A Mechanical Engineering Laboratory Experiment to Investigate the Frequency Analysis of Bells and Chimes with Assessment

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Abstract

The prevalence of bells and chimes throughout college campuses makes them an ideal learning platform for engineering and science students. The operational characteristics of these vibrating metallic objects may be studied by analyzing their frequency content using portable laptop computer built-in microphones and accompanying software packages. This mobile laboratory provides an opportunity for undergraduate mechanical engineering students to gain experience with recording sounds and analyzing the acoustics based on field data. The Fast Fourier Transform (FFT) method is able to calculate the natural frequency of a bell from the system’s vibrations. A bell’s physical structure may be modeled with a Computer Aided Design software package, and then used to apply Finite Element Analysis tools to calculate the natural frequency. This computer-based approach offers a convenient and effective way to test the acoustic characteristics of bells and other components. On the Clemson University campus, two historic bells were tested and resulted in favorable comparisons between the FFT and computer simulation results. Through student assessment, the majority of laboratory participants reported moderate to great gains in the collection of test data and analysis, modeling of system behavior, and confidence that they understand the material. This frequency analysis experiment provides students with an opportunity to study acoustics plus undertake an experiment outside the laboratory facility which accommodates growing enrollment demands.

1. Introduction

Metal bells have been used for centuries around the world with applications ranging from alarming citizens of imminent danger to signaling the beginning of a special ceremony. The first bells originated in China in 1600 BC and were used for music and time. In the middle ages, bells became a staple in European churches. In large cities, church bells played a significant role in people’s life as they served multiple purposes. For instance, they signaled the time for prayers, warned of tempests and enemies, and were utilized during rituals, funerals, and other community events. With the continuing advancements in communication channels and technology, the church bells gradually became more audio decoration than town-wide communication devices. Regardless of their role in society, bells hold a special place in humans’ conciseness due to the generally pleasing sounds and reminder of days gone by in civilization.

Vibration refers to oscillations in a mechanical system which may be influenced by the inertia and elasticity. Vibrations can be divided into free and forced. The first type happens when the mechanical system is excited by an initial input, and the second one occurs due to an initial condition. For bells, the hammer inside of the shell creates the initial input force to begin the vibration of the medium. A vibration test explores the source that makes the sound, and can lead to structure improvements for enhanced performance. Two types of testing exist; sinusoidal (sine) and random vibration. The sine test is more often performed to explore the response of the structural device and/or building, as it is a simple test used to help understand natural vibrations. On the other hand, a random test is used when the object occurs in a real world environment. For
example, the bell rings in a church tower or garden. Generally, a specified acceleration is used to bring the excitement to one and more “input” or “control” points fixed on the side of the device which is under test.

In physics, resonance is the tendency of a system to oscillate at a greater amplitude at some frequencies than at others. This characteristic is known as the system’s resonant (or resonance) frequencies. At these frequencies, even small periodic driving forces can produce large amplitude oscillations, since the system stores vibrational energy. Resonance occurs when a system is able to store and easily transfer energy between two or more different storage modes (such as kinetic energy and potential energy in the case of a pendulum). However, there are some losses from cycle to cycle, called damping. When damping is small, the resonant frequency is approximately equal to the natural frequency of the system, which is a frequency of unforced vibrations. Some systems have multiple, distinct, resonant frequencies which would be typified as pushing a child on a swing or the operation of an inductor-capacitor (LC) circuit.

To evaluate the quality of cast bells, a partial frequency test may be completed that could supplement visual inspection by manufacturers. Samolov applied an analysis of subjective tests with the synthesis sounds of two different sized bells to report the noticeable difference of partial frequency. Similarly, Oancea et al. displayed the spectrogram of the recorded bells, identifying the partial frequency and correlations between the frequency and amplitude. On the other hand, Legge and Petrolito, by choosing a suitable balance between constraints and desirable properties, applied a percussive bar to a church bell to simulate the numerical techniques used in creating the design of musical structures. Recently, Meneghetti and Rossi simulated the dynamic behavior of church bells using a theoretical model to assess design and installation criteria.

The invention of the wind chime is credited to the Chinese circa 1100 B.C. with a purpose and function similar to bells. Wind chimes were originally considered religious in nature, as Buddhists would hang them on temples, islands, and rice paddies to charm the spirits. Over the course of time, they were introduced to the world and constructed out of wood, bamboo, and eventually metal. Now, wind chimes are used as a high technology art form, capable of being cut and tuned to produce musical sounds, melodies, and scales. Similar to bells, wind chimes possess a striking hammer that hits the chime rod, resulting in a musical sound that is dependent on the diameter, length, and condition of the rod. In particular, Baxter and Hagenbuch reported that the frequency is proportional to the inverse square of the length of the rod. Not only are the specifications of the rods important, but also the placement of the rods on the wind chime. Moor denoted that the first node of the standing wave is located 22.4% from the end of a tube. This is the reason that most wind chimes are hung from a wire which is approximately 25% down the length of the tube, while varying tube length will provide the different frequencies to produce the melodic tune.

The paper’s objective is to document and share a self-conducted field and home experiment to initiate a dialog within the academic laboratory community. An interesting aspect of the assignment is the completion outside the laboratory building. The remainder of the paper is organized as follows. Section 2 offers background on the FFT method as well as CAD/FEA simulations. Section 3 introduces some student learning objectives. Section 4 describes two experiments which explore the frequencies of guardian bells in Clemson’s Botanical Gardens.
and Carillon Garden (refer to Figure 1). This makes use of the FFT method in MATLAB, and then an analysis of the bells is applied by an Abaqus simulation. Section 5 considers a case study of these two bells. Lastly, a summary is presented in Section 6, and the Appendix contains the audio code.

![Guardroom Bell and Tillman Hall Tower Clock Bell](image)

Figure 1: (a) Guardroom Bell located in the South Carolina Botanical Garden, and the (b) Tillman Hall Tower Clock Bell located in the Carillon Garden at Clemson University

2. Primer on Frequency Analysis and Computer Graphics

In this proposed laboratory experiment, several software packages are used to analyze field data, model a structure, and evaluate frequencies per finite elements. MATLAB assists in the frequency analysis of an audio input. Two Computer Aided Design (CAD) packages, Solidworks and Abaqus, are applied to model the bell and determine operating characteristics. First, the Fast Fourier Transform (FFT) function in MATLAB allows an audio input to be read as an array and then the frequencies of the sound are calculated. The audio sound sources to be considered are the Guardroom bell in the South Carolina Botanical Garden and the tower clock bell in the Clemson University Carillon Garden. A swinging clapper strikes these bells, causing them to vibrate at their designed frequencies. Second, the vibration analysis is simulated using computer-based finite element analysis (FEA). A model of each bell is created in Solidworks and Abaqus to explore the structure behavior when subject to an impact event. The bell frequency based on field data FFT and simulation models are used in a comparison with discussion.

2.1 Fast Fourier Transforms

A Fast Fourier Transform (FFT) is often used to calculate the natural frequency of a signal that features a significant amount of noise. It is an efficient algorithm to compute the Discrete Fourier Transform (DFT) and its inverse. The primary difference between the FFT and the DFT is that the FFT tools require the number of points to be equal to or less than the power of 2 (e.g., 256, 512, etc.). FFT became popular after Cooley and Tukey\(^{12}\) reinvented the algorithm. Later
Heideman et al.\textsuperscript{13} discovered that Cooley and Turkey obtained the algorithm without knowledge of the algorithm by Friedrich\textsuperscript{14}. The DFT may be defined\textsuperscript{15} as

\[
X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-i2\pi\frac{k}{N}}
\]

where $X_k$ is the amplitude and phase with N points in sum of the sine components of the input function $x_n$ with n points and k ranges from 0 to N-1.

To operate a FFT, the input signal must be converted into an array and may correspond to any waveform (e.g., a sine wave with noise). It does not need to be an audio signal but that will be the focus of this paper. To use MATLAB’s FFT toolset to calculate the frequencies of the audio files, a few programs must be created. The first program uses a microphone to record an audio input, and then converts the audio file into an array which can be analyzed. Second, the FFT will be calculated based on the audio array, and the resulting frequencies will be stored to a new array. Third, the program will be used to produce plots of the audio samples as well as the frequencies obtained. The second program differs from the first one, instead of recording an audio input it will read a previously created audio file of the target bell. This is not necessary for the completion of the experiment, but it could be useful in preventing errors in obtaining data. The plots that will be produced will look similar to Figures 2 and 3.

![Figure 2: Audio recording of a single tube from a wind chime (tube length = 50.6 cm)](image)

The audio file for a single tube on a six tube wind chime being struck, and these tubes range from lengths of 37 cm to 54 cm has been displayed in Figure 2. This data comes from a single tube being struck individually to avoid complexity of many different values of noise level. The tube in question has a length of 50.6 cm, an outside diameter of 2.54 cm, and an inside diameter
of 2.29 cm. Each tube will have a different frequency which is proportional to the tube’s individual length. When the FFT is plotted the natural frequency becomes apparent as shown in Figure 3. Finding the natural frequency corresponds to finding the peak, and for this audio file there is a peak at approximately 590 Hz. The frequency corresponds to the D5 note on a piano which is approximately 587 Hz. This data point compares favorably with a calculated frequency of 599 Hz, and shows that there is only a percent error of 1.5% between the calculated value and the experimental data. The wind chime is presented as an alternate example of a possible application but was not explored in the lab exercise.

![Figure 3: Frequency analysis of the audio recording from the wind chime tube (refer to data in Figure 2)](image)

2.2 Finite Element Analysis

Finite Element Analysis (FEA) is a numerical method which solves sets of ODE or PDE with structure mechanics applications. The computer model is divided into discrete elements which can describe deformation using conservation principles. For this experiment, the Guardroom Bell and the Tillman Hall Bell will be tested by applying a vibration test to determine each bell’s natural frequency. Abaqus is a software package that can analyze part, or assembly, files per operating conditions. Once a file is created, collisions, gravity, and many others forces can be taken into account to determine how the part reacts. The collision of the striker with the bell causes vibration at a frequency that shall correspond to the recorded data. A simulation of the resonance process is applied and a range of frequencies are calculated. The highest level of frequency with the maximum displacement is selected for testing. This provides a value to compare with the experimental data, and the student will learn how to validate their numerical and experimental data to quantify errors.

Computer Aided Design (CAD) is an important toolset used in many fields, including manufacturing, automotive, as well as civil engineering. There are many kinds of three-dimensional mechanical CAD software available for modeling and design. Many industries
which create their own parts and assemblies will use CAD to design and test the parts before implementing them in their machines. Solidworks is one particular software package that takes advantage of an approach based on features such as parameters to create models and assemblies. Those parameters can be either numeric or geometric constraints, such as tangent, parallel, concentric, horizontal, etc. Thus, the original dimensions of the bells for this experiment are needed to create the models. Figure 4 shows the SolidWorks software interface with a common bell model.

![Solidworks software package interface with common bell example](image)

**Figure 4: Solidworks software package interface with common bell example**

A number of differences exists between the Solidworks and Abaqus software packages that students should recognize in their laboratory studies. One of these differences is that Abaqus puts greater emphasis on Finite Element Analysis (FEA) than does Solidworks. Due to the available multiphysics capabilities and a graphical user interface (GUI), Abaqus is popular with research institutions and the academic community. Based on the open-source scripting language Python, it consists of two solvers which are Abaqus/Standard and Abaqus/Explicit. Abaqus/Standard is more of a general purpose FEA tool, as it uses the traditional implicit integration scheme. For more complex systems, the option of Abaqus/Explicit is available, and this uses explicit integration which can solve much higher nonlinear systems. A photo of the Abaqus interface can be viewed in Figure 5 with the imported common bell model.
3. Student Learning Objectives

The collection of acoustic field data and subsequent PC-based analysis offers an experiment that reinforces many important undergraduate concepts within the BSME program. The student learns how to use the vibration to test the mechanical quality of the device. A function of MATLAB is introduced that allows one to calculate the frequency modes from the recorded sound source. The student also gains knowledge of creating a CAD figure and analyzing the mechanical process by using finite element analysis. Finally, students compare experimental and simulation results. Further learning objectives are outlined in greater detail below.

1. Acoustics is an important topic in engineering, although not often covered, and this experiment provides an opportunity for students to analyze acoustic data for sound levels and frequencies.

2. The experiment provides an opportunity for participants to gain experience with many undergraduate ME concepts, such as graphics (SolidWorks), FEA (Abaqus), data collection (sound file), and MATLAB programming experience, via Fast Fourier Transforms.

3. The students learn how to validate the numerical data in comparison with the experimental data, so that they can assess the errors present in the experiment. The data will be collected via laptop with a built in microphone.

The experiment occurs outside the mechanical engineering laboratory which helps to provides a solution to the growing number of mechanical engineering students with respect to the limited laboratory space on campus. This experiment may be completed by students without direct supervision from faculty members.
4. Experimental Testing and Laboratory Procedure

The proposed experiment requires the student to do some preliminary work before starting, then going out on campus to collect data, and finally, using this data for analysis. Once the sound data is collected, quick measurements of the bell(s) should be made so that a model can be built in Solidworks. This model will be used in Abaqus to determine a numerical value for the resonant frequency, and the quantity subsequently used for comparisons with experimental data.

1. Program the MATLAB FFT analysis script.

2. Strike the two bells, and run the program to record the sound and analyze the audio input.

3. Use Solidworks to model the bells separately, export the part files to Abaqus.

4. Apply Abaqus to calculate the vibration in resonance step.

5. Compare the results from the FFT and simulation strategies in each group. Determine what errors are present in the experiment and how to eliminate them.

The process for the experiment requires the collection of sound data from the bell, the use of MATLAB to convert these sounds to frequencies, the applications of a CAD package to design a model and perform analysis on the bell, and finally, the analysis of the experimental and numerical data obtained. The bells used in this experiment are The Guardroom bell in the South Carolina Botanical Gardens, and the clock bell in the Clemson University Carillon Garden. The vibration of the bell is created by the students swinging the clapper, and the data is obtained by the recorder program in the MATLAB software. Next, the audio input is read directly as an array, and the frequencies will be calculated as well as producing plots similar to Figures 3, 7, and 9. The students need to find the natural frequency which is denoted by the max step (peak) in the frequency plot. Abaqus enables students to run a simulation which would test the bell and determine the predicted natural frequency of the structure. Finally, the student is then able to determine whether the simulation adequately represents the physical system and identify error sources. Figure 6 shows the MATLAB script of the recorder program which converts the audio signal to an array and produces an appropriate plot. The full code is listed in Appendix A.

L=5000;                                           % length of the sample
r=audiorecorder;                                   % records audio from microphone
disp('Lets go')                                    % display “Let’s go”
recordblocking(r,5);                               % sets recording for 5 seconds
disp('good,stop');                                 % display “good,stop”
play(r);                                           % plays back recorded audio
Voicetest=getaudiodata(r);                         % stores audio file as an array
dlmwrite('guardroom',Voicetest);                  % saves the input
figure (1); plot(Voicetest);                      % plot audio array
title('Audio file');                              % add title “Audio file”
xlabel('samples');                                % make the label of x axis “samples”
ylabel('Volume');                                 % make the label of y axis “Volume”
The experimental procedure for both bells is the same. First of all, strike the bell and record the sound. Then use MATLAB to record the data and perform FFT analysis. This will produce plots with the corresponding natural frequencies for each bell. The next step is modeling the bell with some CAD software package (i.e., SolidWorks, and exporting the model to Abaqus). In Abaqus, the user will create the simulation, use the solver, and record the results. These results can then be compared with the experimental data obtained when performing the FFT analysis with MATLAB. This experiment is repeated for the other bell on campus.

5.1 Botanical Garden Bell

After collecting the data in the Botanical Garden and running the program, the graph of the FFT analysis plotted by MATLAB can be viewed in Figure 7, which offers some important information. It is apparent that the max step happens at 360Hz (approximately an F$\#4$ note), which corresponds to the experimental value for the natural frequency of the guardian bell. This value can be compared with the numerical solution found during analysis of the CAD model.

$$m\ddot{x} + kx = F(t)$$

where \(F(t)\) is the input force (N), (i.e., the swinging of the bell’s hammer), \(m\) is the mass (kg) of the device, and \(k\) (N/m) is the stiffness of the material. The variable \(x\) denotes the displacement. The natural frequency, \(f_n\) in Hz, may be defined as
In Abaqus, a range of frequencies were selected as bounds which started at 300 Hz and ended at 500 Hz. The result equates to 371.21 Hz, so the natural frequency happens at 371.21 Hz. In comparison, the FFT value of 360 Hz reflects 3% difference. Likely this difference is due to model simplifications for the bell which does not fully reflect complete geometry, noise in data collection, etc.

\[ f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \]  

(3)

Figure 8: Solidworks model of the Guardroom Bell in the Botanical Garden

5.2 Carillon Garden Bell

This second aspect of the case study considers the Carillon Garden Bell (refer to Figure 9) and makes use of the data from the recorder program and analysis of the FFT plot. According to Figure 9, the natural frequency appears to be 710 Hz (approximately an F5 note). Although there is another high value which occurs at approximately 1,050 Hz, it is not the natural frequency but a higher order mode. Other noise mixes with the dominant frequency to form the small step ranged from 950 Hz to 975 Hz. The model of the Carillon Garden bell (refer to Figure 10) is imported into Abaqus once it is finished being modeled in Solidworks. After applying it to the simulation, Abaqus calculated the natural frequency. Once again to avoid an unlimited solution, the chosen bounds for the differential equation were 700 Hz to 1,100 Hz, which were obtained from the FFT data in Figure 9. The natural frequency value obtained numerically is 876.63 Hz. This results in a 23% difference between the FFT and FEA calculations. This error can be attributed to several different things, such as modeling error, the data collection method, or other disturbances such as wind.
For instance, if any part of the bell has broken (e.g., crack), then it would make a different sound. Ultimately this could be the reason for the discrepancy between the numerical and experimental data. The Guardroom Bell should be inspected to recognize some damage and make a repair.

6. Student Assessment of Laboratory

The laboratory experiment was implemented at Clemson University in the senior/graduate level technical elective course ME 4170/6170 – Mechatronic System Design. After the class session was completed, each student filled out an anonymous survey to evaluate the learning materials and interest in the subject matter. The assessment tool was created, and IRB approved,
based on the Student Assessment of Learning Gains (www.salgsite.org) established framework. This questionnaire asked students about their knowledge gains in certain areas including understanding of class content through the laboratory module, course impact on their attitudes, and integrating their learning. The students were also asked to identify the best thing about the laboratory, how to improve it, and reasons for which they would recommend/not-recommend this module to a friend. Of the 32 students, 94% stated they had developed a moderate to great gain in collection of test data and analysis plus modeling of system behavior. In addition, 88% of the participants indicated a moderate to great gain in their confidence of material understanding. The students’ written responses reported that they enjoyed the opportunity to go outside while using their personal laptops to collect field data, perform signal processing in MATLAB, and use FEA tools to determine the theoretical value for each bell’s natural frequency. Finally, 88% of students stated that they would recommend the lab to others, and their reasons included the introduction to frequency analysis which is something that many had never viewed before, new MATLAB application, and applying the classroom concepts to relevant situations.

7. **Summary**

The development of undergraduate laboratory experiments using elements available on the college campus should be intriguing to students. This paper discusses a method for mechanical engineering seniors to explore the frequency of two bells at Clemson University while expanding their knowledge of vibrations and computer analysis. To assist in the assignment, some relative background about Fast Fourier Transforms and Finite Element Analysis is introduced. For experimental activities, the laboratory objectives, procedure, and materials are presented. A case study, based on gathered data and subsequent analysis, shows the experimental results and furthermore discussion about the difference between the results and its possible cause. This discussion also reveals a practical application and utility of the method as well. In completion, this paper shows the usefulness for not only the students but the faculty and department as well. The lab is completely hands off for the faculty unless questions arrive, and the location is outside of the building which allows another lab to be performed in the limited space available.

**References**


Acknowledgements

The authors wish to thank the former students at Clemson University who completed ME 4170/6170 and ME 4930/6930 for their contributions to this experiment and report.
Appendix A: Full Recording Program Coded in MATLAB

%Audiorecorder
clc            %clears command window
clear all      %clears all variables stored in workspace
L=5000;          %length of sample

%Record audio from microphone
r = audiorecorder;         %Sets recorded file as r
disp('Start Talking')      %displays message to screen
recordblocking(r,5);       %Sets recording for 5 seconds
disp('Stop Talking')       %displays message to screen
play(r)                    %plays back r
Voicetest = getaudiodata(r);         %Stores audio file as an array

figure(1);                 %creates a figure window
plot(Voicetest);           %plots Voicetest vs. samples
title('Audio File');       %creates title of plot
xlabel('Samples');         %creates x axis label
ylabel('Amplitude');    %creates y axis label

%Converting to dB
samples = linspace(0,40000,40000); %creates array with 40,000 entries;
pref = (2*10^(-5));      %reference pressure used in calculations
dBArray = zeros(40000,1);  %creates an array of zeroes
for i = 1:40000           %loops through 40,000 times
    if (Voicetest(i,1) == 0)   %if pressure change is 0
        dBArray(i,1) = 0;    %then the dBA is 0
    elseif (Voicetest(i,1) < 0)  % else if the pressure is negative
        dBArray(i,1) = abs(dBArray(i,1));   %then the dBA is positive
    else                        %else
        dBArray(i,1) = 20*(log10(Voicetest(i,1)/pref)); %convert to dBA
    end                      %ends the if statements
end                         %ends the for loop

figure(2)                  %creates another figure window
scatter(samples,dBArray,'filled');  %creates a plot of dBA vs samples

%FFT of the audio array
NFFT = 2^nextpow2(L);    %new input length determined from original signal
Y =fft(Voicetest,NFFT)/L; %converts the signal to the frequency domain
f=8000/2*linspace(0,1,NFFT/2+1);   %defines the frequency domain

%Ploting the Frequency
Yabs = abs(Y(1:NFFT/2+1)'); %takes abs. value of Y array from 1 to 4097

figure(3);                %creates a figure window
plot(f,2*Yabs);            %plots 2*Yabs vs. the frequency
title('Frequency of Audio File') %creates plot title
xlabel('Frequency (Hz)')  %creates plot x axis label
ylabel('Amplitude')    %creates plot y axis label