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College of Engineering and Applied Science
Department of Mechanical & Materials Engineering

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Experiment Title : **Electro-Mechanical Systems**

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Deductions by TA:

Initials	Content	Form/Writ

TOTAL SCORE = ______/200

ABSTRACT

In the experimental part of this lab, the electrical and mechanical equations of the loudspeaker are manipulated to isolate each mechanical and electrical coefficient in order to find them experimentally. The resistance value of the speaker is measured by the DMM and the resistance value R is 7.009Ω . Using a DC power supply, it can be known that the capacitance C of the speaker can be ignored through the circuit in the DMM measurement circuit. The inductance, L, is obtained from a steady-state frequency measurement using a Bode analyzer. Calculate the time constant through the cutoff frequency, and then calculate L to be 131.921 H. By applying a known force to a stationary loudspeaker and measuring the displacement, the stiffness k is found to be 3542.9445 N/m. The magnetic flux coupling coefficient (B) is estimated by using a similar procedure to k, the measured displacement is now induced by a constant current source. B was found to be 1.956 Wb/m. The mass m and damping c are found simultaneously by analyzing the free vibration response of the loudspeaker with no applied voltage and using the logarithmic subtraction method to estimate the frequency characteristics. m is 0.0142kg and c is 1.1251 Ns/m.

In the performance analysis, the optimal values of the parameters are found by adjusting the values of the parameters m, c, k, R, L, B and C to match the experimentally measured images. Inductance L and capacitance C have the greatest and most critical impact on the image. Their size can change the distance between two crests. Stiffness k, mass m, and magnetic flux B will all have a certain impact on performance. Resistor R and damping c have little effect on the image and can be ignored.

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1. Objectives

This experiment had several objectives. The first objective was for students to analyze electromechanical systems and explore how to design experiments to determine parameters. This experiment also taught students to determine parameters using theoretical concepts covered in lectures and previous labs. Students had to use the information obtained to build a system model and compare it with theoretical models. The final objective of this experiment was to determine by comparison whether the procedures used are appropriate and, if not, how they can be improved.

2. Theoretical Background

System Governing Equation

The modified permanent magnet speaker used in this experiment is an electromechanical system, which can be represented by the following initial equation. This equation is the basic equation for evaluating the result.

$$L\frac{di}{dt} + Ri + \frac{1}{C}\int idt \;\; + B\dot{x} = v_{ext}$$
$$m\ddot{x} + c\dot{x} + kx - Bi = F_{ext}$$

Capacitance (C) and Impedance (R):

Initial system equation:

$$L\frac{di}{dt} + Ri + \frac{1}{C}\int idt \;\; + B\dot{x} = v_{ext}$$

Use a DC voltage source.

Connect a DMM to the device to measure the current through the device.

The above formula is used to determine R and c. Since the digital multimeter can be equivalent to a closed loop, in the DC circuit (the current value is constant), the resistance value can be measured directly with the digital multimeter. Thus, a constant current will be applied to the system and cause the device to move to a specific location and stay there. If the DMM can measure resistance, you can verify that there are no capacitors in the system, since a capacitor is like an open circuit in DC and will not cause current to flow.

Inductance (L):

Initial system equation:

$$L\frac{di}{dt} + Ri + \frac{1}{C}\int idt \;\; + B\dot{x} = v_{ext}$$

Use a constant current source:

$\dot{x}$ is eliminated since constant voltage/current results in the device moving to specified position and remaining there, use clamp to fix the position.

C can be eliminated because the measured circuit has no capacitance .

The equation becomes

$$L\frac{di}{dt} + Ri += v_{ext}$$

it can be seemed as a first order equation.

Resulting equation:

$$\tau = \frac{L}{R}$$

Measured input: R

Use DMM to measure the actual resistance of R (Pick 33 Ω)

Measured output: τ, time constant

Clamp the device, build the circuit shown on the breadboard, and measure the step input and response using a function generator and oscilloscope. (Use a low frequency (or large period) square wave, so the input signal will simulate a step input). (Use Bode to measure the frequency domain image, and then calculate the time constant according to the break frequency method)

Calculating:

$$L = R \times \tau$$

Stiffness (k):

Initial system equation:

$$m\ddot{x} + c\dot{x} + kx - Bi = F_{ext}$$

Position constant when taking a measurement: $\dot{x}$ and $\ddot{x}$ are eliminated.

Do not complete electrical circuit and keep it open loop: i is eliminated.

Resulting equation:

$$kx = F_{ext}$$

Measured input: known mass (m)

Measured output: difference (Δx) between the initial displacement (xi) (without m) and final displacement (xf) (with m);

Calculation:

$$k = \frac{F_{ext}}{\Delta x}$$

Mass (m) and Damping (c):

Initial system equation:

$$m\ddot{x} + c\dot{x} + kx - Bi = F_{ext}$$

Do not add additional mass: Fext is eliminated.

Do not complete electrical circuit and keep it open loop: i is eliminated.

Resulting equation:

$$m\ddot{x} + c\dot{x} + kx = 0$$

Measured input: Give the device an impulse in the initial state, such as knocking once.

Measured output: Time response, by PCL Accelerometer and Oscilloscope .

Use measured time response to calculate damped natural frequency (ω_d), undamped natural frequency (ω_n), and damping ratio (ξ) according to the image. Finally, mass (m) and damping (c) can be computed as:

$$\omega_d = \omega_{n\sqrt{1-\xi^2}}$$

$$m = \frac{k}{\omega_n^2}$$

$$c = 2\xi\sqrt{km}$$

3. Experimentation

3.1 Procedure to Determine Resistance R

3.1.1 Equipment

1.Fluke DMM.

2.Banana to spring clips

3.1.2 Procedure

Initial system equation:

$$L\frac{di}{dt} + Ri + \frac{1}{C}\int idt \ + B\dot{x} = v_{ext}$$

Analysis:

$\frac{di}{dt}$ is eliminated since current is constant.

$\dot{x}$ is eliminated since constant voltage/current results in the device moving to a specific position and remaining there.

When using DC source, capacitor impedance is infinite. Therefore, it is assumed that the system capacitance is negligible, which can be verified during this experiment

Resulting equation:

$$Ri = v_{ext}$$

Procedural steps:

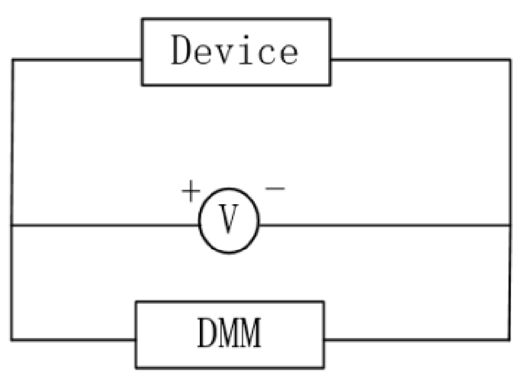


Figure 1 Measuring device resistance

1. Connect the speaker to the Fluke DMM using banana to spring clips as shown in the figure above.

2. Set the Fluke DMM to Resistance measurement mode

3. Record the value of Resistance (the DMM provides input of current and measures the output i voltage to compute the resistance value displayed) the DMM displays v_{ext}.

3.1.3 Results

Calculated by the equation:

$$R = \frac{v_{ext}}{i}$$

Measured R = 7.009Ω.

3.1.4 Analysis

Resistance measured with a Fluke DMM is 7.009 Ω

3.1.5 Discussion

The process is relatively smooth, there is no problem, the error may be caused by the reading error.

3.2 Procedure to Determine Capacitance C

3.2.1 Equipment

1.Fluke DMM

2. Banana to spring clips

3.BNC female to Banana female adapter

3.2.2 Procedure

Initial system equation:

$$L\frac{di}{dt} + Ri + \frac{1}{C}\int idt \ \ + B\dot{x} = v_{ext}$$

Analysis:

If there is a capacitor, the circuit is open loop and the current is zero, so i is eliminated.

Resulting equation:

If i=0, then C=0 as the circuit is open loop.

Procedural steps:

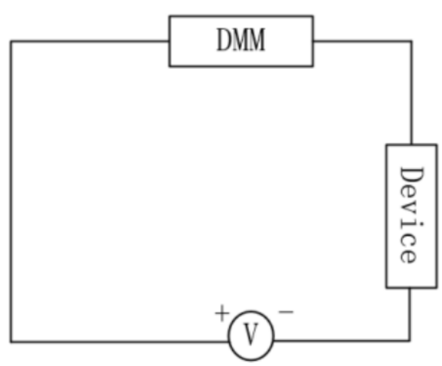


Figure 2 Measuring circuit current

1. Use a DC voltage source.

2. Connect the DMM to the device to measure the current through the device.

If there is a capacitor, the circuit is open loop and the current is zero.

If there is no capacitor, the circuit is a closed loop with current flow.

3.2.3 Results

The current displayed on the Fluke DMM is 0.1131A. This circuit has current and is a closed circuit, so there is no capacitor.

3.2.4 Analysis

The maximum current that the circuit can pass is 200mA, and the maximum voltage that the circuit can withstand is roughly 1.4V calculated by formula $V = Ri$. To be on the safe side, use 0.8V to measure the current value of the circuit to be 0.1131A

3.2.5 Discussion

During the measurement process, the DMM was wrongly connected in parallel to the circuit, and the current value could not be measured, so it was suspected that there was capacitance in the circuit. After careful inspection, the error was found, the circuit was adjusted, and the correct result was obtained.

The cause of the error may be the reading error and the internal resistance of the DMM. Also, although L can be eliminated in theory, the measured resistance is a combination of the internal resistance of the device and the resistance of the inductance, which may lead to inaccurate final resistance.

3.3 Procedure to Determine Inductance L

3.3.1 Equipment

1. ELVIS III System

2. 33 Ω Resistor

3. Spring to Spring Cables

4. Banana to Spring Cables

3.3.2 Procedure

Initial system equation:

$$L\frac{di}{dt} + Ri + \frac{1}{C}\int idt \ \ + B\dot{x} = v_{ext}$$

Analysis:

Position constant when taking a measurement: $\dot{x}$ and $\ddot{x}$are eliminated.

C has already been determined to be negligible.

Resulting equation:

$$L\frac{di}{dt} + Ri = v_{ext}$$

$$\tau = \frac{L}{R}$$

Procedural steps:

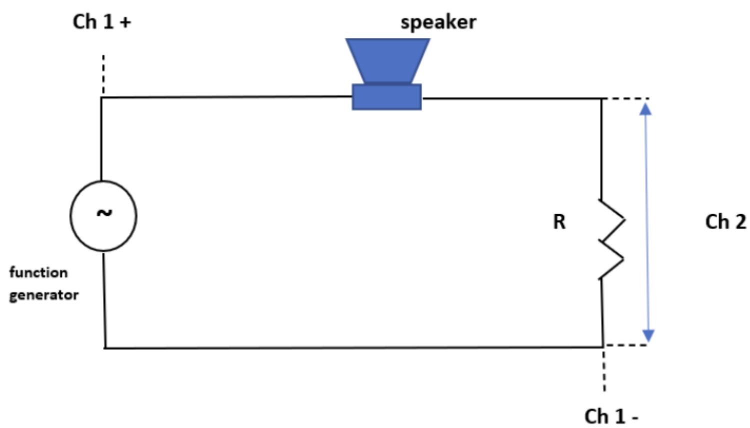


Figure 3 Experimental setup to find inductance

1. Set up a circuit as shown in Figure 3.

2. Set up the Bode analyzer with channel 1 measuring the whole circuit, and channel 2 measuring the 33 Ω Resistor.

3. Hold down the speaker to make sure it doesn't move while taking measurements.

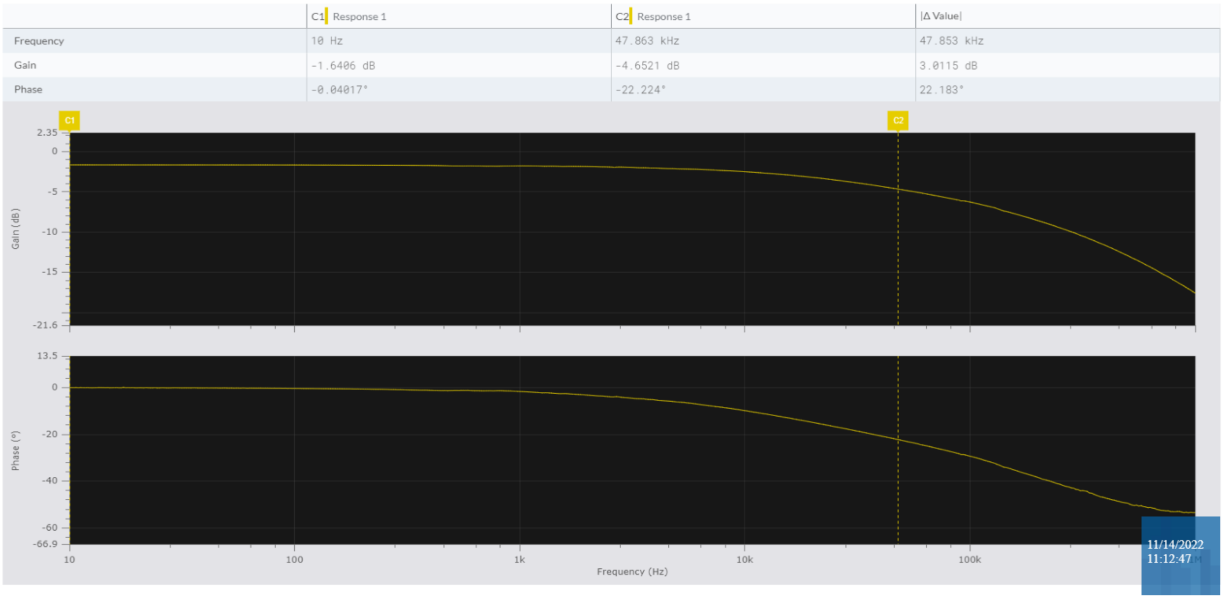
4. Use the results to estimate time constant.

5. Determine L using time constant and resistance.

3.3.3 Results

Table 1 Measured Resistance

	Resistance (Ω)
Speaker	**7.009**
External Resistor	**32.664**



Stimulus Channel	
Start Frequency	10 Hz
Stop Frequency	1 MHz
Steps Per Decade	100
Peak Amplitude	1 V

Response Channels		
Response Name	State	Channel Label
Response 1	Enabled	Oscilloscope CH2
Response 2	Disabled	
Response 3	Disabled	

Reference Channels				
Reference Name	State	Mode	Source File Name	Channel
Reference 1	Disabled			
Reference 2	Disabled			

Figure 4 BODE Analysis

3.3.4 Analysis

$$R = R_{Speaker} + R_{Resistor} = 7.009 + 32.664 = 39.673\ \Omega$$

From Figure 4 BODE Analysis:

$$\omega_b = 47.863\ kHz$$

$$\tau = \frac{1}{2\pi(47863)} = 3.325 * 10^{-6}$$

$$\mathrm{L} = R * \tau = 39.673 * 3.325 * 10^{-6} = 131.921\ \mu H$$

3.3.5 Discussion

The value for inductance could be subject to error for a few reasons. The best way to eliminate motion for this experiment was to hold the speaker down so it wouldn't move, however this is not a perfect method. Another challenge with this experiment is choosing a proper external resistor so that the break frequency isn't too high.

3.4 Procedure to Determine Stiffness k

3.4.1 Equipment

1. Dial Indicator

2. Calibrated Weight 20g and 50g

3. Modified PM speaker

3.4.2 Procedure

Initial system equation:

$$m\ddot{x} + c\dot{x} + kx - Bi = F_{ext}$$

Analysis:

Position constant when taking a measurement: $\dot{x}$ and $\ddot{x}$are eliminated.

Do not complete electrical circuit and keep it open loop, so i is eliminated.

The displacement is only related to the calibrated weight, so the mass of the speaker is irrelevant.

Resulting equation:

$$kx = k\Delta x = F_{ext} = \Delta mg$$

Procedural steps:

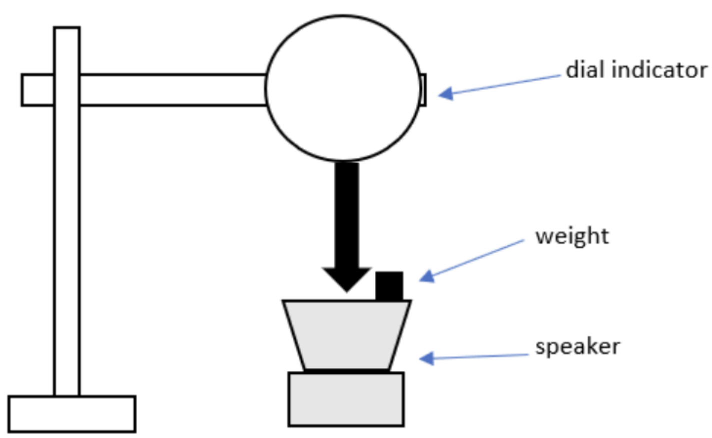


Figure 5 Experimental setup for finding stiffness

1. Place speaker so it sits vertically on table, as shown in **Figure 5 Experimental setup for finding stiffness**, and measured input: known mass (Δm) by Luggage Scale

2. Place dial calipers into position alongside speaker and place 20 g weight on top of diaphragm of speaker, then measured output: difference (Δx) between the initial displacement (x_i) (without m) and final displacement (x_f) (with m) by Dial Indicator

3. Repeat for 50 g weight

5. Determine k from measured Δx values

3.4.3 Results

Calculated by the equation:

$$k = \frac{\Delta mg}{\Delta x}$$

Table 2 Trial Weight and Change in Position of Speaker

Weight (g)	Δx (in)	Calculated k (N/m)
20	0.002	3862.2047
50	0.006	3223.6842
k_{avg}		3542.9445

3.4.4 Analysis

$$k_1 = \frac{\Delta m_1 g}{\Delta x} = \frac{20 \times 10^{-3} \times 9.81N}{0.0508 \times 10^{-3}m} = 3862.2047N/m$$

$$k_2 = \frac{\Delta m_2 g}{\Delta x} = \frac{20 \times 10^{-3} \times 9.81N}{0.0508 \times 10^{-3}m} = 3223.6842N/m$$

$$k_{avg} = \frac{k_1 + k_2}{2} = \frac{(3862.2047 + 3223.6842)N/m}{2} = 3542.9445N/m$$

In this way, it is easy to get k. However, there are still inevitable errors.

1. We assume that the spring curve is linear. If the curve is not linear, there will be some errors in the result.

2. We also cannot be sure that the external force is actually a pound of gravity. The gravitational acceleration of the test area is not $9.81m/s2$. This will cause errors.

3. Assume that the accuracy of the dial indicator is ±0.001. The dial indicator may also have some errors.

3.4.5 Discussion

Since two different weights were used, the stiffness estimations are not exactly the same. The value considered further is the average of the values obtained by experimentation and calculation to minimize the variability due to random errors. Additionally, due to the sizes of the two weights used, it was difficult to place the dial indicator onto a flatter part of the speaker which could have affected the measurements taken and could be a source of random error due to experimental conditions. The results also assume there was no systematic error involved while using the dial indicator. It is also assumed that blunders by the individual conducting the experiment were absent.

3.5 Procedure to Determine Magnetic Flux Coupling Coefficient B

3.5.1 Equipment

1. ELVIS III System
2. 10 Ω Resistor
3. Banana to Spring Cables
4. Spring to Spring Cables
5. Dial Indicator

3.5.2 Procedure

Initial system equation:

$$m\ddot{x} + c\dot{x} + kx - Bi = F_{ext}$$

Analysis:

Position constant when taking a measurement: $\dot{x}$ and $\ddot{x}$are eliminated.

No additional mass: F_{ext} is eliminated

Resulting equation:

$$kx - Bi = 0$$

Procedural steps:

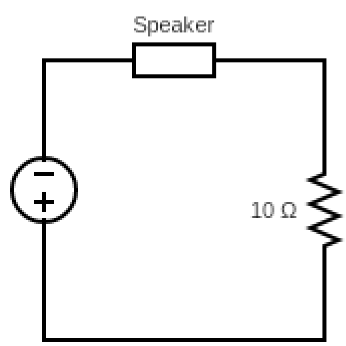


Figure 6 Circuit to Measure B

1. Set up a circuit as shown in Figure 6 Circuit to Measure B.
2. Use the ELVIS DMM to measure the current through the circuit.
3. Use the dial indicator to measure the change in position, similar to the procedure for stiffness.
4. Use the results to find Magnetic Flux.

3.5.3 Results

$$i = 0.23\ A$$

$$x = 0.005\ in = 0.000127\ m$$

3.5.4 Analysis

$$k = 3542.9445\ N/m$$

$$B = \frac{kx}{i} = \frac{3542.9445 * 0.000127}{0.23} = 1.956\ Wb/m$$

3.5.5 Discussion

There are a few possible sources of error with this experiment. Because the displacement of the speaker is small, it is easy to make mistakes when measuring with the dial indicator. If the dial indicator gets shifted around at all during the experiment, the results will no longer be accurate. Also, only one trial was performed during this experiment, so it is unknown how precise the results of this experiment would be.

3.6 Procedure to Determine Mass m and Damping c

3.5.1 Equipment

1. Modified PM speaker
2. PCB Accelerometer
3. PCB Signal Conditioning Box
4. Microdot to BNC cable
5. BNC to BNC cable
6. NI ELVIS III Oscilloscope

3.5.2 Procedure

Initial system equation:

$$m\ddot{x} + c\dot{x} + kx - Bi = F_{ext}$$

Analysis:

Do not add additional mass, so F_{ext} is eliminated.

Do not complete electrical circuit and keep it open loop, so i is eliminated.

Resulting equation:

$$m\ddot{x} + c\dot{x} + kx = 0$$

Procedural steps:

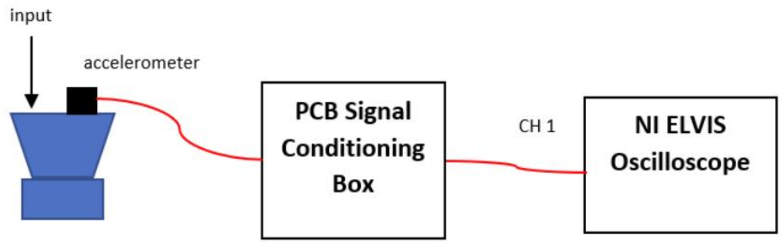


Figure 7 Experimental setup for finding mass and damping

1. Attach accelerometer to Microdot to BNC cable

2. Attach the accelerometer with wax to the speaker diaphragm (apply even pressure and do not damage speaker)

3. Connect Microdot to BNC cable to input of PCB Signal Conditioning Box

4. Use BNC to BNC cable to connect signal conditioning box output to CH 1 of NI ELVIS oscilloscope

5. Turn on signal conditioning box and NI ELVIS

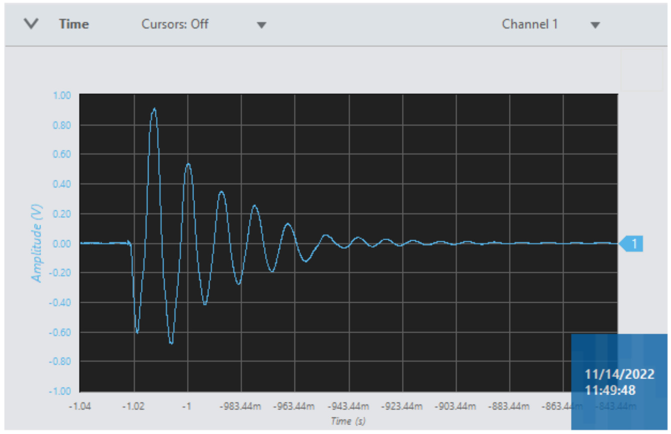
6. Use appropriate divisions per scale for signal analyzer window to obtain useful data

7. Tap the speaker with finger or pen and record the free vibration data for the system, measured input: give the device an impulse in the initial state, and measured output: time response by PCL accelerometer and oscilloscope

8. Use cursors to determine peaks of the output signal and use theory to estimate frequency characteristics

9. Use curve fitting tool to compare theoretical and fitted values

3.5.3 Results



Trigger settings	Values
Mode	Auto
Type	Immediate
Acquisition delay	Disabled
Position	-943.443ms

Horizontal & acquisition settings	Values
Time per division	20ms
Acquisition	Decimate
Sampling	30.7 kS/s

Channel settings	Channel 1 values
Volts per division	200mV
Coupling	AC
Probe attenuation	1x
Vertical offset	0V
Vertical position	0V

Figure 8 Time Response

3.5.4 Analysis

According to the collected time response data, use MATLAB to plot:

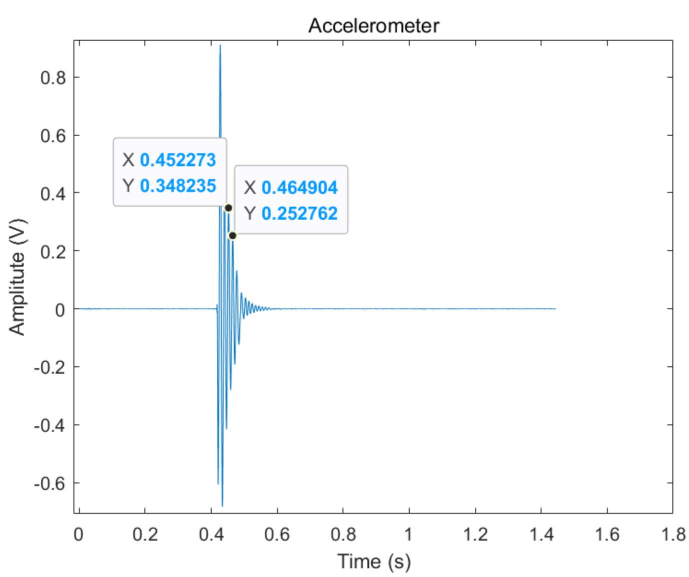


Figure 9 Time Response by Matlab

According to the Matlab present, $\omega_d = \frac{1}{(464.904 - 452.273)ms} = 79.17Hz$.

By fitting the Strain indicator box response following:

$y = a * exp(-b * 79.17 * 2 * pi * x/(sqrt(1 - b^2))) * sin(2 * pi * x * 79.17 + c) + d$

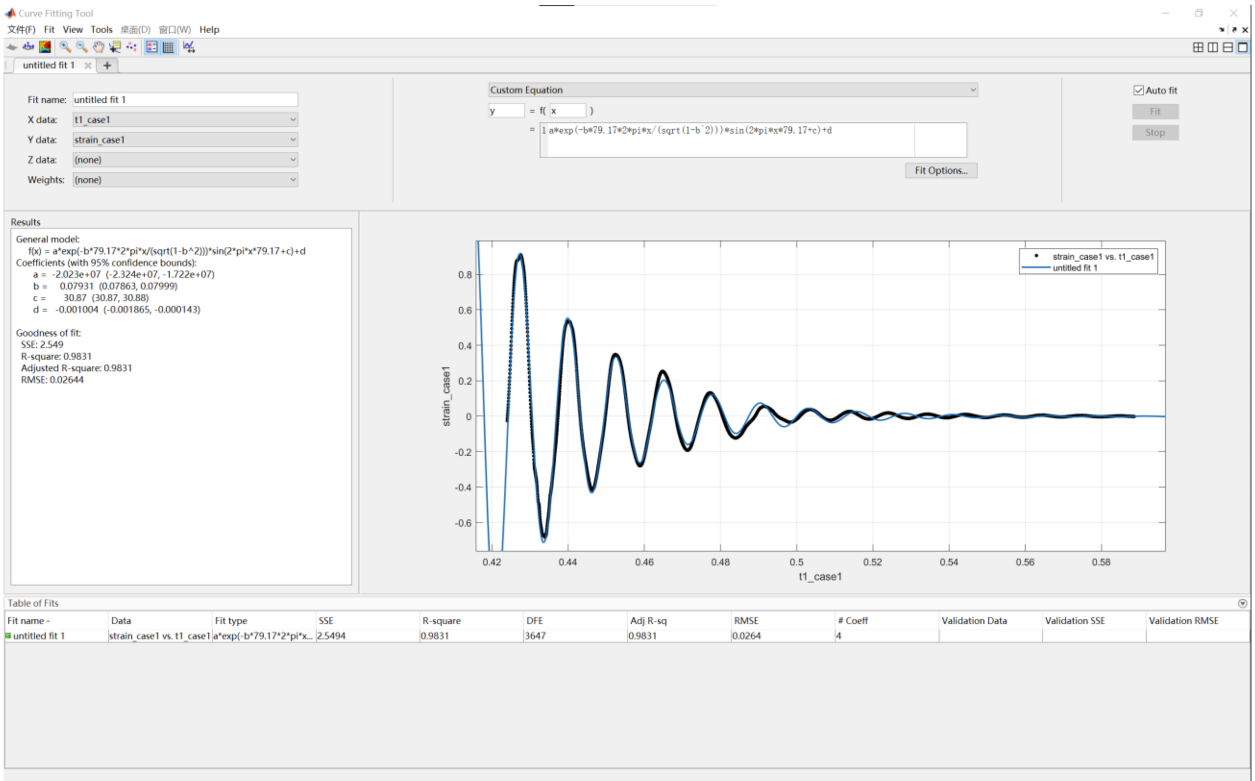


Figure 10 Time Response Curve Fitting

Then, $\xi = b = 0.07931$.

$$\omega_n = \frac{\omega_d}{\sqrt{1-\zeta^2}} = \frac{79.17Hz}{\sqrt{1-0.07931^2}} = 79.42Hz = 499.01rad/s$$

We already know that:

$$\omega_n = \sqrt{\frac{k}{m}}$$

$$\xi = \frac{c}{2\sqrt{mk}}$$

Hence, m and c can be calculated as:

$$m = \frac{k}{\omega_n^2} = \frac{3542.9445N/m}{(499.01rad/s)^2} = 0.0142kg$$

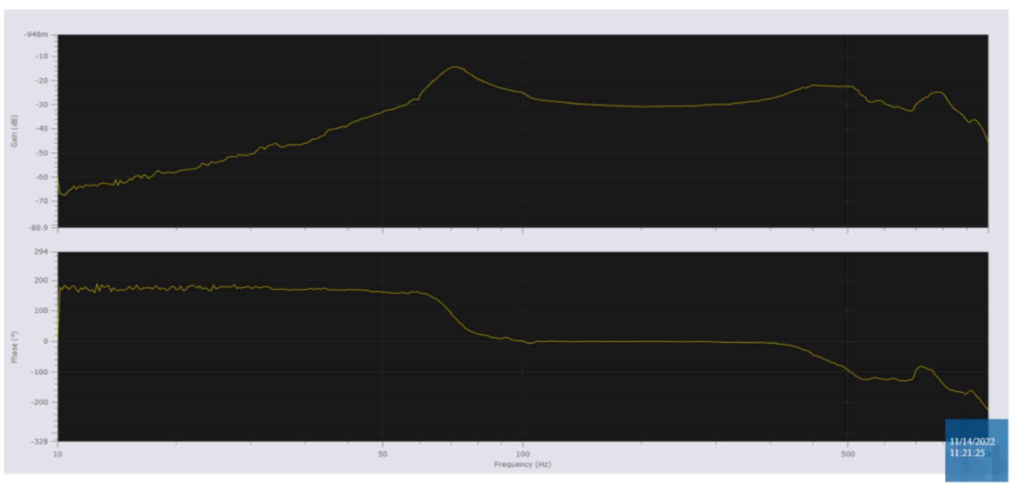
$$c = 2\xi\sqrt{mk} = 2 \times 0.07931 \times \sqrt{0.0142kg \times 3542.9445N/m} = 1.1251Ns/m$$

The value of m was assumed to be a good estimate with the assumption that the value of k obtained was also a good estimate, free from any errors during measurement and calculation. The value of c further depended on k and m being reasonably good estimates, as errors in the estimation of k and subsequently m would compound the error in the value of c that was estimated.

3.5.5 Discussion

The curve fitting did not give a representative estimate of damping ratio (the coefficient b= 0.07931), because the fourth peak of the recorded time data skews the fit and does not allow accurate coefficient values to be estimated. This error could have been mitigated by taking more data, had time permitted in lab.

4. Performance Analysis



Stimulus Channel	
Start Frequency	10 Hz
Stop Frequency	1 kHz
Steps Per Decade	200
Peak Amplitude	5 V

Response Channels		
Response Name	State	Channel Label
Response 1	Enabled	Oscilloscope CH2
Response 2	Disabled	
Response 3	Disabled	

Reference Channels				
Reference Name	State	Mode	Source File Name	Channel
Reference 1	Disabled			
Reference 2	Disabled			

Figure 11 FRF of Bode analyzer

Table 3 Original Parameters

Parameters	Value
Resistance (R)	**7.009 Ω**
Capacitance (C)	$\mathbf{10^{-5}}$ **F**
Inductance (L)	**131.921** $\boldsymbol{\mu H}$
Stiffness (k)	**3542.9445 N/m**
Magnetic flux coupling coefficient (B)	**1.956 Wb/m**
Mass (m)	**0.0142 kg**
Damping (c)	**1.1251 Ns/m**

To evaluate whether the system parameters estimated by experimental measurements are credible, the corresponding control equations are transformed to match the measured FRFs and compared with them. Adjust to X / V.

Initial governing equation:

$$L\frac{di}{dt}+Ri+\frac{1}{C}\int idt \;+B\dot{x}=v_{ext}$$

$$m\ddot{x}+c\dot{x}+kx-Bi=F_{ext}$$

Convert to matrix form:
Initial governing equation:

$$L\frac{di}{dt}+Ri+\frac{1}{C}\int \; idt+B\dot{x}=v_{ext}$$
$$m\ddot{x}+c\dot{x}+kx-Bi=F_{\text{ext}}$$

Convert to matrix form:

$$\begin{bmatrix} m & 0 \\ L & 0 \end{bmatrix}\begin{bmatrix} \ddot{x} \\ \ddot{q} \end{bmatrix}+\begin{bmatrix} c & -B \\ B & R \end{bmatrix}\begin{bmatrix} \dot{x} \\ \dot{q} \end{bmatrix}+\begin{bmatrix} k & 0 \\ 0 & \frac{1}{c} \end{bmatrix}\begin{bmatrix} x \\ q \end{bmatrix}=\begin{bmatrix} F_{\text{ext}} \\ V_{\text{ext}} \end{bmatrix}$$

According to the properties of Fourier transform, define A as:

$$\mathrm{A}=\begin{bmatrix} m & 0 \\ L & 0 \end{bmatrix}(j\omega)^2+\begin{bmatrix} c & -B \\ B & R \end{bmatrix}(j\omega)+\begin{bmatrix} k & 0 \\ 0 & \frac{1}{c} \end{bmatrix}$$

Then it converts to:

$$\mathrm{A}\begin{bmatrix} x \\ q \end{bmatrix} = \begin{bmatrix} F_{\text{ext}} \\ V_{\text{ext}} \end{bmatrix} \rightarrow \begin{bmatrix} x \\ q \end{bmatrix} = A^{-1}\begin{bmatrix} F_{\text{ext}} \\ V_{\text{ext}} \end{bmatrix}$$

$$A^{-1} = \begin{bmatrix} 0 & \dfrac{x}{V_{\text{ext}}} \\ \dfrac{q}{F_{\text{ext}}} & 0 \end{bmatrix}$$

$$Z_{\text{device}} = R + \frac{1}{j\omega C} - j\omega L$$

$$\frac{x}{V_{\text{ext}}} \xrightarrow{*(j\omega)^2} \frac{\ddot{x}}{V_{\text{ext}}} \xrightarrow{*\text{Accelerometer Calibration}} \frac{V_{\text{acc}}}{V_{\text{ext}}} \xrightarrow{*\frac{z_{\text{device}}}{R_{\text{ect}}}} \frac{V_{\text{acc}}}{V_{\text{out}}}$$

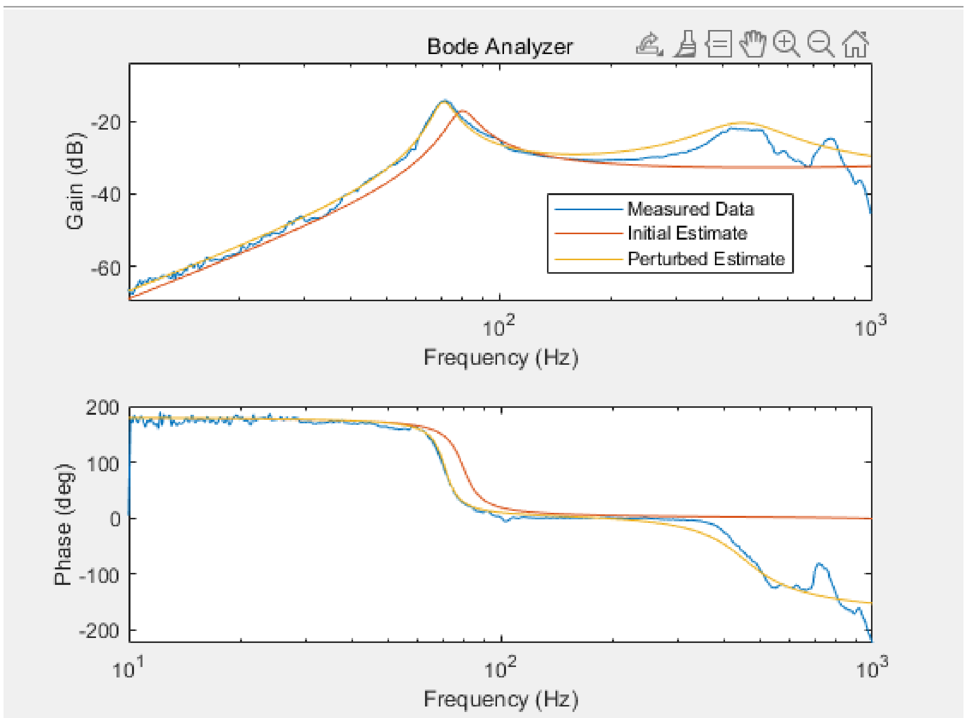


Figure 12 Bode Analyzer

Table 4 Original and Perturbed Parameters

Parameters	Original Value	Perturbed Value	Error
Resistance (R)	**7.009Ω**	**7.009 Ω**	**0%**
Capacitance (C)	10^{-5} **F**	**2.5*10^-6 F**	**95%**
Inductance (L)	**131.921** μH	**5*10^-3 H**	**3690%**
Stiffness (k)	**3542.9445 N/m**	**4000 N/m**	**12.9%**
Magnetic flux coupling coefficient (B)	**1.956 Wb/m**	**2.8 Wb/m**	**43.15%**
Mass (m)	**0.0142 kg**	**0.02 kg**	**40.84%**
Damping (c)	**1.1251 Ns/m**	**1.1251 Ns/m**	**0%**

<u>Analysis:</u>

For Resistance (R)

In testing, the plot did not change appreciably when changing the value of R. Therefore, the parameter R has no effect on the model. The way to measure resistance is to simply connect a multimeter to the speaker and measure the resistance. Comparing the initial value and the value after disturbance, it can be seen that R is very accurate.

For Capacitance (C)

Although capacitance is negligible for loudspeakers, the presence of small amounts of parasitic capacitance during data collection means that it needs to be included in your system model in order to theoretically generate the second peak seen in the collected performance relationship data. In testing it was found that reducing the value of the capacitor shifted the second peak to the left. The reason for the error may be that the specific quantity of a small amount of capacitance is not known.

For Inductance (L)

In testing, when changing the value of L, the phase plot shows a second peak. Therefore, the parameter L has a significant impact on the model. The method of measuring inductance is not very accurate. The error is as high as 3690%. We believe that the error mainly comes from the measurement of the time constant. We use the method of break frequency to find the time constant in the frequency domain. The time constant is very small, and the accuracy of the fitting is very high, so the error is caused. And we only measured one set of data. For such a small measurement value, measuring several sets of data may improve the accuracy of our measurement results.

For Stiffness (k)

In testing, when increasing the value of k, the image shifts to the right. The method of measuring the stiffness is accurate. The error is 12.9%, which is acceptable. The error may be due to reading errors when reading the displacement change. We measured two sets of data and averaged them. The final result may be more accurate if more sets of data are measured. Furthermore, the displacement can be larger if a larger additional mass is used. This reduces the impact on the accuracy of the measuring instrument.

For Magnetic flux coupling coefficient (B)

In testing, when increasing the value of B, the image moves up. The method of measuring the flux coupling coefficient is not very accurate. The error is 43.15%, which is relatively large. The reason for the error may be the following two. The reading of the dial indicator may be completely inaccurate. The measured displacement is too small, and the reading on the dial indicator fluctuates greatly, making it difficult to judge the actual displacement. This method can be improved by using a different dial gauge, taking more measurements, and averaging the results. The value of B will depend on the measured value of K, so any error in the stiffness measurement will affect the final result of B.

For Mass (m) and Damping (c)

In testing, when increasing the value of m, the image shifts to the left. Variations in parameter c have little effect on the model and can be ignored. For mass m and damping c: The method of measuring mass m and damping c is effective, but the error of m is 40.84%, which is relatively unacceptable. The time response of the device is measured by an accelerometer. Estimate the damped natural frequency and damping ratio from the time response. There are two reasons for the error. When selecting data points, it is greatly affected by random errors and noise, which will cause errors. The calculation of m and c depends on the stiffness k calculated in the previous experiment, and the error of k will affect the error of method m and c.

5. Conclusions

The steps of each experiment are sufficient for the purpose of determining each parameter of the electromechanical system. Many parameters and numbers depend on certain parameters determined in advance, so the error may increase. The trend of the corrected performance curve is basically consistent with the measured data, with a little error, which may be caused by the "noise" during the measurement. For the performance curve, the inductance L has the greatest impact on the performance of the speaker, the stiffness k, the mass m, the capacitance C, and the magnetic flux B will have a certain impact on the performance. Resistor R and damping c have little effect on the image and can be ignored. The measurement method of stiffness K and resistance R is relatively accurate, and the initial value is in good agreement with the disturbance value. There are certain errors in the measurement methods of magnetic flux B and inductance L, which may be caused by the accuracy of the experimental equipment and the number of measurements. The method of using the accelerometer to measure the time response to estimate the value of mass m and damping c is effective, but there are still some errors.

APPENDICES

A – EQUIPMENT LIST

Table 5. Equipment List

Equipment Description	Model Number	Serial Number
Speaker		4
Prototyping Base	NI ELVIS III	3169FF7
PCB Signal Conditioning Box		00032976
Accelerometer	333B30	LW56751
Dial Indicator		

B – MATLAB Code (or Excel, other computational software, etc)

```
%% Section 3.2
clear;close all;clc
%% 3_2_A_Strain indicator box
% Load data
t1_case1=xlsread('m&c_2.csv','A2:A32001');
strain_case1=xlsread('m&c_2.csv','B2:B32001');

t1_case1=t1_case1(9400:13050);
strain_case1=strain_case1(9400:13050);

% Plot
figure(1)
plot(t1_case1,strain_case1);
hold on
xlim([0 2]);
xlabel('Time (s)');ylabel('Amplitute (V)');
title('Accelerometer');

% Fit data
cftool(t1_case1,strain_case1)

% Performance
clear;close all;clc
% load measured data
dataF=xlsread('Mon_Device4.csv','A2:A402');
dataM=xlsread('Mon_Device4.csv','B2:B402');
dataP=xlsread('Mon_Device4.csv','C2:C402');


% theoretical with original parameters
m_o=0.0142; % kg
c_o=1.1251; % N.s^2/m
k_o=3542.9445; % N/m
L_o=1.31921*10^(-4); % H
R_o=7.009; % ohms
C_o=1*10e-6; % F
B_o=1.956; % Wb/s
```

```
% theoretical with perturbed parameters
m_p=0.02; % kg
c_p=1.1251; % N.s^2/m
k_p=4000; % N/m
L_p=5*10^(-3); % H
R_p=7.009; % ohms
C_p=2.5*10e-6; % F
B_p=2.8; % Wb/s

% other parameters needed
w=2*pi*dataF; %rad/s
R_ext=67.59; %ohms
Acc_calibration=106.1*10^(-3)/9.81; %V/(m/s^2)
Z_device_o=R_o+1./(j*w*C_o)-j*w*L_o;
Z_device_p=R_p+1./(j*w*C_p)-j*w*L_p;

% convert to X/V
XV_o=zeros(1,length(w));
XV_p=zeros(1,length(w));
for kk=1:length(w)
 invA_o=inv([m_o 0;0 L_o]*(j*w(kk))^2+[c_o -B_o;B_o
R_o]*(j*w(kk))+[k_o 0; 0 1/C_o]);

 invA_p=inv([m_p 0;0 L_p]*(j*w(kk))^2+[c_p -B_p;B_p
R_p]*(j*w(kk))+[k_p 0; 0 1/C_p]);

XV_o(kk)=invA_o(1,2)*(j*w(kk))^2*Acc_calibration*Z_
device_o(kk)/R_ext;

XV_p(kk)=invA_p(1,2)*(j*w(kk))^2*Acc_calibration*Z_
device_p(kk)/R_ext;
end

% plot
figure (1)
subplot(2,1,1)
semilogx(dataF,mag2db(dataM),dataF,mag2db(abs(XV_o)
),dataF,mag2db(abs(XV_p)))
```

```
title('Bode Analyzer')
xlabel('Frequency (Hz)')
ylabel('Gain (dB)')
legend('Measured Data','Initial
Estimate','Perturbed Estimate')
subplot(2,1,2)
semilogx(dataF,dataP,dataF,angle(XV_o)*180/pi,dataF
,angle(XV_p)*180/pi)
xlabel('Frequency (Hz)')
ylabel('Phase (deg)')
```

C – Scanned Lab Notes

11.7

Lab 5 Measure the Resistance

R: Governing Eq: $L\cancel{\frac{di}{dt}} + Ri + \cancel{\frac{1}{C}\int i\,dt} + \cancel{B\dot{x}} = V$

Procedure: Connect device to a digital multimeter

Select resistance measurement

Record the value ~~given~~ displayed on the D/M/M

Material: D/M/M. Banana to Spring Clips x 2

Result: $R = \cancel{6.792}\ \Omega$

7.008

Satya 11/07 Reason for $\frac{1}{C}\int i\,dt$?

Assume C negligible

C: Procedure: Use a DC voltage source

Connect the D/M/M ~~the device~~ to measure the current through the device

If there is a capacitor, the circuit would be an open loop, the current would be 0

If there is no capacitor, the current would not be 0.

Material: D/M/M. two more Banana to Spring Clips. BNC-female to Banana-female adapter

Result: When V = 1 V, A = ~~0.4116~~ A > 0, there is no capacitor.

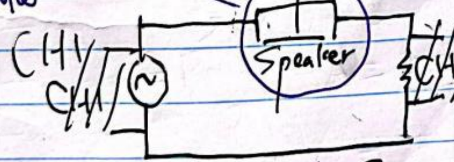
0.11305A

$\cancel{X}$ Governing Eq: $L\frac{di}{dt} + \overset{known}{Ri} + \cancel{\frac{1}{C}\int i\,dt} + \cancel{B\dot{x}} = V_{ext}$

Procedure: Use variable power supply to generate a constant voltage: $\dot{x}$ is eliminated since constant voltage/current results in the device moving to specific position and remaining there.

The resistor R ~~can~~ have been measured by D/M/M, and there is no capacitor.

high pass device The equation becomes $L\frac{di}{dt} + Ri = V_{ext}$



$\tau = \frac{L}{R}$

Spring to spring x1

BNC to spring Clips x1

Material: ~~Banana to Spring Clips x2, adapter x2~~

Result: ~~$\tau = 1.488\,ms$~~

~~$\tau = 1.488 \times 10^{-3}$~~

$R = 46.8\ \Omega$

$\tau = \frac{1}{2\pi\omega_b} = 1.592 \times 10^{-6}$

$L = \tau \cdot R = 1.592 \times 10^{-6} \times 7.008$

$= 11.157\ \mu H$

Satya 11/07

~~K: Gramey: $k = \frac{\Delta mg}{\Delta x}$~~ $m\cancel{\ddot{x}} + \cancel{c\dot{x}} + kx - \cancel{Bi} = F_{ext}$ Output: x Input: $F_{ext} = mg = W$

Procedures: Measure the input m

Measure the output Δx between x_i and x_f by dial indicator

$\ddot{x}$, $\dot{x}$, B could be ignored, because there is no velocity (no movement) ~~acceleration and circuit~~

O.C. (no circuit)

Result ~~$\Delta x = 0.015$ in = 0.015~~ 0.381 mm

$m = 100$ g

$k = \frac{\Delta mg}{\Delta x} = \frac{100 \times 10^{-3} \times 9.81}{0.381 \times 10^{-3}} = 2574.8$ N/m

建议

至少

两次

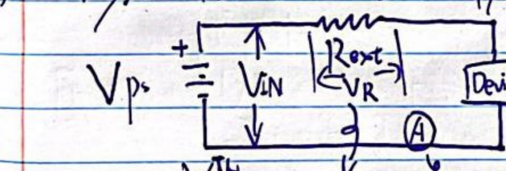
只测K时可以倒置

11.14

B $m\cancel{\ddot{x}} + \cancel{b\dot{x}} + kx - Bi = \cancel{F_{ext}} \Rightarrow kx = Bi$ Input: i Output: x

Material: Banana to spring ×4

Spring to spring ×1



$i = \frac{V_{IN}}{R_{ext} + R_D}$ 测V_R更好 可能出现measurement loading

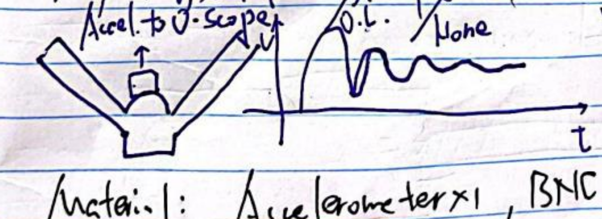
Result: $R = 10.046\ \Omega$ $x = 0.005$ in

Log Dec $i = 0.23$ A $V = 1.94$ V

Satya 11/14

M.C $m\ddot{x} + b\dot{x} + kx - \cancel{Bi} = \cancel{F_{ext}}$ $\omega = \sqrt{\frac{k}{m}}$ $\zeta = \frac{c}{2\sqrt{mk}}$

Accel. to O-Scope O.C. None



Material: Accelerometer ×1, BNC Cable × 1

$\omega_d = \sqrt{03.488 - 491.473} = 91.8$ Hz

Satya

RC Box: 00032P76

ELVIS III: 316PFF7

K $k = \frac{\Delta mg}{\Delta x}$ $m\ddot{x} + c\dot{x} + kx - Bi = F_{ext}$

Measure m, Δx (10g, 20g)

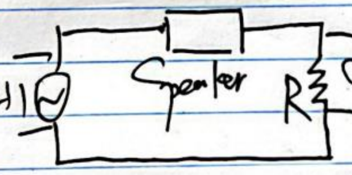
when m = 20g, Δx = 0.002 in = 0.0508 mm

$$k = \frac{\Delta mg}{\Delta x} = \frac{20\times10^{-3}\times 9.81}{0.0508\times10^{-3}} = 3862.2\ N/m$$

when m = 50g Δx = 0.006 in = 0.152 mm

$$k = \frac{\Delta mg}{\Delta x} = \frac{50\times10^{-3}\times 9.81}{0.152\times10^{-3}} = 3223.6842\ N/m$$

L



$\tau = \frac{L}{R}$ $\tau = \frac{1}{2\pi\omega_b}$

Result: R = ~~98.86~~ Ω 32.764 Ω

ω_b = 47.863 kHz

$\tau = \frac{1}{2\pi\omega_b} = 3.3252\times10^{-6}$

$L = \tau\cdot(R + R_{speaker}) = 1.3192\times10^{-4}\ H = 131.92\ \mu H$

Final Result: m = 0.0142 kg c = 1.1251 Ns/m k = 3542.9445 N/m

R = 7.08 Ω C = 0 L = 131.92 μH

B = 1.956 Wb/m

$$m\ddot{x} + b\dot{x} + kx - Bi = F_{ext}$$

$$L\frac{di}{dt} + Ri + \frac{1}{c}\int i\,dt + B\dot{x} = V_{ext}$$

$$\begin{bmatrix} m & 0 \\ 0 & L \end{bmatrix}\begin{Bmatrix} \ddot{x} \\ \ddot{q} \end{Bmatrix} + \begin{bmatrix} b & -B \\ B & R \end{bmatrix}\begin{Bmatrix} \dot{x} \\ \dot{q} \end{Bmatrix} + \begin{bmatrix} k & 0 \\ 0 & 1/c \end{bmatrix}\begin{Bmatrix} x \\ q \end{Bmatrix} = \begin{Bmatrix} F_{ext} \\ V_{ext} \end{Bmatrix}$$

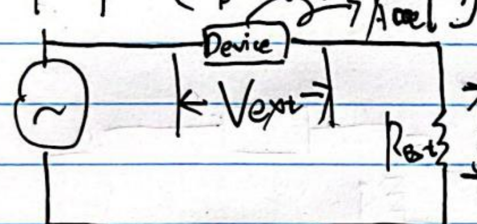
$$[A]\begin{Bmatrix} x \\ Q \end{Bmatrix} = \begin{Bmatrix} F \\ V \end{Bmatrix}$$

$$\begin{Bmatrix} x \\ Q \end{Bmatrix} = [A]^{-1} = \begin{bmatrix} \frac{x}{F} & \frac{x}{V} \\ \frac{Q}{F} & \frac{Q}{V} \end{bmatrix}\begin{Bmatrix} F \\ V \end{Bmatrix} \quad \frac{x}{V}$$

Ch2 → Accel

$\downarrow$ to ?

$$\begin{cases} x * (j\omega)^2 = \ddot{x} \\ V_{Dev} \cdot \dfrac{R_{ext}}{Z_{device}} = V_{ch1} \end{cases}$$



$$\frac{\ddot{x}}{V_{ch1}}$$

$$\frac{x}{V_{Dev}} \xrightarrow{*(j\omega)^2} \frac{\ddot{x}}{V_{Dev}} \xrightarrow{*\frac{Z_{Dev}}{R_{ext}}} \frac{\ddot{x}}{V_{ch1}}$$

Units: $\frac{m}{V} * \left(\frac{RAD}{s}\right)^2 \rightarrow \frac{m/s^2}{V} \; \cancel{\frac{\Omega}{\Omega}} \rightarrow \frac{m/s^2}{V} \; \frac{V}{V}$

$\downarrow$

Accelerometer Calibration $\left(\frac{mV}{g}\right)$