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Musical Analogies as a Teaching Tool for Engineering Concepts

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Abstract

This project investigated the inclusion of a music laboratory experience within the existing core Mechanical Engineering curriculum at Lafayette College. Music is a natural addition to engineering curricula as it can easily be used to illustrate many different engineering concepts. This allows students to think about their engineering topics from a different perspective, which helps to improve their understanding of these concepts. Additionally, by using music as a teaching tool, students are also exposed to topics from the art of music. Students completed a survey both before and after the experience in order to reflect on their learning. On average, the students reported a 30.5% and 39.9% increase in their understanding of engineering and musical concepts, respectively.

Introduction

This paper details the introduction of a new laboratory experience in a junior level Mechanical Engineering laboratory course (Instrumentation and Data Acquisition). This laboratory experience is intended to develop the students' comprehension of continuous and discrete signals, time and frequency domain analysis, and filtering and transforms. Students tend to struggle with these difficult concepts as they tend to be abstract and highly mathematical in lecture[1,2]. In addition, students find it challenging to incorporate their natural knowledge of signal analysis with data acquisition concepts presented in class (*e.g.* clipping, sample rate, phase). Incorporating music into instrumentation not only helps to expand students' understanding of music through various engineering concepts such as amplitude (loudness) and frequency (pitch), but also deepens their comprehension of signals and systems in terms of musical concepts that they already intuitively know[3,4]. Thus, students can not only improve their appreciation and understanding of music, but also develop a firmer grasp of difficult concepts that have been presented in class[5].

Music has shown a clear benefit in the education of students[6,7]. The connection between music and STEM is well-established[8], particularly within the field of mathematics[9,10]. There are also many different connections between music and engineering. For example, pattern recognition techniques can be applied to musical signals in order to classify a musical artist[11]. In fact, this form of engineering technology has been implemented into phone applications, e.g. SoundHound, to in order to identify popular music. Since music can be analyzed as a time domain signal, it provides a natural medium for exploring time domain signal analysis[12]. Other research has used music as inspiration for improving engineering control systems[13]. One of the most appealing aspects of integrating music and engineering education is the direct analogies between concepts, examples of which are offered in Table 1. These analogies can serve to either apply knowledge of music to better understand engineering, or vice versa. Often, students have some concrete ideas about a musical concept that they had not previously associated with an engineering concept. These types of connections fascinate the students, speed their grasp of difficult signal analysis ideas, and deepen their understanding and appreciation of music.

Table 1. Examples of Music and Engineering Analogies

Musical Concept		Engineering Concept
Loudness	⟺	Amplitude
Pitch	⟺	Frequency
Range	⟺	Bandwidth
Overtones	⟺	Fourier Series

Implementation

This new laboratory experience is centered on the idea of using music to illustrate and reinforce engineering concepts relevant to data acquisition and instrumentation. This is the second laboratory experience that the students see during the semester. The first lab experience is a very typical three-week introduction to oscilloscopes, LABVIEW™, MATLAB™, circuit construction, power supplies, function generators, etc. This introductory lab introduces dynamic systems concepts through the use of first- and second-order systems (RC and RLC circuits). Students see the response of these systems to step and sinusoidal inputs. They experimentally see the amplitude and phase lag which appears in the output and are challenged to consider that these systems act as filters. The students then begin to appreciate that the theoretical dynamic systems concepts learned in class have practical application. The completion of this section is then the initial point for the discussion of discrete time signals and their methods of acquisition and analysis. Here the students typically lose their physical intuition at the introduction of the Fast Fourier Transform (FFT), concepts of signal digitization, and the effect of finite sampling rates on signal reconstruction. Thus, a laboratory experience was necessitated which tied these more abstract ideas to concepts for which the students had a natural feel.

The newly created laboratory experience extends over three laboratory periods (each three hours long). Students are required to complete a set of four exercises designed to illustrate specific engineering concepts in the context of music and sound using various instruments, microphones, LABVIEW™ and MATLAB™. These exercises are briefly summarized as follows:

1. Investigate the use of different sampling frequencies and record lengths in order to see and hear the effect of aliasing on a signal using Discrete Fourier Transforms (DFTs)
2. Explore the concepts of volume, amplitude, clipping, and microphone placement and their effect on how an audio signal is recorded, sounds, and appears visually
3. Identify the fundamental frequencies produced by a musical instrument and relate them to musical notes using DFTs.
4. Produce a beat note (both seen and heard in MATLAB™) and use this idea to tune a ukulele "by ear"

For the first exercise, students use LABVIEW™ and a microphone to record musical tones generated from striking a single bar on a xylophone. The sounds are recorded at different sampling rates to help illustrate the concept of frequency aliasing. Using the recorded data, students use MATLAB™ to calculate FFTs of the signals and identify the fundamental frequency content of the signal. Students also listen to their recorded data and compare how it sounds to the sound of the "live" performance. At lower sampling rates, this exercise illustrates aliasing as the higher order frequency content is filtered by the limited data acquisition rates.

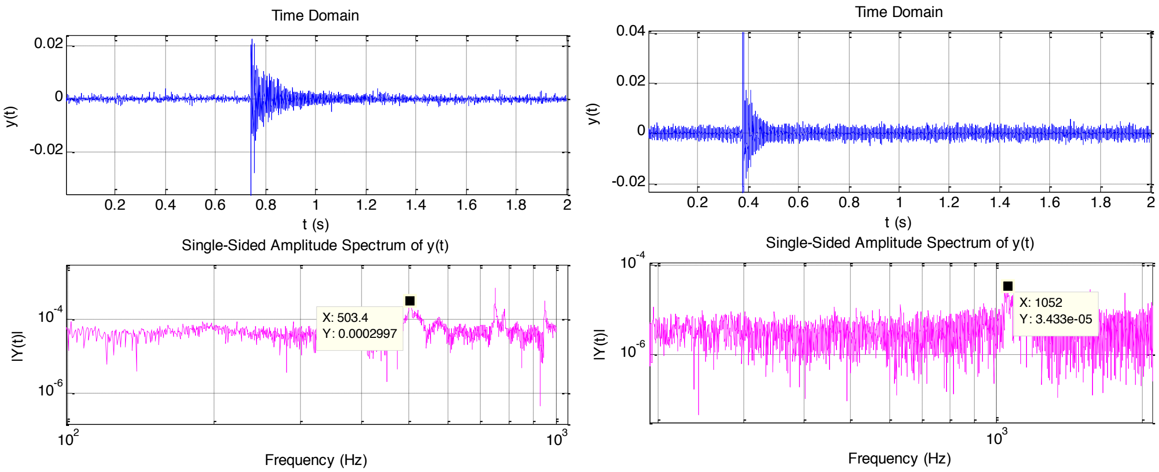

Figure 1. Example xylophone note C6 (1046.50 Hz) recordings with (left) and without (right) aliasing.

Students can both see this phenomenon through comparing the FFTs of the signal at different sampling rates as well as hear the lack of higher order harmonics which give the xylophone its characteristic timbre. Example figures for this exercise are shown in Figure 1**Error! Reference source not found.** for recordings with (left) and without (right) aliasing.

In the second exercise, students explore the concepts of loudness and clipping. Students use a microphone preamp to interface with LABVIEW™. By adjusting the input gain of the microphone, students record the sound of a strumming ukulele in order to illustrate the effect of clipping. Students use MATLAB™ to visualize the effect of clipping, as shown in Figure 2 as well as to listen to the effect of clipping on how the recording sounds. Students also investigate the effect of varying the distance between the sound source and the microphone on the amplitude (loudness) of the signal to visualize the r^2-law dependence.

For the third exercise, students record the sound of each bar on a xylophone, and then use MATLAB™ to calculate FFTs to identify the musical note produced by each bar. An example of student work for this exercise for a single xylophone bar ("yellow" note G6, 1568 Hz) is shown in Figure 3. This exercise helps students relate the concepts of frequency and pitch, and also demonstrates to the students the possible differences between the intended note of an instrument and the frequency that it actually produces. This exercise is also used to communicate concepts of frequency precision associated with record length. The students vary the record length of their data acquisition while using the same tone from the xylophone to see the effect on the determined note. This exercise also is used to discuss concepts associated with scales and how the frequencies of notes in a scale are mathematically related.

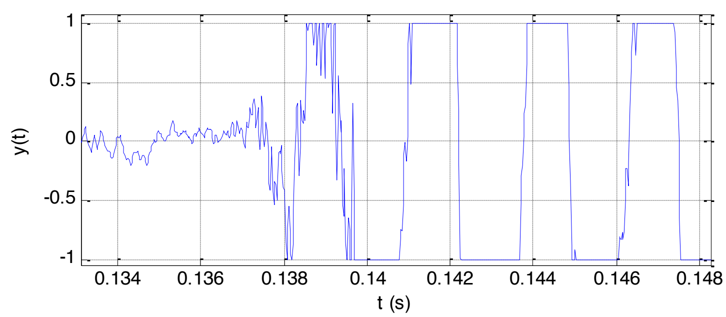

Figure 2. Segment of recording of ukulele strumming with very high input gain causing clipping.

The fourth exercise revolves around the concept of beat frequencies. Students first generate beat frequencies using MATLAB™ by adding together two different sinusoidal signals of similar frequencies. Four different cases are used to illustrate different beat frequencies each using a baseline signal of 440 Hz. Example figures of simulated beat frequencies are shown in Figure 4.

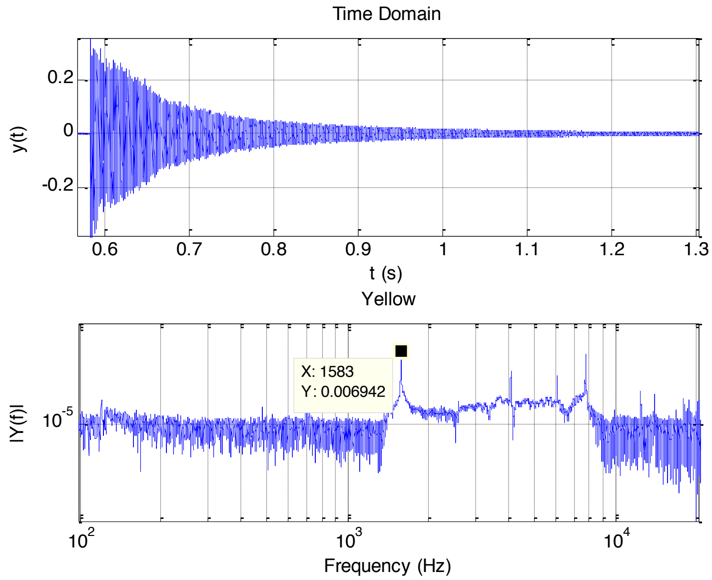

Figure 3. Time and frequency domain data for the "yellow" xylophone bar *(Note G6, 1568* Hz).

The second part of this exercise has students apply the concept of beat frequency to tune a ukulele "by ear." This form of tuning involves comparing the sound produced by each ukulele string with a tone produced in MATLAB at the desired frequency. As students get close to the correct frequency, they should be able to hear the beat produced by the similar frequency sounds. The students then apply their knowledge of beat frequency from the first part of this exercise to "make the beat go away." After completing the tuning of the instrument, students assess their tuning by recording and identifying the frequencies of each string using the methods they learned in the third exercise.

In addition to these four exercises, this experience culminates in student generated projects and presentations to explain a musical concept using engineering tools. This requires students to develop and perform experiments which illustrate a musical phenomenon. Then they analyze their results and give a technical presentation to articulate their understanding of both musical and engineering elements to their peers. Suggestions were made in the laboratory handout as to some particular phenomena their projects could explore: intonation; indefinite vs. definite pitch; timbre; overtones and harmonics. Some pictures of students working on the laboratory experiments are shown in Figure 5, and example slides from student presentations are shown in Figure 6. Students were energized by the open nature of the project and were eager to bring their own musical capabilities into the lab (as evidenced by many students bringing in their own instruments to examine their particular timbre). Students also looked

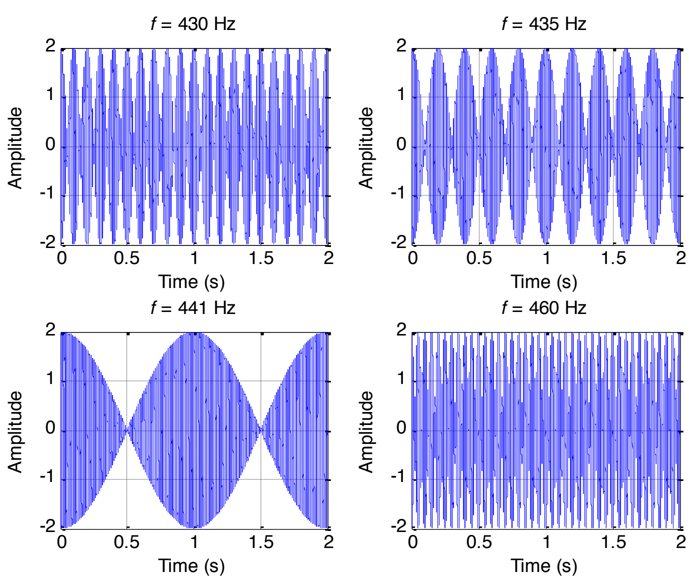

Figure 4. Simulated beat frequencies from varying frequencies added to 440 Hz sound signal.

to explore the engineering side of music creation, examining the directional response of microphones, creating synthesized instruments, or exploring auto-tune and other dynamic filtering strategies.

Figure 5. Pictures of students working on laboratory experiments.

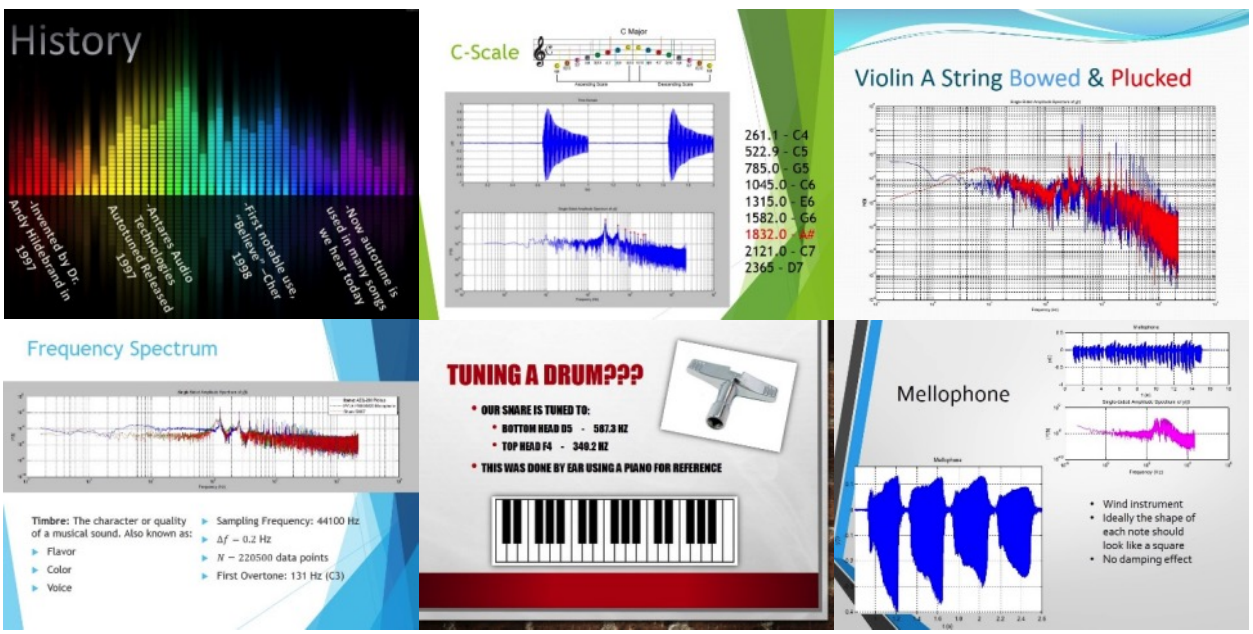

Figure 6. Example presentation slides from student projects on engineering and music.

Results

In order to assess the learning outcomes of this project, a pre-laboratory survey was given to determine the students' initial experience and confidence in both engineering and music concepts. A post-laboratory survey was then used to determine the growth in student understanding stemming from this new lab experience. These surveys used traditional Likert item ratings for students' overall reflections on the project, and a similar scaling system for rating their understanding of individual concepts, as outlined in Table 2.

Table 2. Rating System for Pre- and Post-Laboratory Surveys

Numerical Rating	Likert Scale	Concept Scaling
1	Strongly Disagree	I have never heard of that
2	Disagree	I may have heard of that
3	Neutral	I think I know what that is
4	Agree	I know what that is
5	Strongly Agree	I understand what that is very well

The student responses for three central statements are summarized in Figure 7:

1. I use my engineering knowledge to better understand music
2. I use my musical knowledge to better understand engineering
3. I feel confident in my understanding of music concepts

Figure 7 shows a clear improvement in how students think about both music and engineering. Another interesting observation from Figure 7 is that the students at a baseline had a relatively high reported understanding of musical concepts. This is likely due to the liberal arts environment at Lafayette College, which is an appealing characteristic for musically inclined students who are interested in engineering.

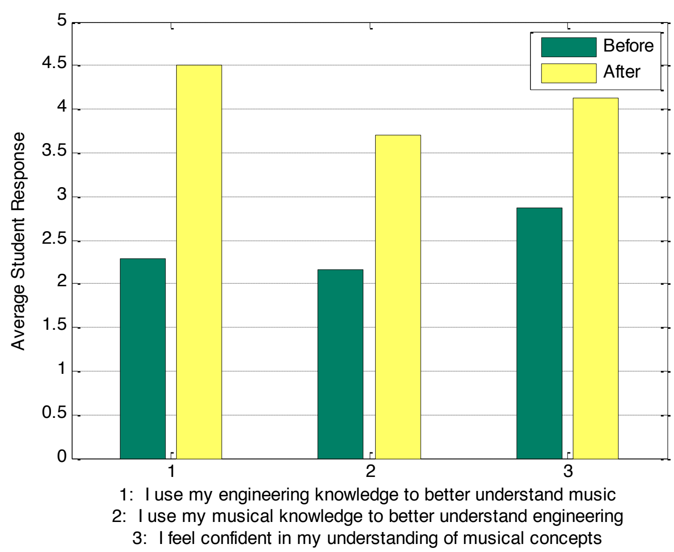

Figure 7. Pre- and post-laboratory survey results for central questions.

Students also rated their understanding of individual concepts for both engineering and music, as shown in Figure 8. On average, the perceived student understanding of engineering concepts increased from 3.54 to 4.62 (30.5%), while music concepts increased from 3.28 to 4.59 (39.9%).

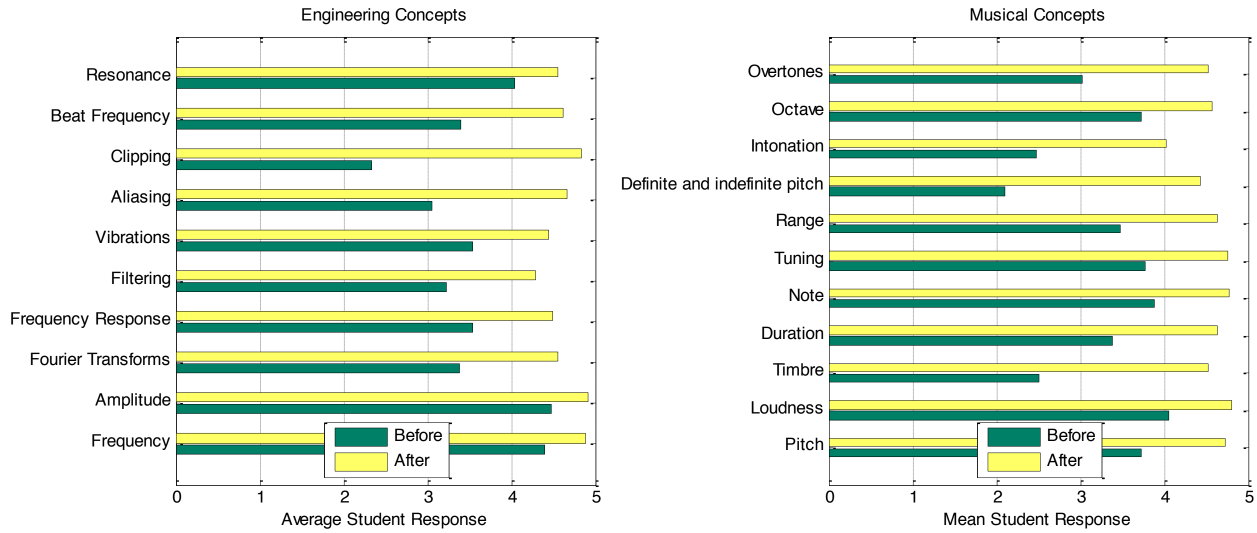

Figure 8. Survey results for engineering (left) and musical (right) concepts.

Due to the significant number of students with musical background either from formal music education or personal experience as a musician, student responses were also analyzed based on their identified background. Students with responses of "Agree" or "Strongly Agree" for "I have some formal educational background in music" and "I have some experience as a musician" were separated from the remaining students noted as "neither." The student responses for these subcategories of students were averaged across all engineering and musical concepts and are displayed in Figure 9.

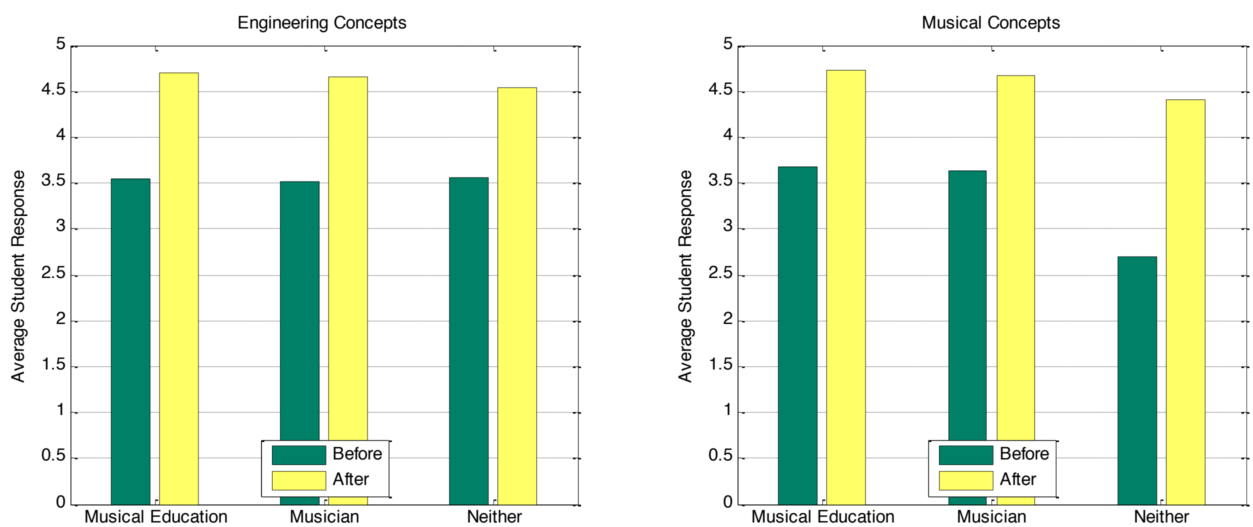

Figure 9. Results for different musical backgrounds for engineering (left) and musical (right) concepts.

It is interesting to note from Figure 9 that regardless of musical background students perceived a similar improvement in their understanding of engineering concepts. This indicates that it is not necessary to have formal musical experience to benefit from this type of project. Students without any formal musical background received a significant (63.5%) increase in their understanding of musical concepts. Students with musical background were also able to improve their understanding of music through the completion of this project. This demonstrates the benefit of applying engineering knowledge to musical concepts.

As a final assessment of the project, the following two statements were included in the post-laboratory survey in order to provide an overall reflection on the project:

1. I feel more confident in my understanding of engineering
2. I feel more confident in my understanding of music

The student responses to these questions are shown in Figure 10.

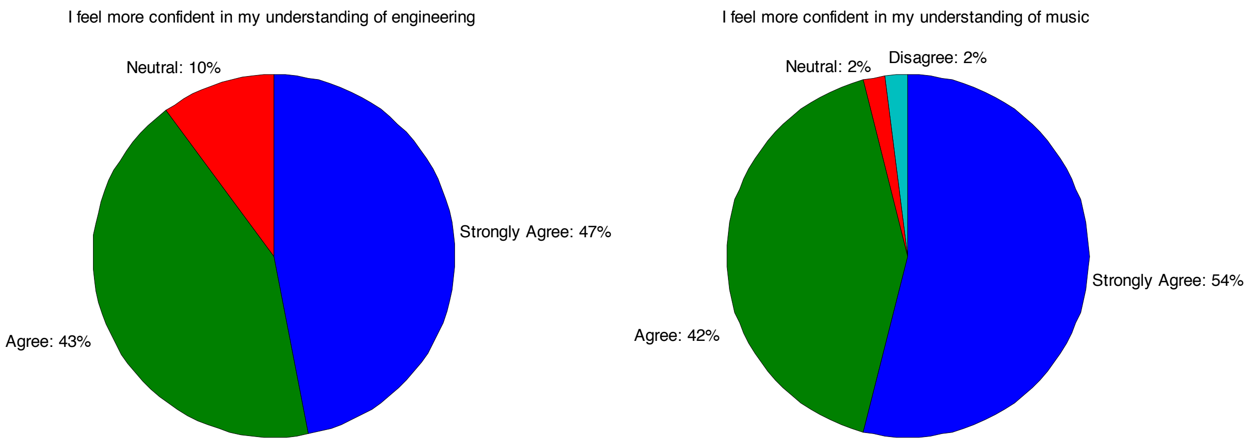

Figure 10. Overall student reflection for understanding of engineering (left) and music (right).

Capabilities attained from this laboratory experience also influence the students' analysis capabilities in the lecture portion of the course. An in-class quiz was administered before the completion of the music lab that focused on FFT fundamentals, aliasing, and time and amplitude accuracy associated with discrete time sampling of analog signals. The class average score for this quiz was 6.4/10. The same skills were then assessed on the final exam (one problem out of five, six weeks after completion of the music lab) where the students scored an 8.8/10. Not only had the students reported more engagement and confidence in their understanding of fundamental data acquisition concepts from the post lab survey, these skills had been shown to improve and be retained until the end of the course.

Conclusions

Overall this project has demonstrated success in introducing music concepts into an engineering course in order to improve student learning. The primary goal of this project was to improve student understanding of engineering. With 90% of students agreeing that they are more confident in their understanding of engineering, and the remaining 10% identifying as neutral, this project demonstrated reasonable success. The vast majority of students agreed that they are also more confident in their understanding of music, which is an excellent by-product of this type of integrated learning project. Data from pre- and post-laboratory surveys indicated that the students perceived a 30.5% and 39.9% increase in their understanding of individual engineering and musical concepts, respectively. In addition, student understanding and retention of the data acquisition concepts were shown to significantly improve.

Acknowledgments

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