AC 2010-1098: COURSE-RELATED ACTIVITIES FOR MECHANICAL VIBRATION IN THE ABSENCE OF A FORMAL LABORATORY

B. Sridhara, Middle Tennessee State University

Dr. B. S. Sridhara is a professor in the Department of Engineering Technology at Middle Tennessee State University. He received his B.S.M.E. and M.S.M.E. degrees from Bangalore University and Indian Institute of Science, Bangalore, India. He received his M.S.M.E. and Ph. D. degrees from Stevens Institute of Technology, Hoboken, New Jersey, and Auburn University, Alabama. Dr. Sridhara has published several peer-reviewed articles in the areas of Acoustics, Vibration, finite element methods, and Engineering Education.

Course-Related Activities for Mechanical Vibration in the Absence of a Formal Laboratory

Abstract

The Engineering Technology (ET) program at Middle Tennessee State University has approximately 350 students. Our Mechanical Engineering Technology (MET) concentration was started in the fall of 2004 and currently it has 120 majors. All MET students are required to take several senior level courses including Mechanical Vibration. The author started teaching this course formally in the fall of 2006. Although Vibration is a lecture/lab course currently we do not have a lab due to budget restrictions and therefore, the author decided to include a relevant hands-on project and an industrial visit. The student teams are required to design, build and test a Helmholtz resonator. A Helmholtz resonator, which can be modeled as a spring-mass system, consists of a body (cavity) and a neck whose dimensions can be selected to tune the resonator to respond at a desired natural frequency. In the fall of 2007 student teams as well as the author built resonators using steel and aluminum. We used a laptop computer and a freeware (software) to test the resonators. The testing included pressing the resonator neck opening against our lower lip and quickly blowing once and simultaneously recording the time domain data. The freeware was useful in recording the time domain data but the frequency response was not good because it did not display a well-defined peak. Therefore, we could not compare the calculated and measured natural frequencies satisfactorily. In spring of 2009 the author received an internal grant to purchase the frequency analysis software, SpectraPlus. This software can perform an FFT on an existing audio wave file using the sound card in a pc or laptop. It also has the capability of recording and performing fast Fourier transform (FFT) in real time. It can generate colorful frequency response and 3-D surface (signal, time and frequency) plots in a matter of seconds. In the summer of 2009 the author calculated the frequency response using SpectraPlus for the fall of 2007 and 2008 time-domain data. All 2007 and 2008 resonators were built/tuned to respond at a natural frequency of 1000 Hz. The FFT results showed a well-defined peak consistently at the same but lower than the calculated value for all cases. This means the software is reliable and that some damping was present in the resonator. The damping could be due to the viscosity of air or the fabrication techniques used. We wanted to investigate this matter further. In the fall of 2009 each student team was asked to design three resonators to respond at 1000 Hz, for consistency and comparison with the earlier results, using different metals. The students learned to use SpectraPlus as part of the laboratory activity. They were able to obtain several time domain data and generate the frequency response and 3-D surface plots. Each team submitted a formal report on their resonator project which included introduction, design, fabrication, testing, and discussion of results. In addition to the Helmholtz resonator project the students were given a tour of a local industry which performs dynamic balancing of multi-disk rotors that are used to produce corn flour for cattle feed.

Introduction:

Our Engineering Technology (ET) program at Middle Tennessee State University has approximately 350 students and the Mechanical Engineering Technology (MET) concentration has approximately 120 majors. The MET program that was started in the fall of 2004 has grown well and we are fortunate to be located in a highly industrialized area. Our MET students are required to take several senior level classes such as Fluid Power, Heating, Ventilation and Air Conditioning (HVAC), Robotics, and Mechanical Vibration. We started teaching Vibration formally in the fall of 2006 and currently this course does not have a formal laboratory. We may not be able to set up such a laboratory in the near future because of the budget cuts we are facing at the departmental and university levels. Therefore, the author decided to include two vibration related hands-on activities, the Helmholtz resonator project and an industrial visit. The student teams are required to design, build and test Helmholtz resonators, and write a formal report. They are also required to visit a local industry and observe dynamic balancing of multi-disk rotors that are used to produce corn flour for cattle feed.

Helmholtz Resonator

There are several mechanical systems or devices that undergo oscillatory motion and can be modeled as spring-mass-damper systems. The damping in these could be seen as a separate entity as in the case of an automotive shock absorber or it could be an integral part of the system such as the internal/external friction as in the case of a vibrating hack-saw blade, for example, mounted as a cantilever. It is not easy to find a pure spring-mass system because damping is always present in some form. However, there are some devices in which the damping is negligibly small and they can be approximated as pure spring-mass systems. The Helmholtz resonator[1] is one such device. This is used in automotive mufflers in combination with simple expansion chambers. The theory of Helmholtz resonator is briefly discussed below.

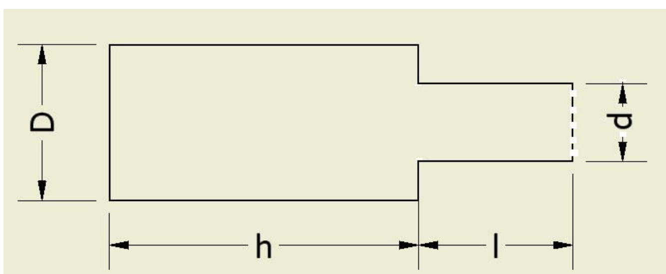

Figure 1. Schematic diagram of a Helmholtz Resonator:
d = neck diameter; D = body diameter, l = neck length;
h = body length

In the Helmholtz resonator (Figure 1) the volume of the air in the body functions as a spring and the air in the neck as the mass. The mass of air in the neck is given by[2]

$$m = (l\,A)\,(\rho),$$

Where A = neck cross-sectional area,
ρ = density of air.

The stiffness of the air spring is given by

$k = dp/dx$,

Where dp = the small pressure change that causes the oscillatory motion,
dx = the elemental displacement of the air mass, m.

Considering adiabatic conditions during the oscillatory motion of the air mass we can write

$$pV^k = constant,$$

Where p = air pressure in the resonator body,
V = volume of the air in the resonator body,
k = adiabatic index.

Following the steps given in Reference 2 we can write for the natural frequency of the above Helmholtz resonator as

$$f_0 = (c/2\pi)\,[A/(Vl)]^{1/2}\,,$$

Where c = speed of sound.

In the above expression f_0 is the undamped natural frequency in cycles per second (*cps* or *Hz*) as the viscosity (damping property) of air is negligibly small.

The author simplified the expression for f_0 in terms of the resonator geometry shown in Figure 1 so that the students can work with different values of (d/D), (hl) and a numerical constant for tuning the Helmholtz resonator to the desired natural frequency. Noting that the speed of sound in air is c = 343 m/s, the final expression for f_0 is given by

$$f_0 = 5460\,(d/D)\,[1/\,(hl)^{1/2}]\,, \qquad \text{(i)}$$

Where h and l are measured in centimeters.

Design and Fabrication of Helmholtz Resonators

In the fall of 2007 and 2008 the Vibration students designed their Helmholtz resonator using AutoDesk Inventor and built it using steel or aluminum. The author designed a resonator (Figure 2) using (d/D) = 0.5 and (hl) = 8 so that the natural frequency will be approximately 1000 Hz. Some resonators were built in the ET department's machine shop while the others were built at the students' workplace. The bottom plate and the top cylindrical parts were press-fitted to avoid any air leakage. The student teams also tuned their resonator to an approximate natural frequency of 1000 Hz but used different (d/D) and (hl) values. One team even generated a series of different *d, D, h* and *l* values for the same 1000 Hz natural frequency. Some steel and aluminum Helmholtz resonators built by student teams and the instructor are shown in Figure 3.

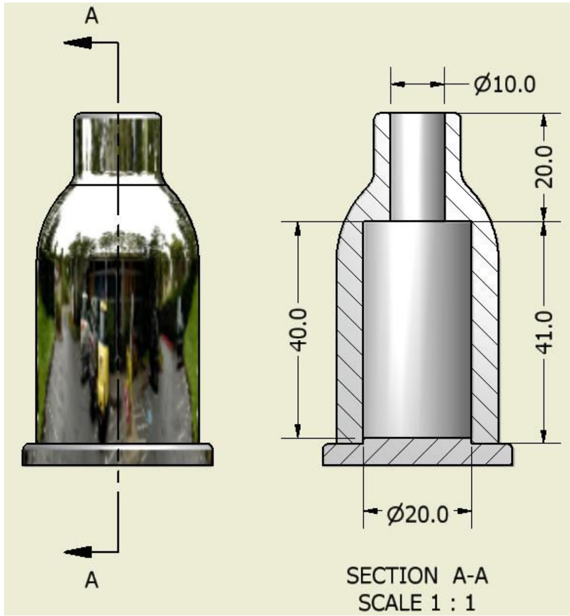

Figure 2. Full and sectional views of the 3-D model of a Helmholtz resonator designed using AutoDesk Inventor.

Figure 3. Steel and aluminum Helmholtz resonators built by student teams and the author.

In the fall of 2009 each Vibration student team designed three Helmholtz resonators. One team used mild steel, aluminum and the polymer, Delrin (Figure 4). Another team used cold- rolled steel, aluminum and the tungsten alloy, Elkonite 10W3 (Figure 5). They were asked to achieve a fine interior surface superfinish and tune the resonator to respond at its natural frequency of 1000 Hz. This was done for consistency with the earlier resonators so that the results can be compared and analyzed. It should be noted here that it is extremely difficult to design a Helmholtz resonator to respond at an exact frequency, 1000 Hz in this case, because of the practical limitations. We started with a natural frequency of 1000 Hz, chose suitable values for (d/D) or (hl) of Equation (i) and arrived at the geometry of the resonator. We rounded off the calculated resonator neck and body dimensions suitably so that the precisions can be achieved and recalculated the natural frequency. The recalculated value for the resonators shown in Figures 2-5 is 965 Hz.

Figure 4. Steel, aluminum and Elkonite resonators designed and fabricated by Team-1 (Fall of 2009).

Figure 5. Steel, aluminum and Delrin resonators designed and fabricated by Team-2 (Fall of 2009).

SpectraPlus 5.0, the Frequency Analysis Software

In 2007 and 2008 we used a freeware which was good for recording the time-domain data of the Helmholtz resonator but did not provide a satisfactory frequency response. We needed a software that is capable of performing the fast Fourier transform (FFT) on the time domain data in order to study the resonator's performance quantitatively. The author received an instructional evaluation and development grant from Middle Tennessee State University to purchase the software, *SpectraPlus real time spectrum analyzer*[3] (http://www.spectraplus.com/index.html).

We could easily install SpectraPlus on a PC and obtain the authorization key from the software manufacturer. It took less than ten seconds for the software to be ready for use. It came with a 136-page users guide and we could also download a PDF version from the company's website. SpectraPlus has several capabilities and we have listed below the three major features that are useful to our project.

Time domain data

All we need is a PC and a microphone to acquire the time-domain data. The software has the Real-Time, Recorder, and Post-Processing modes. In the Real-Time mode, the program acquires an FFT sized block of digitized sound data directly from the sound card, computes the spectrum and displays the results. The Recorder mode is similar to the Windows "Sound Recorder" and it allows us to record and playback sound files. Unlike "Sound Recorder" however, we have control over the sampling format and sampling rate. The program will also display the spectrum of the signal while recording or playing. The Post-Processing mode allows us to analyze a previously recorded sound file in the WAV format. This mode provides greater control over the processing than the Recorder or Real-Time modes. A typical Helmholtz resonator time-domain data is shown in Figure 6.

Spectrum (Frequency Response)

Several options including *Compute and display average spectrum* will be displayed by right-clicking the selected time segment that is highlighted in cyan (Figure 6). Once the spectrum option is selected from the pop-up menu the software will perform the FFT on the selected time-domain data and generate the spectrum or frequency response. Two frequency response plots for the fall of 2007 and 2008 are shown in Figures 7 and 8.

3-D Surface

By right-clicking the selected time segment and clicking the *Compute and display average 3-D surface* option we can plot the time-domain data, frequency response and relative amplitude along three mutually perpendicular axes. The resulting three-dimensional surface will give us a visual relationship between the corresponding time and frequency domain data. A typical 3-D surface plot is shown in Figure 9.

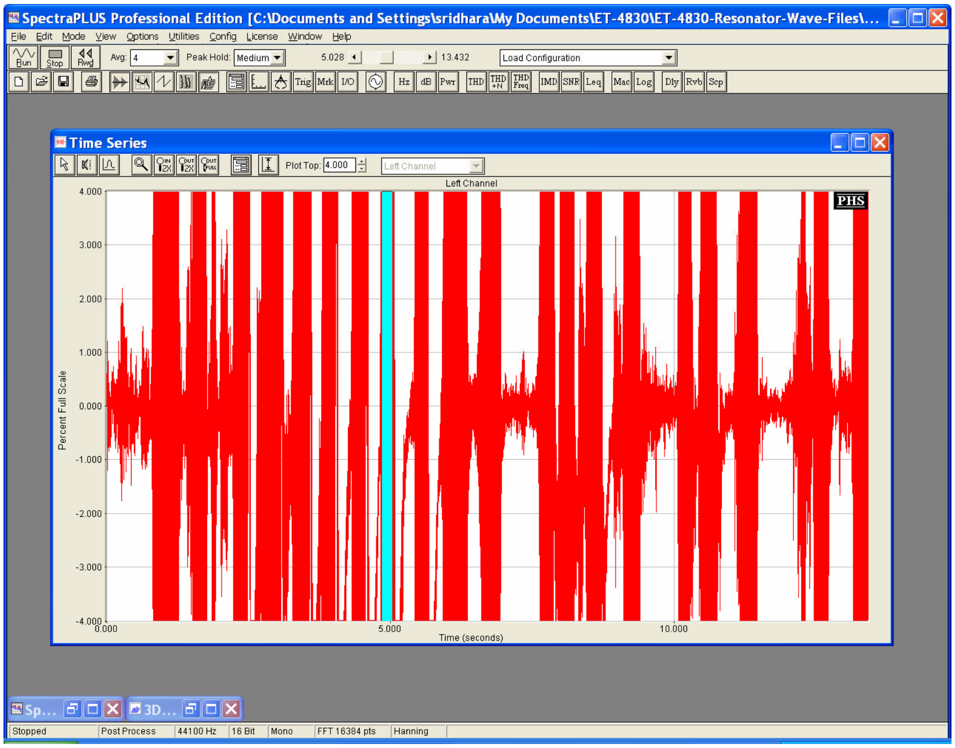

Figure 6. Helmholtz resonator time-domain data. The selected time segment is highlighted in cyan (fall of 2007 data).

Figure 7. Helmholtz resonator frequency response (fall of 2007 data).

Figure 8. Helmholtz resonator frequency response (fall of 2008 data).

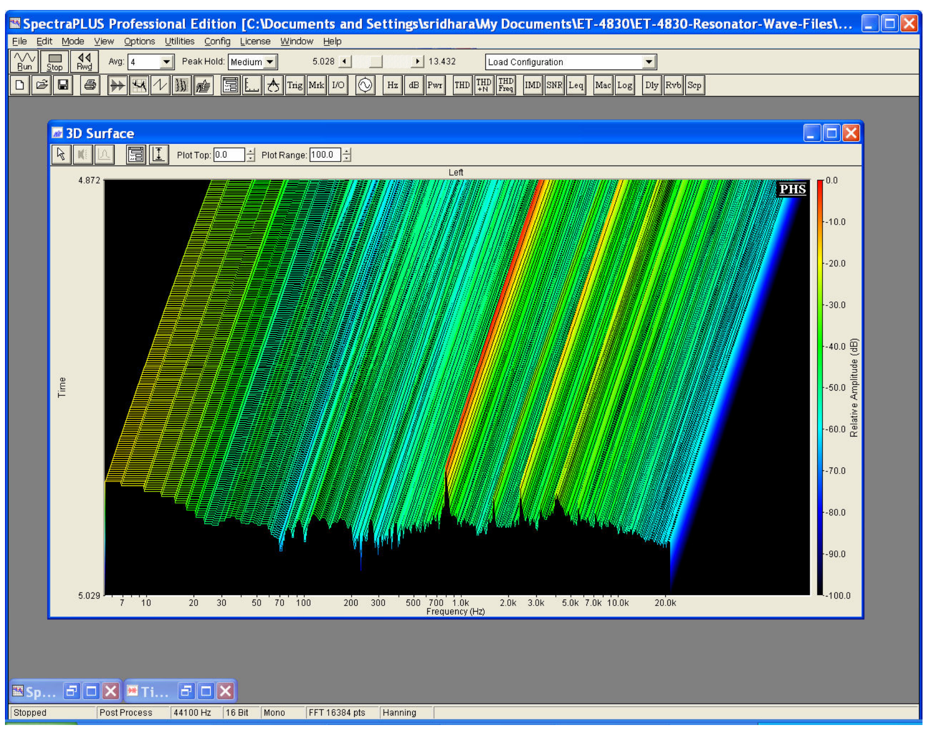

Figure 9. Three-dimensional (3-D) surface plot of the Helmholtz resonator signal amplitude, time and frequency (fall of 2008 data).

Testing the Resonators and Discussion of Results

Testing the Helmholtz resonator is typically done by pressing its opening against our lower lip, quickly blowing to produce a short beep and simultaneously recording the time domain data. One can also blow compressed air using a nozzle making sure the compressor is turned off after the desired pressure is reached. We used both of these methods to produce a sound signal and the recording was done using a Logitech unidirectional microphone and SpecraPlus (installed in a PC). Each resonator was tested several times under identical conditions and the frequency response was verified to make sure the results were consistent.

We selected two Helmholtz resonator audio files from the fall of 2007 and 2008, and used the post-processing mode as it will allow us to obtain the frequency response for any resonator sound signal recorded in the WAV format. Each red-colored spike (Figure 6) represents a resonator sound signal and some of these may not be a clear beep and may have some low frequency signals such as a hiss. SpectraPlus will allow us to select a time segment and play to make sure we have a clear beep. Figure 6 shows one such selected time segment in cyan. We obtained the frequency response for all resonators that were built by different student teams in the fall of 2007 and 2008, and results for two cases are shown in Figures 7 and 8. In all cases the peak which gives the measured natural frequency of the two resonators occurred around 800 Hz. The difference between the calculated and measured values is approximately 170 Hz and raised concerns about the tolerances used for the press fitting of the resonator base and cylindrical part, the interior finish and the damping effect of air. As we know the viscosity of air is negligibly small and therefore, it cannot reduce the natural frequency significantly. We cannot verify the other two factors without sectioning the resonators. Therefore, we decided to address these issues in the fall of 2009. The student teams were instructed to use the standard tolerances for the interference fit.[4] They were also asked to achieve a superfine interior surface using a honing tool after machining and drilling/boring of the resonator base, neck and body. Typically, a *superfinish* honing process will yield a surface finish in the range of 0.013-0.025 mm with reference to a previously machined hole.[5]

Some frequency response results are shown for the fall of 2009 resonators in Figures 10-13. The aluminum resonator shown in Figure 10 has responded at approximately 925 Hz which is very close to the calculated natural frequency of 965 Hz. The mild steel resonator's measured natural frequency is approximately 870 Hz (Figure 11). The Delrin resonator has an approximate measured frequency of 750 Hz (Figure 12) and this is probably due to the relatively low rigidity of the polymer. The Elkonite resonator has a measured natural frequency of approximately 770 Hz (Figure 13). Apparently the tungsten alloy has not made a significant difference in the resonator performance. We want to investigate this matter further and find out why the aluminum resonator has performed better than the steel and Elkonite resonators. All of our resonators have been fabricated using materials donated by different local companies. Therefore, we want to find out the composition of the aluminum and steel used in this project by working with a local metallurgical company. Our fall of 2010 Vibration students will get an opportunity to visit this industry and work with them on a course-related project. We also want to section some resonators that have not performed as well as that of Figure 10 and inspect the interior surface finish to find out if that is a contributing factor.

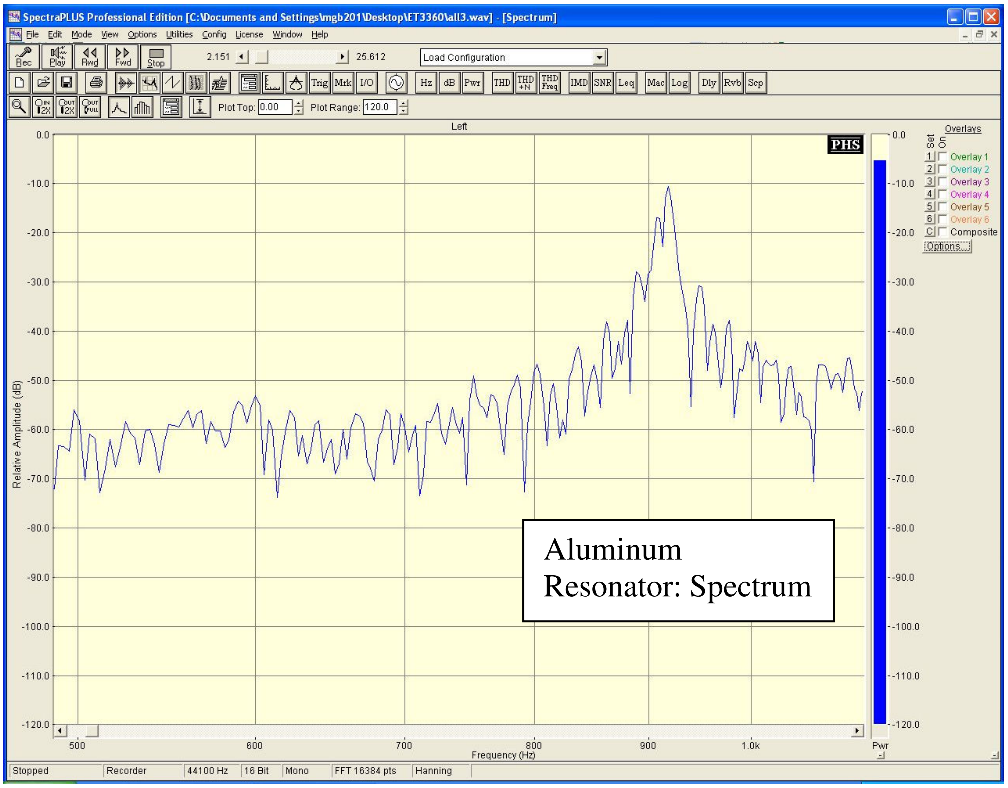

Figure 10. Helmholtz resonator frequency response (Team-2 data, fall of 2009).

Figure 11. Helmholtz resonator frequency response (Team-2 data, fall of 2009).

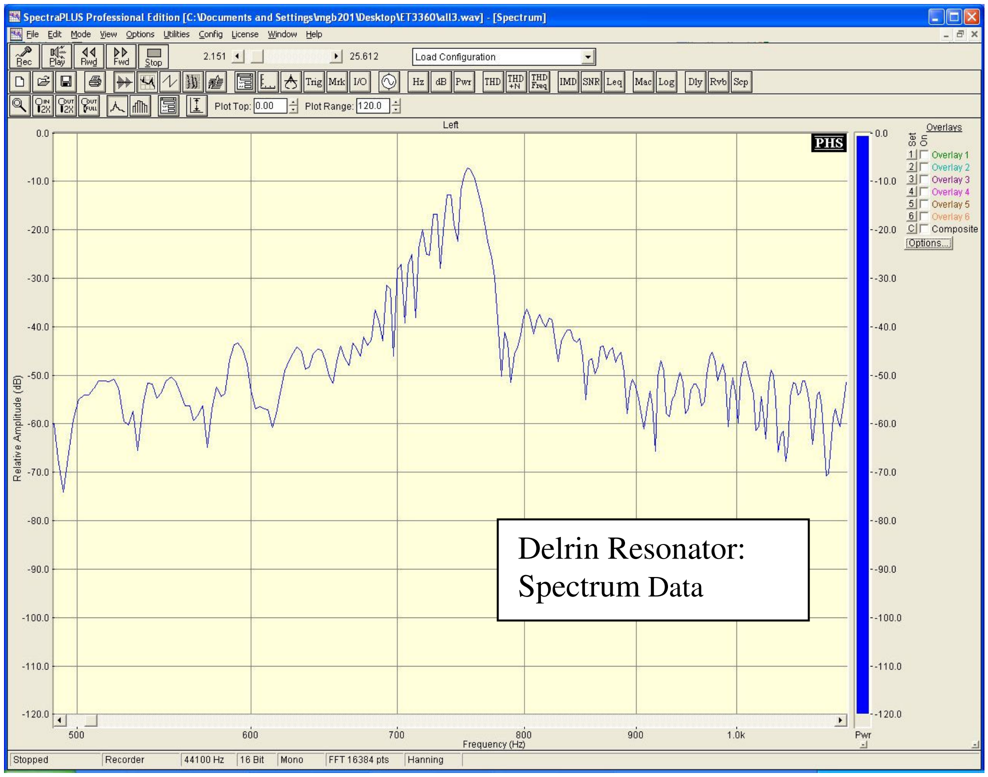

Figure 12. Helmholtz resonator frequency response (Team-2 data, fall of 2009).

Figure 13. Helmholtz resonator frequency response (Team-1 data, fall of 2009).

As part of our laboratory activities our students got an opportunity to visit a local industry that manufactures as well as rebuilds multi disk rotors. These units mounted with impact hammers at the rotors' periphery are used to produce corn flour of required grain size for making cattle feed. The multi disk rotor unit without the hammers was mounted on the two end bearings of the dynamic balancing machine. The balancing machine had sensors mounted at the bearings and gave the radial and angular positions of the unbalance and the balancing mass to be added in milligrams. This visit complimented our classroom discussion of rotating unbalance, the effect of the centrifugal force due to the unbalanced mass and the rocking moment that can damage the bearings.

Course Objectives and Learning Outcomes Related to the Resonator Project

In the fall of 2006 we prepared the objectives and learning outcomes for all MET courses as part of our preparation for the ABET accreditation. We included the following objectives in the ET 4830 – Vibration syllabus.

a. Oscillatory Motion: Students learn the basics of oscillatory motion such as simple harmonic motion and periodic motion, and vibration terminology.
b. Free Vibration: Students study the basics of free vibration. They calculate natural frequencies of spring-mass systems using the equations of motion, energy method, and principle of virtual work. They study the free vibration of viscously damped spring-mass-damper systems and learn to calculate the natural frequency using the equations of motion and the logarithmic decrement method.
c. Harmonically Excited Vibration: Students learn to formulate the equation of motion for a spring-mass-damper system subjected to forced harmonic vibration. They calculate amplitude and phase of oscillation and obtain complex frequency response. They learn the basics of rotating unbalance, support motion and vibration isolation. They study the working principles of vibration-measuring instruments such as seismometers and accelerometers.
d. Systems with Two or More Degrees of Freedom: Students study vibration of multi-degree-of-freedom systems with emphasis on the normal mode analysis, initial conditions and coordinate coupling. They learn to formulate the coupled equations of motion and represent in the matrix form for translational and rotational systems, and coupled pendulums. They learn to calculate eigenvalues and eigenvectors for different spring-mass systems. They learn the basics of forced harmonic vibration of multi-degree of freedom systems.
e. Vibration Measurements: Students learn about instrumentation and control related to mechanical vibration

We developed twelve learning outcomes for our MET concentration based on the ABET a-k criteria. As has been done at several U.S. universities, we use the tests, final exam, homework and laboratory activities as direct methods to evaluate the learning outcomes. The major field test (MFT), exit interview (oral and anonymous questionnaire) and employer and/or employee survey are used as the indirect methods to evaluate the learning outcomes. In the Vibration class the author gives two tests and one final exam, and each of these carry one-fourth of the final grade. The Helmholtz resonator project carries one-fourth of the final grade. The ET 4830 is a three credit-hour course with two credit-hours of lecture and one-credit hour (three contact hours) of lab. Students are required to design, fabricate and test resonators made of at least three different materials. This part carries seventy percent of the project grade. They are required to submit a professional quality project report that should include introduction, design, fabrication, testing, discussion of results and conclusion, and bibliography. The report carries thirty percent of the project grade. Typically the first three weeks are spent in discussion of the project among the student team members and with the instructors. This is also a period for questions and answers, and clarifications regarding different aspects of the project. Student teams spend about eight of nine weeks designing, fabricating, testing and modifying their resonators. In the following one or two weeks they learn the SpectraPlus frequency analysis software and test the resonators in front of the other teams and the instructor. They spend one or two weeks in preparing the final report.

The Helmholz resonator project addresses the course objectives *a*, *b* and *e* listed above. We use this, in addition to the tests and the final exam, to evaluate the following learning outcomes,

- The ability to conduct, analyze and interpret experiments and apply experimental results to improve process.
- The ability to function effectively on teams and communicate effectively.
- The ability to utilize their knowledge of engineering materials, statics, dynamics, and strength of materials and solve problems related to mechanical systems that are stationary as well as in motion.

In our anonymous exit interview questionnaire for the graduating seniors some students have complemented the Helmholtz resonator project as a very useful hands-on activity. We started teaching Vibration in the fall of 2006 but the MET major field test (MFT) was developed in early 2005. Therefore, we could not add questions from Vibration later as we could annually modify/replace only five percent of the MFT questions mainly based on the students' feedback. Currently we are developing a brand new MFT for 2011-12 academic year that includes questions from Vibration. We hope some of these questions will help us assess student learning outcomes related to the resonator project.

Conclusions

Under the current budget situation we find that the Helmholtz resonator project is a suitable substitution for a Vibration laboratory activity. This team project provides students with an opportunity to design fabricate and test the resonators. However, this project and one industrial visit cannot make up for a semester-long laboratory activities. We are in the process of developing a dynamic vibration absorber and plan to make it a required laboratory activity in the fall of 2010.

In the fall of 2009 our students learned to use a new software and obtained the frequency response from the time-domain data. They were creative and voluntarily fabricated resonators using new materials such as Delrin and Elkonite. One team has made a helpful recommendation that we increase the interference depth from 1 mm (Figure 2) to 4 mm for the ease of press-fitting the resonator base and body. We are gratified to learn that some of our graduating seniors have complemented the Helmholtz resonator project as a very useful hands-on activity. This project provides scope for further research regarding the resonator materials and fabrication techniques. In fall of 2010 the students will get an opportunity to work with a local metallurgical company. Our students highly appreciate the interactive demonstration of the dynamic balancing of rotors. Currently we have two tests, a final exam, the resonator project and the industrial visit for credit in Vibration. Each of these with the exception of the industrial visit carry the same number of points and we found out that the resonator project makes at least a letter grade difference in the final standing of most students. So far all of our students have done well in the resonator project and improved their grades. We started teaching Vibration in the fall of 2006 but the MET major field test (MFT) was developed in early 2005. Therefore, we could not include questions from Vibration later as we could annually modify/replace only five percent of the MFT questions mainly based on the students' feedback. Currently we are developing a brand new MFT that includes questions from Vibration. We hope some of these questions will help us assess student learning outcomes related to the resonator project.

Acknowledgement

The SpectraPlus software was purchased from an internal grant and the author would like to thank the Instructional Evaluation and Development Committee at Middle Tennessee State University.

Bibliography:

1. B. S. Sridhara, "Some Interesting Engineering Problems with Objects of Simple Geometry and Relatively Complex Mathematical Formulation," Proceedings of the 2008 ASEE Annual Conference and Exposition, Pittsburg (PA), June, 2008.
2. Van Santen, G.W., "Introduction to a Study of Mechanical Vibration," Philips Technical Library, 1958.
3. The SpectraPlus software website: http://www.spectraplus.com/index.html.
4. Jensen, et al., "Engineering Drawing and Design," Glenco McGraw Hill, 2001.
5. Baumeister, et al., "Marks' Standard Handbook for Mechanical Engineers." Eighth Edition, McGraw Hill Book Company, 2006.