MECH420

Sensors and Actuators

Laboratory Manual for Experiment 4

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The University of British Columbia

Department of Mechanical Engineering

Table of Contents

Laboratory Exercise #4: Transducer Dynamic Characteristics – Frequency Domain

Learning Objectives

The objectives of this laboratory exercise are:

- To understand transducer dynamics using the example of a voice coil transducer
- To understand the coupling between mechanical and electrical parameters in an electromechanical system using the example of a voice coil transducer
- To identify the dynamic transfer characteristics of a transducer.

Background

Voice coil transducers or electrodynamic transducers are widely used as both actuators and sensors, using the dc motor principle and the electric generator principle, respectively [4.1]. While their most popular application is in electrodynamic shakers (in vibration testing) and loudspeakers, where they are used to generate vibratory excitations and acoustic sound waves, they are also used for precision positioning applications such as in the positioning of hard drive read-write heads. In addition, many vibration velocity pickups are based on voice coil transducers.

1. System Overview

Figure 4.1 shows a schematic diagram of the setup used in the present laboratory exercise. An electrodynamic transducer, with its actuating coil, carries an experimental platform (vertically movable) underneath which an accelerometer is mounted. The coil is subjected to the magnetic field of a stationary ring magnet. Two proximity sensors detect the vertical position (variable) of this platform. The proximity sensor signals, the accelerometer signal, the coil voltage, and a voltage signal corresponding to the coil current are fed into a signal conditioning interface. The conditioned voltage signals are read into a PC via analog-to-digital conversion (ADC) through a data acquisition board. Data acquisition occurs using the software package LabVIEW. The voice coil may be electrically actuated using a voltage source, as in the case of a shaker table or dc motor (the actuator mode), or it can be mechanically actuated (e.g., by hand) as in the case of the electric generator (the sensor mode, where the generated current measures the mechanical motion). Details of operating principles of electrodynamic transducers (e.g., shakers or vibration exciters) are similar to those of a dc motor or an electric generator, and are found elsewhere. Such details are beyond the scope of the present experiment.

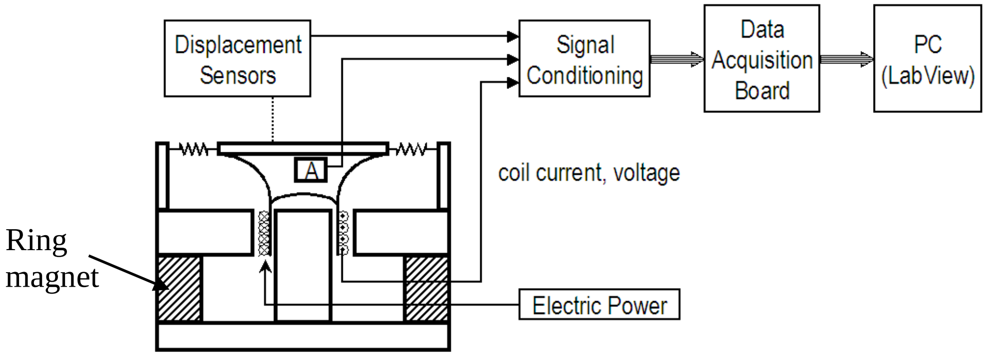

Figure 4.1: Schematic diagram of the voice coil system including instrumentation; A indicates the location of the accelerometer.

2. The Voice Coil Transducer

Figure 4.2 shows the schematic diagram of a typical electrodynamic transducer (or voice coil transducer) with a coil of length l in a circular air gap having a radial magnetic flux density B through an area A. The coil can be represented by an electrical resistor of resistance R in series with an inductor of inductance L. *Note*: This inductance is in fact the "leakage inductance" [4.1] and not the entire inductance. The main inductance is represented in the back e.m.f, as noted below. The coil (and the acoustic membrane) moves with the experimental platform, on which the accelerometer is mounted. The total mass of the moving assembly is m. This moving part is attached to a rigid support through a spring of "vertical" stiffness k. In the sketch of Figure 4.2, the springs are shown horizontally, corresponding to the shape of the speaker; the vertical effect of this spring is the same as that of a spring mounted vertically (k represents this vertical effect). The vertical motion will be resisted by mechanical friction, which is approximated (linearly) by the viscous damping constant b; this friction will be ignored in the present analysis of the system. The moving coil is subjected to the magnetic field of a fixed permanent magnet (ring magnet).

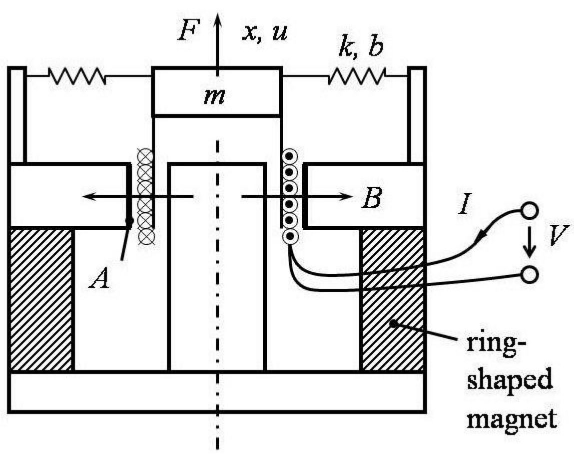

Figure 4.2: Schematic diagram of a cylindrical electrodynamic transducer (shaker).

An electric current I through the coil will lead to the Lorentz force $F_L = BlI$, due to the interaction of the magnetic field generated by I and the fixed magnetic field of the ring magnet, as in the case of a DC motor [4.1]. Simultaneously, according to Faraday's law of induction, moving the coil at velocity u through the magnetic field (from the magnet) in the air gap will induce a voltage (back electromotive force or back e.m.f.) $v_i = Blu$ in the coil. The supply voltage V to the coil is balanced by the voltage drops across the resistor (resistance R), the leakage inductor (inductance L), and the back e.m.f., as given by,

$$V = RI + L\dot{I} + Blu$$

For harmonic (sinusoidal) signals $I(t) = \widehat{I} \cdot e^{j\omega t}$ in the complex notation (i.e., in the frequency domain), a time derivative corresponds to multiplication by $j\omega$. Then we have,

$$V = RI + j\omega L I + j\omega Bl x .$$

Here, x denotes the vertical displacement of the platform (*Note*: $u = \dot{x}$).

3. The Components of the Experimental Setup

3.1 The Electrodynamic Apparatus

The apparatus for electrodynamic transducer characterization, as shown in Figure 4.3, consists of a base, 4 rigid posts holding a loudspeaker with the experimental platform, and a sensor support structure. Electric actuation of the electrodynamic transducer coil, in the magnetic field of the ring magnet, moves the platform up and down, which can be detected by the proximity sensors above the platform and the accelerometer mounted underneath the platform. All sensor signals can be recorded over time by the PC. The coil supply voltage and a voltage corresponding to the coil current are simultaneously recorded as well.

3.2 The Electrodynamic Transducer

The electrodynamic transducer used for this experiment is the PWFX 107 by Pyramid. This is a 700 W 10” high performance subwoofer.

3.3 The Displacement Sensors

The LED displacement sensor and the IR reflective object sensor used in this experiment are the same as the sensors used in laboratory experiment #1.

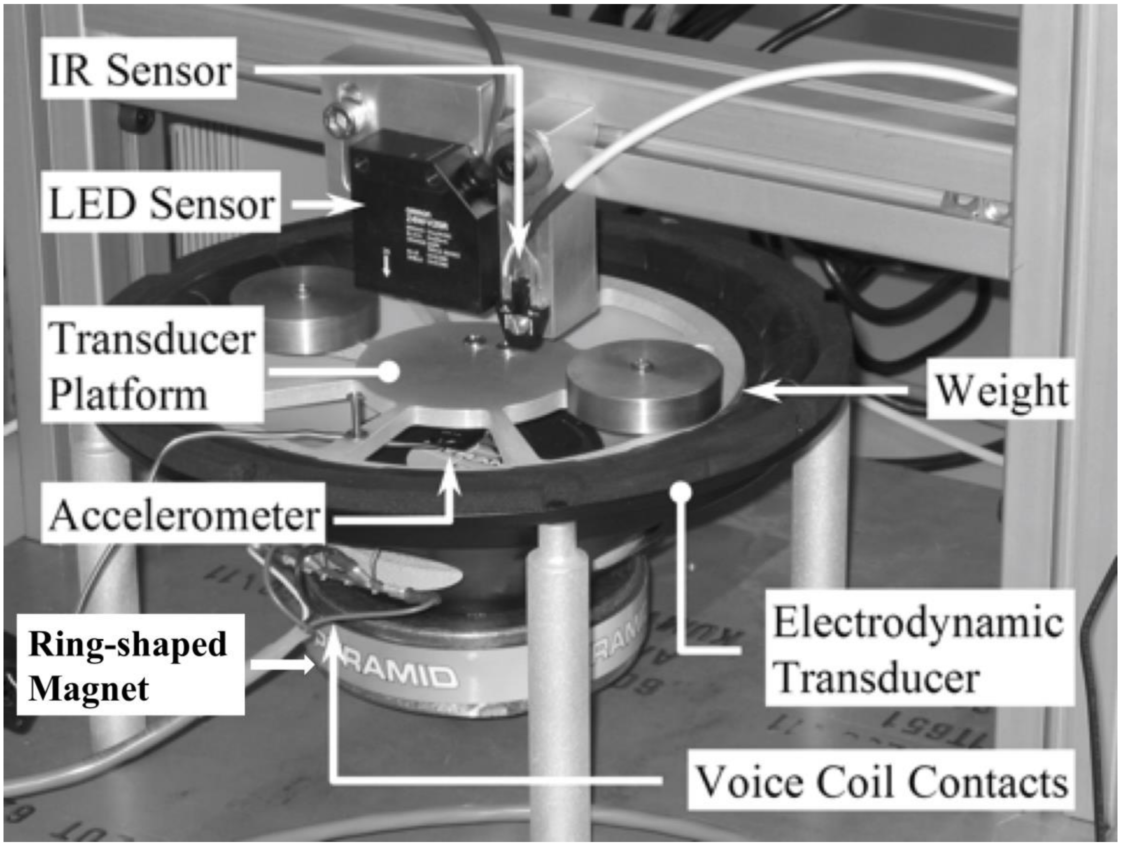

Figure 4.3: The apparatus for characterization of the electrodynamic transducer.

3.4 The Accelerometer

The accelerometer used for this experiment is the same model as the one used in laboratory experiment #3. One axis of the 2-axis ADXL203 EB by Analog Devices is used in the current setup. The accelerometer is connected to an ADXL203 EB evaluation board, which includes filtering capacitors that limit the bandwidth to 2.5 kHz, which is much higher than in laboratory experiment #3.

3.5 Current Measurement

Coil current measurement occurs via voltage measurement across a 0.2 Ω shunt resistor.

3.6 The Data Acquisition Interface

The data acquisition interface is identical to that used in laboratory experiments 1 through 3, with the exception that the cut-off frequency of the signal conditioning circuit is much higher, at $f_c = 10\,\text{kHz}$.

3.7 The Linear Amplifier

The resistors for the linear amplifier have been chosen such that the amplifier provides a fixed gain voltage amplification at gain $G = 10$.

3.8 Data Acquisition

The LabVIEW program Lab4.vi is set up to record the signals from the accelerometer, the LED and the IR displacement sensors, the supply voltage of the voice coil transducer, and the voltage corresponding to the current through the voice coil. We will use the same program for all the measurements. However, we have to decide which sampling frequency is most adequate for various measurements that we will be taking. We can also adjust the number of samples for each measurement. The sampling frequency for each measurement will be noted. You may need this information for your lab report.

4. Experiments

System component list

1. One LED proximity sensor
2. One capacitive accelerometer (2.5 kHz)
3. A computer with the LabVIEW system (including the data acquiring board)
4. Signal conditioning interface with a low pass filter of cut-off frequency 10 kHz
5. 3 power supplies, two of which are for the signal conditioning interface
6. A linear amplifier with a fixed gain of 10 and a 0.2 Ω shunt resistor (built in)
7. Two power supplies for the linear amplifier
8. A function generator
9. Experimental platform
10. Mounts for the voice coil transducer
11. Voice coil transducer
12. Connection cables

Experiment A: Transducer Static Transfer Characteristic

Experimental Procedure

1. We connect the voice coil to the DC power supply. We connect all sensors, the coil voltage connector and the connector for the voltage corresponding to the coil current to the signal conditioning interface, into the following input ports: A0 – accelerometer, A1 – LED sensor, A3 – coil voltage, A4 – coil current. The IR sensor is currently not in use.
2. We position the LED sensor vertically so that it can detect the surface of the transducer platform roughly in the centre of its operating range (see the results from laboratory experiment #1).
3. We record all signals to get a zero reference for the transducer at rest.
4. Now we select two of the brass weights (those used in laboratory experiment #2) and place them symmetrically on the transducer platform. We make a note of the value of these weights.
5. We record all signals again, so we can determine the displacement of the platform.
6. We add two additional weights, make a note of their values, and record the signals. Then we remove all the weights.
7. Now we apply the following constant voltages to the coil and record all signals for each coil voltage: V = 0.5 V, 1.0 V, 1.5 V, 2.0 V, 2.5 V.

Analysis

1. Using the information on the LED sensor and the sensor calibration from laboratory experiment #1, determine the displacement x of the transducer platform as a function of the gravitational force F_g of the weights (for $I = 0$). Use this result to determine the spring vertical stiffness k. If you do not think you have a reliable sensor calibration for the LED sensor, use the data sheet of the sensor to determine the displacement.
2. For each different constant coil voltage, determine the coil current, the platform displacement from its reference position, and the coil resistance R. Take offsets of the DAQ channels into account if applicable. Calculate the average coil resistance R.
3. Knowing the spring vertical stiffness k, determine the vertical spring force F_s for different coil currents, using the displacement. Plot I vs. F_s where the slope corresponds to the reciprocal product of the magnetic flux density and the corresponding coil length: $1/Bl = \Delta I / \Delta F_s$. Determine Bl.

Experiment B: Transducer Dynamic Transfer Characteristic

Experimental Procedure

1. We connect the function generator to the input of the linear amplifier. We make sure that both power supplies are connected to the linear amplifier. We connect the voice coil transducer to the output of the linear amplifier.
2. We set the function generator to 20 Hz and the “sin” function. We set the peak-to-peak output voltage to 200 mV and observe all signals from the sensors and coil voltage, and the voltage signal of the coil current, on the computer screen. We increase the peak-to-peak voltage in 200 mV increments up to 800 mV, while recording one data set for each voltage setting. We observe severe nonlinearities in the voltage signals at higher amplitudes, partially caused by nonlinearities of the amplifier. In order to operate the transducer in its linear range, we reduce the peak-to-peak voltage of the function generator to 200 mV and leave it there for the remaining tasks of experiment B.
3. We increase the frequency of the sinusoidal signal generated by the function generator in increments of 1, 2, 5, 10 … from 1 Hz to 5,000 Hz. We have to change the sampling frequency accordingly, to observe the waveforms on the screen and to record the data. About 200 data points for 4 periods are sufficient for each frequency; however, the DAQ cannot sample at a frequency higher than 50 kHz, which limits the number of data points per period at higher frequencies. We make a note of all experimental settings so you can use them for your analysis. We observe the peak-to-peak value of the voltage corresponding to the coil current, V_I. The input impedance of the transducer $|\underline{Z}| = V / I$ has a local maximum at a frequency near 40 Hz. We take additional data sets to find this maximum, which corresponds to the lowest value of V_I. We find this mechanical parallel resonant frequency f_p of the mass and spring combination, at an accuracy of 1 Hz.

4. Now we select two of the brass weights (those used in laboratory experiment #2) and place them symmetrically on the transducer platform. We make a note of the additional weight of the transducer platform.

5. We find the new parallel resonant frequency f'_p by performing the frequency sweep as before, but over a much smaller range. We make a note of the new resonant frequency f'_p. After finishing this part of the experiment, we remove the weights from the platform.

Analysis

1. Determine all peak-to-peak values for current and coil voltage. Calculate and plot the electric input impedance $|\underline{Z}| = V/I$ as a function of frequency.

2. From the force balance you established in the additional exercises indicated below, you know that the gravitational acceleration is balanced by the spring force for the reference displacement x_0 of the mass. Count x from this reference position. Now you only need to consider the force F_L provided by the voice coil and the spring force F_s. Apply Newton's second law (see additional exercises). Consider only harmonic excitations so that the second derivative of x with respect to time becomes $\ddot{x} = -\omega^2 x$. Solve for x as a function of the current I.

3. Now use the expression for the coil voltage given at the end of Section 2 and replace x with the expression that you derived from Newton's second law. The resonance we found during the experiment is at a frequency where the influence of the coil (leakage) inductance L can be ignored, so neglect the term with L. Solve for the electric input impedance of the system $Z = V / I$. By comparing this expression with the plot from the experimental data, you will find that the resonance measured for the electric input impedance is in fact a mechanical resonance. Use this measured mechanical parallel resonance f_p to determine the mass of the transducer platform m using the spring stiffness k derived earlier.

4. Adding the two weights has led to a change in the mechanical resonant frequency of the electrodynamic transducer to f'_p. Verify if this change is adequately described by the system parameters k and m determined above.

Experiment C: Motion Sensing with the Voice Coil Transducer

Experimental Procedure

1. We unplug the voice coil from the linear amplifier (we open the switch, then $i = 0$). According to Faraday's law of induction, the voice coil can be used as a velocity sensor (in the "electric generator" mode, which is the motion sensor mode).

2. We press carefully (by hand) on the transducer platform, fast enough so we generate a coil voltage. We record the sensor signals over 1 second.

Analysis

1. Convert the recorded signal from the LED sensor into displacement, the signal form the voice coil into velocity, and the signal from the accelerometer into acceleration, and plot these quantities with respect to time (i.e., time histories).
2. Comment on the shape and the relationship between these different signals.

5. Additional Exercises (These should be included at the end of your report)

1. Establish the vertical equation of motion for the experimental platform containing the Lorentz force, gravitational force, spring force, and the damping force. Provide expressions for each of these forces. Include the gravitational forces from both the mass m of the experimental platform and the mass M that will be added to it.
2. What is the "downward" displacement x_0 of the platform for zero current ($I = 0$) under static conditions and without the additional weight ($M = 0$)? This corresponds to the static equilibrium condition.
3. Search and obtain the data sheets and images of the following items (not those used in the present experiment): 1. A voice coil with drive hardware (or a miniature shaker—vibration exciter); 2. A piezoelectric accelerometer; 3. A microcontroller. Suppose that the accelerometer is mounted on the voice coil (moving platform), and the microcontroller is programmed to acquire the signal from the accelerometer, and based on that information and the required motion profile (vibration profile), a signal is generated and provided to drive the voice coil. Give a schematic diagram that contains the images of these components and any other required hardware for this system. In the diagram, show how the components are interconnected, using lines to represent cable strands (signal paths). *Note*: No knowledge on programming the microcontroller, how to properly match the components, and how to operate the system, is needed to be included here. Only the interconnection details of the components should be presented.

Reference

[4.1] *Sensors and Actuators: Engineering System Instrumentation*, 2nd Edition, C. W. de Silva, CRC Press, Taylor & Francis, Boca Raton, FL, ISBN: 978-1-4665-0681-7, 2016.

Lab 4:

Voice Coil

- Operates as a DC actuator or as an electric generator (motion sensor)
- Field from ring magnet interacts with the field from the electro-magnet (coil with current) to generate a vertical force (Lorentz force). This is the "actuator" mode
- Moving the coil by hand in the field from ring magnet, induces a voltage in the coil (as in a generator). Induced voltage measures the coil velocity. This is the sensor mode

- *k* and *b* are effective spring stiffness and damping constant in the "vertical" direction (even though shown horizontally to be consistent with the physical form of the transducer diaphragm)