



Construction of a Vibrating Structure for Demonstration of Vibration Measurement and FFT Analysis

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Abstract:

Many Mechanical Engineering Technology (MET) programs include a Basic Instrumentation class structured to give students hands-on experiences with measurement and analysis systems. As part of a module on vibrations and the Fast Fourier Transform (FFT), a lab was developed to create a three-tiered vibrating structure. This test apparatus consists of relatively inexpensive components with threaded rods for the columns, plywood for the tiers, and an adjustable orbital sander for the vibration source. The vibration source is mounted to the top tier, and its rotational speed is adjusted by a controller made for common power tools.

Different vibrational modes for the structure can be observed by varying the speed of the vibration source. In one mode the entire structure sways back-and-forth with the top tier showing the largest displacement. In a second mode the center tier is vibrating while the upper and lower tiers remain nearly motionless.

One or more accelerometers may be attached to the tier having the largest displacement for a specific mode. The accelerometer output is measured using either an oscilloscope or a computer data acquisition system (DAS). A second test may be performed using a weight on the center tier to demonstrate a change in natural frequency with the added mass to the system. It is also possible to adjust the natural frequency by adjusting the position of the center tier relative to the upper and lower tiers.

Including the oscilloscope in the required measurements gives the student exposure to a second measurement system as well as allowing them to double-check the results of their analysis of the data from the DAS. Analysis of the data is performed outside of the lab using MathCAD or Excel and builds off a previous tutorial lab on frequency analysis methods based on Fast Fourier Transform (FFT) methods. The students are required to use the FFT results to identify the resonant frequencies as part of their lab report.

Introduction:

A three-tiered structure serves as an excellent platform for students to conduct accelerometer vibration measurements and analyze the acquired data with the ubiquitous Fast Fourier Transform (FFT). While the concept behind the structure was originally developed at the University of Pittsburgh at Johnstown¹, the current laboratory procedure has expanded the concept by simplifying the structure, adding in an inexpensive adjustable vibration source that allows for the exploration of multiple modes, and expanding the mounting possibilities of the accelerometer(s).

In conducting this lab, students gain experience with the mounting and use of accelerometers, learn about different vibrational modes and how they are changed by mass and shape, get familiar with current data acquisition systems, and learn how to utilize an FFT to analyze data. Each of these skills are likely to be required of MET students post-graduation.

Construction of the Structure:

Cost and flexibility were prioritized in the design of the three-tiered structure. While the utilized dimensions are arbitrary, the discussed systems (**Figure 1**) consists of three tiers of $\frac{3}{4}$ " thick square wooden plates that are $11\frac{7}{8}$ " on a side, 4 threaded rods of size $\frac{5}{16}$ "-18 that range in length from 24" to 36", and the associated fastening hardware.



Figure 1: Completed Assembly

Construction of the structure begins with cutting the four threaded rods matching lengths. The location of the center platform is then established by positioning nuts and washers at the same position along the threaded rod. It is recommended that two nuts be used in combination at each point so that the second nut acts as a jam nut as shown in **Figure 2**. When vibrating, the nuts will frequently loosen causing undesirable secondary vibrations in the system.

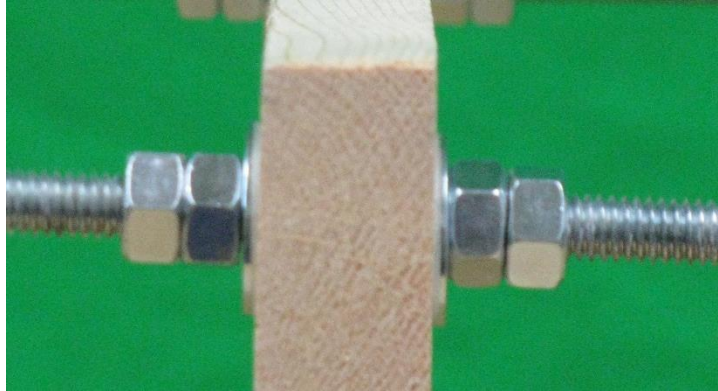


Figure 2: Central Tier Fastened with Washer and Jam Nuts

For a sufficiently long threaded rod, turning the nuts by hand for the central tier can be quite tedious. A simple shortcut uses a jam nut on the end of the rod so that an electric screwdriver with a socket can spin the rod allowing a nut to ascend from the other end (**Figure 3**). This will vastly improve the flexibility of the system as it makes a modification of the level height trivial.



Figure 3: Use of the Jam Nut to Spin the Threaded Rod for Nut Placement

Once the locating nuts and washers for the center tier have been placed, the tier should be lowered onto the threaded rods allowing it to rest on the pre-positioned washers. The opposite side should then be locked down with another set of washers and nuts. The same process should then be repeated for the upper and lower tiers. Once all levels have been positioned, it is simple to ensure they are parallel with the use of a standard bubble level.

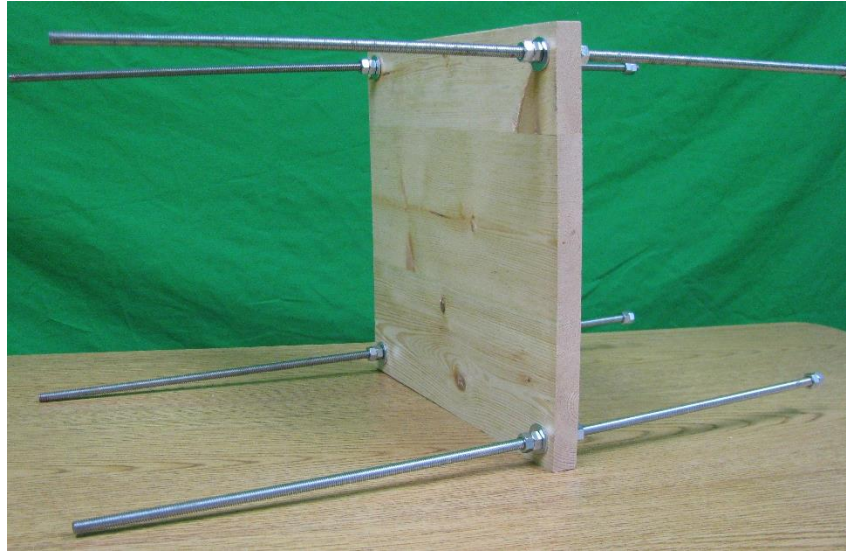


Figure 4: Central Tier Locked In and Ready for Assembly of End Tiers

The vibration source can be mounted once the structure is complete. An orbital sander with a continuously variable speed control makes an excellent rotational vibration source. In the present setup, the pad of the orbital sander has been permanently affixed to a thin block of wood with four bolts. The block of wood is then bolted to the upper tier of the structure as shown in **Figure 5**. This arrangement gives the sander a firm foundation, but also gives good flexibility in modifying the setup. The vibration frequency of the sander can be determined by placing a piece of reflective tape on the orbiting mass (internal to the sander) and using an optical tachometer to measure the revolutions.



Figure 5: Mounting of the Orbital Sander Vibration Source

The accelerometer can be mounted in several different manners. The easiest is a simple drill and tap in the side of the wooden tier. This is sufficient for a short time, but the threads will eventually strip and a new fastening hole must be created. If a longer lasting mount is desired, it is possible to use a small nut to hold the accelerometer (**Figure 6**). In order to install the nut, drill a shallow hole in the side of the wooden tier. The hole should be slightly smaller than the corner-to-corner width of the nut. The hole should then be filled with epoxy adhesive and the nut press-fit into the hole. The press-fit will assist the epoxy in preventing rotation of the nut.



Figure 6: Mounting Nut for the Accelerometer

Finally, it is recommended that the lower tier be weighted or bolted to a fixed surface and that a damping layer be placed between. This will limit extraneous modes that will result from a vertical degree of freedom.



Figure 7: Damping Layer Underneath the Lower Tier

Modes of Operation:

With the lower tier weighted to the ground, only the upper two tiers will have possible mode shapes. The orbital sander applies a forcing function in a circular direction so the rotational modes the most evident. If desired, it would be possible to excite the translational modes with a linear action tool such as a jig-saw.

The first rotational mode rotation consists of a rotation of the entire structure. The vibrations in this mode aren't usually as interesting so students are instructed to adjust the vibration to find the second mode. In the second mode, the upper two tiers rotate out of phase with each other. The upper tier has a much larger weight due to the orbital sander so it appears to be practically motionless. Conversely, the central tier will have a rather large amplitude. Since the purpose of this lab activity is to demonstrate the use of accelerometers and to give the students experience in using the FFT to analyze vibration data, it is an accelerometer on the center tier in this mode that produces the most dramatic measurement results.

In order to familiarize the students with multiple pieces of equipment, it is helpful to have them measure the acceleration with several devices. This lab procedure gives a good opportunity to use both a data acquisition system and an oscilloscope. The oscilloscope allows them to instantly observe the acceleration and most modern oscilloscopes will allow the students to overlay an FFT on the acceleration results. Additionally, the oscilloscope helps the student find the resonant frequency by giving instant feedback in the magnitude of the FFT. The data acquisition is then used for collecting data to be analyzed and compared to the oscilloscope readout.

The flexibility of the testing platforms means that every lab can be modified to come up with a unique result. Simply moving the center tier up or down along the threaded rod will change the resonant frequency of the apparatus. Additionally, the resonant frequency can be modified by changing the mass of the central tier. It is a good exercise to have the student make multiple measurements of the resonant frequency while changing the mass of the center tier.

Data Analysis:

Students begin the lab by using a Data Acquisition System to acquire acceleration versus time data. They are instructed on the best method for mounting the accelerometer, how the accelerometer works, and what kind of result to expect. The data in *Figure 8* is typical of the results the students will obtain with the standard tower when the sander is adjusted to give the maximum displacement of the center tier. While the students could figure out the resonant frequency simply by counting the peaks and dividing by the time, this does not help them to visualize the switching from the time domain to the frequency domain given by an FFT. *Figure 9* shows the FFT results the students would obtain using the Fast Fourier Transform function in the Excel Data Analysis Toolpack.² As expected from counting the accelerometer peaks, it shows a resonant frequency of around 26.9 Hz. As a comparison, students are then asked to add weight to the center tier and repeat the data acquisition. *Figure 10* and *Figure 11* demonstrate that adding just one pound of mass to the center tier causes the resonant frequency to be shifted down to 21.5 Hz from the 26.9 Hz. obtained previously. This gives the students an excellent perspective on the mechanism behind the resonant frequency.

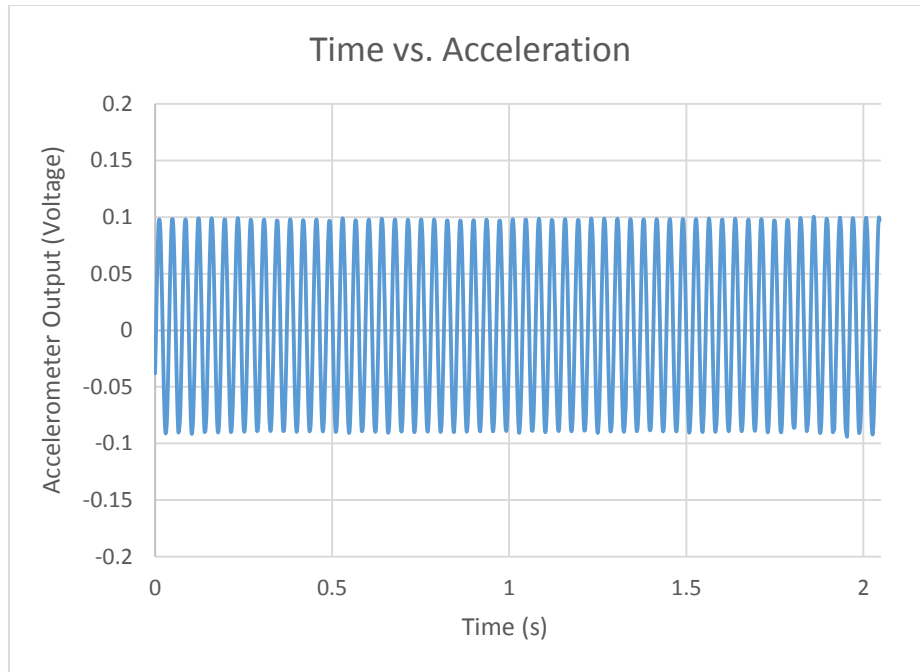


Figure 8: Raw Accelerometer Data for Un-Weighted Structure

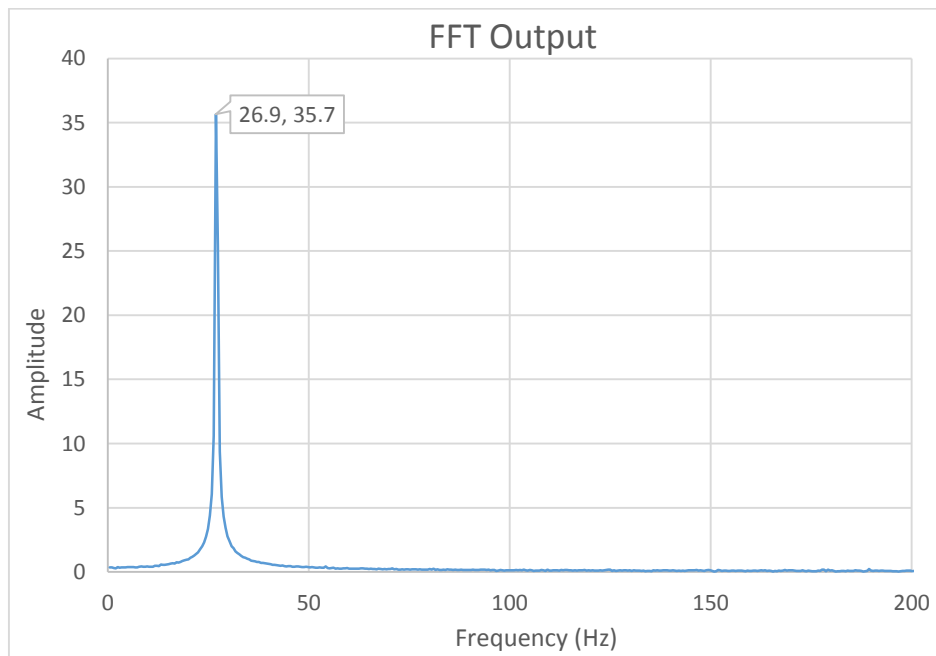


Figure 9: FFT Output of the Accelerometer Data for Un-Weighted Structure

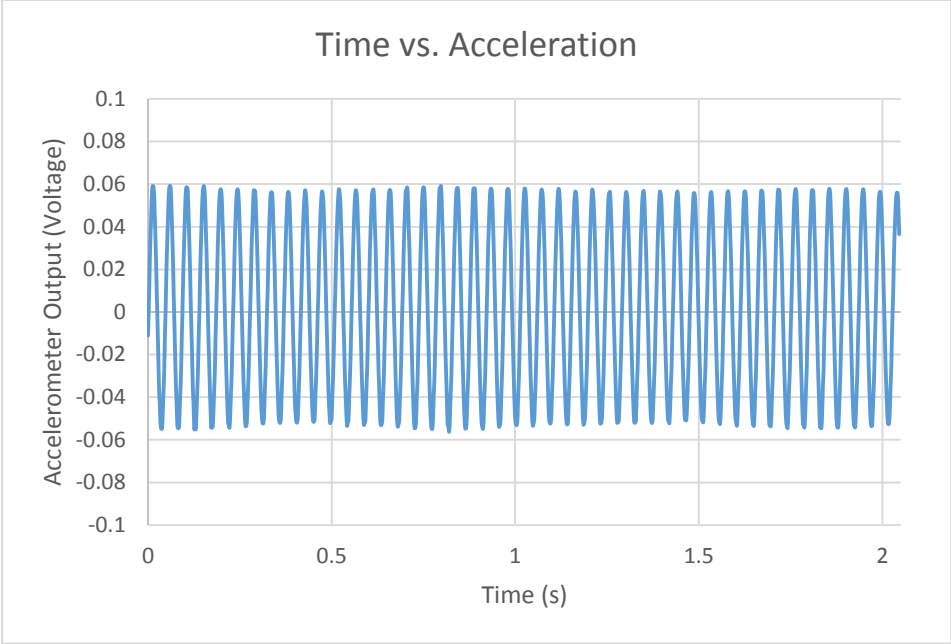


Figure 10: Raw Accelerometer Data for Weighted Structure

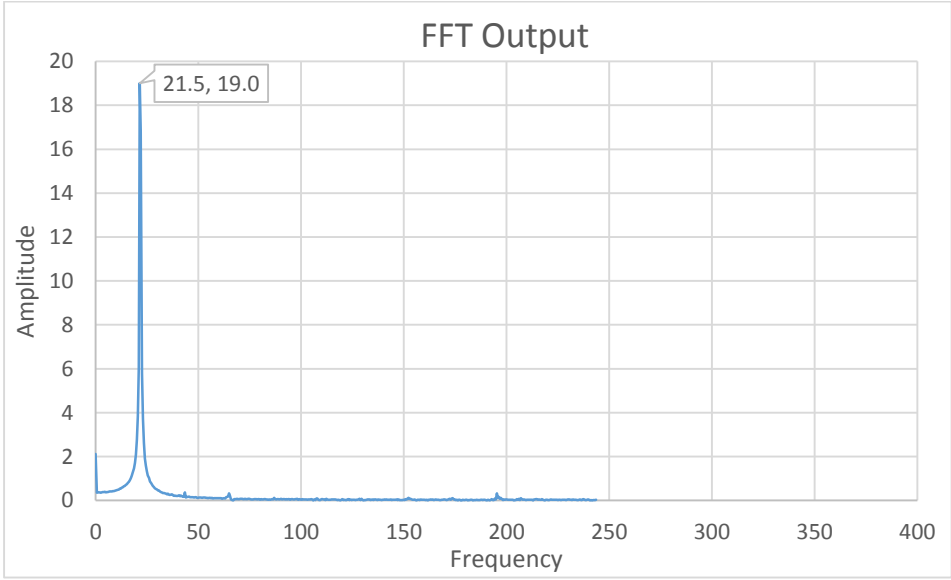


Figure 11: FFT Output of the Accelerometer Data for Weighted Structure

Parts List:

Part	Approximate Cost
Threaded Rod x 4	\$10
Nuts x 44	\$10
Washers x 24	\$5
Wooden Tiers x 3	\$15
Orbital Sander with Variable Speed	\$80
Total:	\$120

Table 1: Parts List and Approximate Cost

Student Outcomes:

This lab has proven most effective when coupled with previous computer labs familiarizing the students with Microsoft Excel, vibrations, and the Fast Fourier Transform. While necessary as background for understanding the calculations, these labs tend to have poor engagement due to their dry nature. The students learn the mechanisms of the calculations, but they do not develop an intuition about the underlying principles. Giving them a toy that they can touch and modify helps to develop an understanding of vibration. Seeing the actual modes with the differences between bending and torsion and allowing them to discover how they can affect the result by modifying the system gives them an insight that raw calculations could never provide.

In general, student engagement with this project has been excellent. Students express a greater understanding of vibration once they can directly experience the effects. Additionally, they now more intuitively grasp the concept and purpose of the FFT.

Conclusion:

Analyzing vibrations and understanding the role of the Fast Fourier Transform can be difficult for students to grasp. Utilizing this lab has allowed the students to visualize, perhaps for the first time, what vibrations mean, how to utilize accelerometers in measuring vibrations, and how the results can be given more meaning with the Fast Fourier Transform. When utilized with complementary classroom material, this lab has been quite effective in helping students successfully grasp previously opaque material.

Bibliography

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2. **Klingenberg, L.** Frequency domain using excel. [Online] 2005. <http://online.sfsu.edu/~larryk/Common%20Files/Excel.FFT.pdf>.