure 5.17, we would observe that the relaxation and reverse relaxation curves are generally the same as in the PPR, however the degree of randomness in the experimental data is higher. As a result, the curves obtained by joining the points are not smooth or rather as smooth as those of the PPR. The reason for this behavior of the LDPE might be related to its good elastic property. Also, this elastic property of the LDPE makes it more sensitive to external disturbances.

![Figure 5.17](image.png)

*Figure 5.17 LDPE: Frequency-time figure in dynamic extension.*
5.2.2 Trends for Each Cycle

Apart from the issue mentioned above, the other results obtained from the LDPE data looks quite alike. These are in figures 5.18, 5.19 and 5.20 for the three big cycles as shown below.

Figure 5.18 LDPE: (Reverse) Relaxation and their 4th polynomial curve fitting (first dynamic cycle).
Figure 5.19 LDPE: (Reverse) Relaxation and their 4th polynomial curve fitting (second dynamic cycle).

Figure 5.20 LDPE: (Reverse) Relaxation and their 4th polynomial curve fitting (third dynamic cycle).
Table 5.5: LDPE: The start and end values of the first dynamic cycle
(Units x[s] and y[Hz]).

<table>
<thead>
<tr>
<th>Order</th>
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Table 5.6: LDPE: The start and end values of the second dynamic cycle
(Units x[s] and y[Hz]).

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Table 5.7: LDPE: The start and end values of the third dynamic cycle
(Units x[s] and y[Hz]).

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</table>
5.2.3 Trends for Similar Points

The trends for the similar points are the same as in the PPR. The figures are shown as follows:-

**Figure 5.21** LDPE: Curves of \textit{up1}, \textit{up2}, \textit{low1} and \textit{low2} in the first cycle.
Figure 5.22 LDPE: Curves of up1, up2, low1 and low2 in the second cycle.

Figure 5.23 LDPE: Curves of up1, up2, low1 and low2 in the third cycle.
Figure 5.24 **LDPE: Comparison of end points (up1) of up extension for three major cycles.**

Figure 5.25 **LDPE: Comparison of end points (up2) of up extension for three major cycles.**
Figure 5.26 LDPE: Comparison of end points (low1) of low extension for three major cycles.

Figure 5.27 LDPE: Comparison of end points (low2) of low extension for three major cycles.
5.2.4 Exponential Curve Fitting

Equation 5.1 below shows the formula that was chosen in making the exponential curve fitting which has double exponents indicating the two phase recoveries that we observed in the materials. This is a simplification of what happens in real life though a third exponent might exist. The description should work for both the relaxation and the recovery.

\[ y = K_0 + A_1 e^{-\frac{t}{\tau_1}} + A_2 e^{-\frac{t}{\tau_2}} \]  

(5.2)

Where \( \tau_1 \) is the time taken for the first sharp decline/incline and \( \tau_2 \) is the immediate following slow decline/incline.

To know more about the determination of the above parameters, do see the literatures [5] to [10]. In the equation (5.2), \( K_0 \) is a constant of proportionality which is chosen discretionally both for the relaxation and the recovery. Unlike in the previous works where stress \( \sigma \) was used for \( y \), \( f^2 \) was used in ours instead. This is because we are interested in using the analysis from the resonance frequency shifts alone in characterizing the materials.

5.2.5 Recovery

The recovery curve of the LDPE is also similar to that of the PPR except that the points fluctuate a lot. However, making the extension of the LDPE on the MTS machine to be different from that of the PPR and laminate, say 40mm or more, this fluctuation might be reduced to a minimum amount. We cannot say with certainty because we were restricted to 5mm extension as in [3].
Figure 5.28 LDPE: Long time reverse-relaxation and its curve fitting in the first major cycle.

Figure 5.29 LDPE: Long time reverse-relaxation and its curve fitting in the second major cycle.
5.3 Laminate: Slow Dynamics Experiment

5.3.1 Initial Result

There are two laminates used in this experiment:

1. Laminate of PPR and LDPE.
2. Laminate of PPR, LDPE and Aluminium.

For the laminated thin membrane material, the MTS machine setting is as in Table (5.5):

The settings in LabVIEW are similar to the previous ones. However, in this experiment; the wave generator is sweeping from 10Hz to 400Hz and the same range is used for the filter in the LabVIEW setting.

The FFT data of the frequency-time response obtained from LabView and processed in MATLAB is as shown in figure (5.31).

Figure 5.30 LDPE: Long time reverse-relaxation and its curve fitting in the third major cycle.
Table 5.5 Laminate MTS settings.

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</table>

Figure 5.31 Laminate (PPR/LDPE): Frequency-time figure in dynamic tension.
Similarly, the trend of the dynamics is decreasing in time advance. The decrease in frequency is due to the relaxation, while the increase is due to the reverse-relaxation.

### 5.3.2 Trends for Each Cycle

Ignoring the long time reverse relaxations, we plotted the curves of the ten periods for each dynamic cycle. Check figures (5.32, 5.33, and 5.34).

![Figure 5.32 Laminate (PPR/LDPE): (Reverse) Relaxation and their 4th polynomial curve fitting (first dynamic)](image)

**Figure 5.32** Laminate (PPR/LDPE): (Reverse) Relaxation and their 4th polynomial curve fitting (first dynamic).
Figure 5.33 Laminate (PPR/LDPE): (Reverse) Relaxation and their 4th polynomial curve fitting (second dynamic cycle).

Figure 5.34 Laminate (PPR/LDPE): (Reverse) Relaxation and their 4th polynomial curve fitting (third dynamic cycle).
Table 5.8: Laminate (PPR/LDPE): The start and end values of the first dynamic cycle (Units x[s] and y[Hz]).

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**Table 5.9: Laminate (PPR/LDPE): The start and end values of the second dynamic cycle (Units x[s] and y[Hz]).**

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**Table 5.10: Laminate (PPR/LDPE): The start and end values of the third dynamic cycle (Units x[s] and y[Hz]).**

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**Figure 5.35** Laminate (PPR/LDPE): Curves of \textit{up1}, \textit{up2}, \textit{low1} and \textit{low2} in the first cycle.

**Figure 5.36** Laminate (PPR/LDPE): Curves of \textit{up1}, \textit{up2}, \textit{low1} and \textit{low2} in the second cycle.
Figure 5.37 Laminate (PPR/LDPE): Curves of \textit{up1}, \textit{up2}, \textit{low1} and \textit{low2} in the third cycle.

Also, the curve fitting is done using the 4th polynomial as shown in equation (5.1).

For the three dynamic curves, the value of the starting point of the first dynamic cycle is approximately $1.1 \times 10^5$ Hz$^2$, for the second dynamic cycle is $0.95 \times 10^5$ Hz$^2$, and the third is about $0.9 \times 10^5$ Hz$^2$. The decreasing speed is coming down in time advance.

When comparing the figures obtained from the PPR, we observe some differences with the figures from the laminate. For example, the curve’s decrease seems to be decreasing faster than in PPR.

5.3.3 Trends for Similar Points

We also pick the four types of points from the figures to make the new plots. The data are shown in the table (5.6, 5.7, and 5.8).
Plot the four types of lines (up1, up2, low1 and low2) in the figures (5.38, 5.39, 5.40 and 5.41). The different color lines respond the different lines from the three dynamic cycles.

**Figure 5.38** Laminate (PPR/LDPE): Comparison of start points of high extension for the three cycles.
Figure 5.39 Laminate (PPR/LDPE): Comparison of end points of high extension for the three cycles.

Figure 5.40 Laminate (PPR/LDPE): Comparison of start points of low extension for the three cycles.
Figure 5.41 Laminate (PPR/LDPE): Comparison of end points of low extension for the three cycles.

Just as in the PPR results, the trend line seems to decrease faster from the beginning then slowly towards the end of the curve, both for the high extension and low extension.

In the four figures (5.38, 5.39, 5.40 and 5.41), the difference between the first and second lines are greater than that of the second and the third.

Additionally, it seems that for the first dynamics, the curves decrease more sharply and then slowly. The pace of the decrease is lower in the second and the third dynamics.

5.3.4 Exponential Curve Fitting of the Recovery

The plots of the reverse relaxation of the long time recovery are shown in the figures (5.42, 5.43, and 5.44).

In the plots, black lines are the exponential curve fitting of the red lines (plotted from the experimental data.)
Figure 5.42 *Laminate (PPR/LDPE): Long time reverse relaxation and its curve fitting in the first dynamic cycle.*

Figure 5.43 *Laminate (PPR/LDPE): Long time reverse relaxation and its curve fitting in the second dynamic cycle.*
Figure 5.44 Laminate (PPR/LDPE): Long time reverse relaxation and its curve fitting in the third dynamic cycle.
5.3.5 Laminate: PPR/LDPE/AL

**Figure 5.45** Laminate (PPR/LDPE/AL): Frequency-time figure in dynamic tension.
**Figure 5.46** Laminate (PPR/LDPE/AL): (Reverse) Relaxation and their 4th polynomial curve fitting (first dynamic).

**Figure 5.47** Laminate (PPR/LDPE/AL): (Reverse) Relaxation and their 4th polynomial curve fitting (second dynamic).
**Figure 5.48** Laminate (PPR/LDPE/AL): (Reverse) Relaxation and their 4th polynomial curve fitting (third dynamic cycle).

**Table 5.11**: Laminate (PPR/LDPE/AL): The start and end values of the first dynamic cycle (Units x[s] and y[Hz]).

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<td>161</td>
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<td>157.8</td>
<td>157.6</td>
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<td>156.2</td>
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</table>
Table 5.12: Laminate (PPR/LDPE/AL): The start and end values of the second dynamic cycle (Units x[s] and y[Hz]).

<table>
<thead>
<tr>
<th>Order</th>
<th>First</th>
<th>Second</th>
<th>Third</th>
<th>Fourth</th>
<th>Fifth</th>
<th>Sixth</th>
<th>Seventh</th>
<th>Eighth</th>
<th>Ninth</th>
<th>Tenth</th>
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</thead>
<tbody>
<tr>
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<td>8355.9</td>
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<td>9572.5</td>
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<td>255</td>
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<td>8751.3</td>
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<td>9968</td>
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<td>153.6</td>
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<td>147.9</td>
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</tbody>
</table>

Table 5.13: Laminate (PPR/LDPE/AL): The start and end values of the third dynamic cycle (Units x[s] and y[Hz]).

<table>
<thead>
<tr>
<th>Order</th>
<th>First</th>
<th>Second</th>
<th>Third</th>
<th>Fourth</th>
<th>Fifth</th>
<th>Sixth</th>
<th>Seventh</th>
<th>Eighth</th>
<th>Ninth</th>
<th>Tenth</th>
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<td>16315</td>
<td>16721</td>
<td>17127</td>
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<td>18749</td>
<td>19155</td>
<td>19561</td>
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<tr>
<td>up1y</td>
<td>260.2</td>
<td>257.2</td>
<td>256.6</td>
<td>256.2</td>
<td>255.9</td>
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<td>249.2</td>
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<td>17329</td>
<td>17735</td>
<td>18141</td>
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<td>18952</td>
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<td>135.1</td>
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<td>16711</td>
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<td>low2y</td>
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<td>145.2</td>
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<td>142.6</td>
<td>142.2</td>
<td>141.8</td>
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</tr>
</tbody>
</table>
Figure 5.49 Laminate (PPR/LDPE/AL): Curves of up1, up2, low1 and low2 in the first cycle.

Figure 5.50 Laminate (PPR/LDPE/AL): Curves of up1, up2, low1 and low2 in the second cycle.
Figure 5.51 Laminate (PPR/LDPE/AL): Curves of \textit{up1}, \textit{up2}, \textit{low1} and \textit{low2} in the third cycle.

Figure 5.52 Laminate (PPR/LDPE/AL): Comparison of start points of high extension for the three cycles.
**Figure 5.53** Laminate (PPR/LDPE/AL): Comparison of end points of high extension for the three cycles.

**Figure 5.54** Laminate (PPR/LDPE/AL): Comparison of start points of low extension for the three cycles.
Figure 5.55 Laminate (PPR/LDPE/AL): Comparison of end points of low extension for the three cycles.

![Graph showing comparison of end points of low extension for the three cycles.]

Figure 5.56 Laminate (PPR/LDPE/AL): Long time reverse relaxation and its curve fitting in the first dynamic cycle.

![Graph showing reverse relaxation of the first dynamic with exponential curve fitting.]

Experimental Data

Curve fitting: $\Gamma^2 = -2345 \times e^{-t/79} + 1595 \times e^{-t/1089} + 25993$
Figure 5.57 Laminate (PPR/LDPE/AL): Long time reverse relaxation and its curve fitting in the second dynamic cycle.

Figure 5.58 Laminate (PPR/LDPE/AL): Long time reverse relaxation and its curve fitting in the third dynamic cycle.
Chapter 6

Experimental Conclusion and Further work

6.1 Conclusion

The results that we obtained from the record of the resonance frequency shifts are quite similar to those from tensile machine (MTS machine). From the relaxation and recovery curves, we can draw some reasonable conclusions such as:

- Confirmed the existence of considerable slow dynamics of these types of material/sheet materials.
- Improved the accuracy of the non-contact technique (introduced by Mfoumou E.) to obtain better estimates of the recovery parameters.
- Shown the differences in recovery speed between the simple materials and the composites.
- Points to the importance of taking into account time-recovery behavior in the manufacturing processes of materials particularly the composites. With further testing like this, we will no longer consider only the external conditions at the time of making the composite, but also how it has been handled before, influences the composite.

6.1.1 Difficulties encountered during the experiment

In the course of the experiment, we encountered some difficulties which are mentioned below:

i. The experimental environment: -

There exists some noise from other equipment in the laboratory coupled with the wind that is coming from the air-conditioner. Also, the reverberation from the walls of the laboratory affects the measurement of the experiment. However, this effect can be said to be minimal because we measure at a higher frequency range.

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ii. **The MTS tensile machine:**

We noticed that the extension control of the MTS machine is not very stable because we did set it to remain at a fixed position but it moved a little (about 0.01 mm). The concern is that a little extension would affect the tension especially when it is in the high extension. To minimize this effect, we did not use high extension except for the LDPE.

iii. The experiment with LDPE looks different from the others. The start points of the high and low extensions seem to decrease too sharply to the level that is nearly equal to the other points after it. The initial measurements were not encouraging as they look whipsawed. This was minimized by increasing the extension. The implication (of the sharp decline/ascent) is that the LDPE recovers faster than the others.

iv. Though some of the experiments went into the non-linear elastic region, the material still tends to recover to its original position.

6.1.2 **Advantages and improvements**

i. In this thesis work, the theoretical and experimental bases are of much importance. They reveal the linear relationship between the resonance and the tension.

ii. They also form the basis for the relaxation and reverse relaxation theory and slow dynamics in general.

iii. It is interesting to note that the modal parameters extracted from the materials could be used to characterize them.

iv. In this method, we apply the non-contact excitation and measurement approach. It is useful and more practicable in many cases where it is difficult to apply the contact methods. For instance, we could not have placed an accelerometer on the thin sheets when extracting the modal parameters.

6.1.3 **Precautions**

- The loudspeaker was centered to the middle of the belt as close as possible to avoid the influence of the higher modes.
• The laser beam was aligned to the middle of the membrane and also kept in focus to produce the best result.
• We carefully mounted the membrane on the MTS machine to avoid pre-damage before test.

6.2 Further Discussion

• Interesting further research would be to correlate the amount of slow dynamic to the quality of the materials (like for regular solids, where a higher degree of slow dynamics means a higher amount of damage in the material).
• There could be the possibility to predict the life-span of materials when considering the amount of slow dynamics in them, or at least include slow dynamics in the calculation of the life-span of the material.
Appendix A

%*** PPR 250MD15 : 22 August 9:33- 19:44
% Test speed 10mm/min - step perturbation 0.6mm to 1mm
% Tensile test: 10 cycles / Hold time 200s
% Labview 100kS@10kHz / Sweep 50-400Hz / 10s / 10Vpp/cut-off freq = 50Hz
% Wave Generator 100kS@10kHz / Sweep 50-400Hz / 5s / 10Vpp
% first dynamic

clear all
close all
clc

load acoustics1new.mat;
t2=labview(:,1);
freqFRF=labview(:,2); f1=freqFRF;
freqFFT=labview(:,4); f2=freqFFT;
amplFRF=labview(:,3); a1=amplFRF;
amplFFT=labview(:,5); a2=amplFFT;

A=figure;
plot(t2,f2);
% figure; hold on; grid on;
xlabel('Time [s]');
ylabel('Frequency [Hz]');
title('PPR: Frequency vs Time');
% first dynamic : do the same for the second and third dynamic
up1=[1 42 82 123 163 203 244 284 324 365];
up2=[20 61 100 141 182 222 263 303 342 384];
low1=[22 62 102 143 183 224 264 304 345 385];
low2=[41 81 122 162 202 243 283 323 364 405];
figure; hold on; grid on;
xlabel('Time (s)');
ylabel('Frequency in Square (Hz^2)');
title('PPR: (Reverse) Relaxation and 4th polynomial curve fitting(first
dynamic)');
for i=1:10
    a=up1(i);b=up2(i);
    plot(t2(a:b),f2(a:b).^2,'r','LineWidth',2); % first i-th line
    xdate = (t2(a:b) - mean(t2(a:b)))./std(t2(a:b));
    p = polyfit(xdate,f2(a:b).^2,4);pop4 = polyval(p,xdate);
    plot(t2(a:b),pop4,'g--','LineWidth',3);
    c=low1(i);d=low2(i);
    plot(t2(c:d),f2(c:d).^2,'r','LineWidth',2); % first i-th line
    xdate = (t2(c:d) - mean(t2(c:d)))./std(t2(c:d));
    p = polyfit(xdate,f2(c:d).^2,4);pop4 = polyval(p,xdate);
    plot(t2(c:d),pop4,'g--','LineWidth',3);
end
legend('Real Data','Polynomial Curve Fitting');
clear all
close all
clc

load acoustics1new.mat;

T2=labview(:,1);
FreqFRF=labview(:,2); f1=FreqFRF;
FreqFFT=labview(:,4); f2=FreqFFT;
AmplFRF=labview(:,3); a1=AmplFRF;
AmplFFT=labview(:,5); a2=AmplFFT;

A=figure;
plot(T2,f2);
% figure; hold on; grid on;
xlabel('Time [s]');
ylabel('Frequency [Hz]');
title('PPR: Frequency vs Time');
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```matlab
% first
up1=[1 42 82 123 163 203 244 284 324 365];
up2=[20 61 100 141 182 222 263 303 342 384];
low1=[22 62 102 143 183 224 264 304 345 385];
low2=[41 81 122 162 202 243 283 323 364 405];

figure; hold on; grid on;
xlabel('Time (s)');
ylabel('Frequency in Square (Hz^2)');
title('PPR: (Reverse) Relaxation and 4th polynomial curve fitting(first
dynamic)');
for i=1:10
    a=up1(i);b=up2(i);
    plot(t2(a:b),f2(a:b).^2,'r','LineWidth',2); % first i-th line
    xdate = (t2(a:b) - mean(t2(a:b)))./std(t2(a:b));
    p = polyfit(xdate,f2(a:b).^2,4);pop4 = polyval(p,xdate);
    plot(t2(a:b),pop4,'g--','LineWidth',3);
    c=low1(i);d=low2(i);
    plot(t2(c:d),f2(c:d).^2,'r','LineWidth',2); % first i-th line
    xdate = (t2(c:d) - mean(t2(c:d)))./std(t2(c:d));
    p = polyfit(xdate,f2(c:d).^2,4);pop4 = polyval(p,xdate);
    plot(t2(c:d),pop4,'g--','LineWidth',3);
end
legend('Real Data','Polynomial Curve Fitting');
```
References


