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Designing Electric Guitars to Teach Mechatronics and Advanced Manufacturing Techniques

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Gavin Garner holds a bachelor's degree in Physics from Colby College and Master's and Ph.D. degrees in Mechanical and Aerospace Engineering from the University of Virginia. His primary area of expertise lies in the burgeoning field of Mechatronics (aka robotics). Over the past decade, he has built UVA's Mechatronics program from scratch, developing over 50 hours of unique laboratory experiments as well as dozens of open-ended design projects. Through this experience, he has gained valuable insight into how to engage engineering students and teach them difficult, interdisciplinary material both efficiently and effectively. He was named a "Graduate Teaching Fellow" by the American Society of Mechanical Engineers from 2007-2009. Since then, he has won numerous other teaching awards for his creativity and dedication to student learning. He is especially interested in updating traditional mechanical engineering courses to better integrate the modern tools and techniques used to solve today's design problems in industry.

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Background

The electric guitar has been a staple of modern music for the past fifty years. Most students (and faculty) tend to agree that electric guitars are quintessentially “cool”, and, for this reason, they provide a perfect medium through which to engage students and teach fundamental concepts of engineering design. Since 2008, students taking an Advanced Mechatronics course at University of Virginia have been designing and fabricating electric guitars from scratch as a project that helps them to explore 3D modeling using Computer Aided Design (CAD) software, Finite Element Analysis (FEA), Computer Aided Manufacturing (CAM) software, and CNC machining techniques. This project also provides students with the agency to be creative, which is evidenced by the vast array of different shapes and themes that they have incorporated into their designs over the years. Others within academia have also documented success in motivating engineering students by constructing either electric guitars or effects pedal circuits.[1][2][3]

Introduction

For this project, students must balance the aesthetics of their guitars with their optimal resonance properties (predicted using FEA), structural integrity, and manufacturability. Running modal analysis simulations in CAD software allows students to predict the fundamental resonance frequencies of their guitars. They are encouraged to then experiment with changing the shape and features on their guitar models to bring out as many commonly played notes as possible. The more a guitar’s body vibrates at these frequencies, the fuller the overall tone and timbre of the guitar will be. This exercise helps to reinforce a fundamental theme in engineering: math models help engineers to make things better by allowing them to predict how their designs will perform before they have taken the time and money to actually fabricate and test them in real life.

Furthermore, this project provides a fun and exciting way for mechanical engineering students to dive into the electrical engineering world of analog filter circuits while designing custom “effects pedal” circuits for their guitars. Effects pedals are used by electric guitarists to modify the sound of their instruments, and there are many different types of effects and styles with which students can experiment as they create their own unique sounds. Students model and analyze their custom analog effects circuits using National Instrument’s MultiSim software and then build them out of real hardware components on a breadboard to test the accuracy of their simulations. Analog filter circuits play a critical role in Mechatronics since most sensors output weak analog signals that need to be filtered and amplified. However, more often than not, in this electric guitar project, students tend to apply the principles of analog circuit design to amplify the noise in their system rather than try to attenuate it – such is the nature of popular modern music!

Figure 1: A few examples from some of the 60+ student-designed electric guitars that have been created over the past nine years

Project Objectives

Through this project:

1. Students learn how to use solid modeling software and a computer numerical control (CNC) milling machine to rapidly create parts from 3D computer models.
2. Students study ways that a structural design can be optimized using finite element analysis (FEA) software tools to perform modal analysis. They also better understand and

appreciate that real-world optimization often involves establishing a compromise between various design parameters. (In the case of an electric guitar, visual aesthetics vs. acoustical resonance vs. structural integrity vs. manufacturability.)

3. Students understand how an inductive guitar pickup system (magnetic transducer) can be created using iron nails, permanent magnets, and magnet wire.
4. Students explore analog circuitry (including amplifiers and filters) on their own and incorporate this knowledge into the design of a custom guitar effects pedal.
5. Students learn how to design, analyze, and optimize circuits using simulation software based on SPICE algorithms within National Instrument's MultiSim software.
6. Students learn how to use electric circuit design software and how to rapidly manufacture printed circuit boards (PCB) with surface mount components.

Methods and Tools Used

Students start by designing and drawing their electric guitars in computer CAD software (both Autodesk Inventor and SolidWorks have been successfully used for this project in the past). They then perform a modal FEA on their guitar shape based on the loading that they anticipate strummed strings will create. They are provided with a chart of the frequencies most commonly played on a guitar and their goal is to match the natural resonant frequencies of their guitar's shape with as many of these musical notes as possible. In a sense, they are trying to create a guitar that acts like several tuning forks that are all glued together. In reality, a bit of luck is involved in this trial-and-error, iterative process. (Automatic topology optimization techniques have not yet been applied to this project, but could be a useful addition once standard software tools become available.) Also, the wood that their guitars are being constructed from is an anisotropic material with varying grain, moisture content, etc., which leads to variance in their FEA models parameters such as Young's modulus (i.e. admittedly their mathematical models are far from perfect, but they are certainly better than nothing in terms of making acoustical predictions).

Once students are satisfied with their guitar's shape and predicted resonance properties, they learn how to program toolpaths into a CNC milling machine using computer aided manufacturing software. (HSMworks is currently used and is currently offered as a plugin for both Inventor and SolidWorks, and Autodesk currently provides this software for free to students and faculty.)

Under the supervision of the instructor, students then use a Shopbot PRSalpha 96-48 CNC router to cut out their electric guitars from a solid piece of 2x12 Douglas Fir lumber up to 4ft in length. The cross section of this piece of wood is about 1.5in tall by 11.25in wide (this is not exactly consistent from board to board). Cutting each guitar on this CNC machine usually takes between 4 to 8 hours depending on the complexity of the model. Douglas fir was selected because it is a relatively inexpensive soft wood that can be acquired in large boards without knots. This makes the CNC machining process significantly easier and faster, since the milling bit can fly through it at around 1in/sec and one does not have to worry about slowing the federate whenever knots (much harder areas) are encountered. The tradeoff is that Douglas fir does not have acoustical resonance properties on par with the commonly used hard woods used in professional-grade electric guitars such as maple, ash, oak, and mahogany. If cost and manufacturing time are not a factor, then these hardwoods are highly recommended instead.

The second portion of this project involves designing, modeling, and creating custom analog effects pedals circuits using diodes, transistors, capacitors, inductors, and op-amps (all of which have been covered in this course prior to this project). Students are encouraged to look through circuit schematics for homemade and reverse-engineered guitar effects pedals available online for ideas. However, they are expected to significantly modify these and to understand every part of their circuits. Students are taught how to use NI Multisim to model their circuits and create simulated plots (virtual oscilloscope screen images) of important points in their circuits.

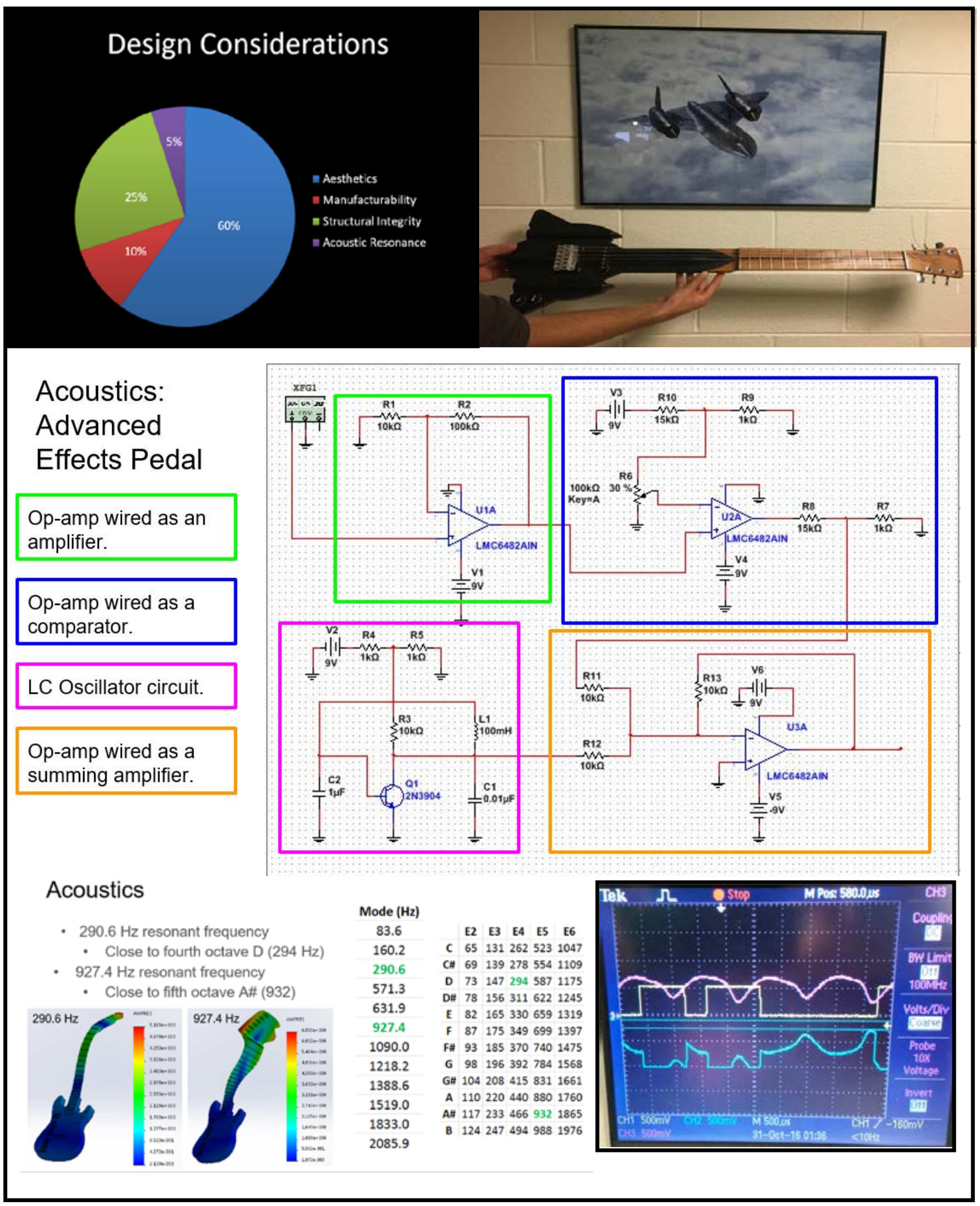

Figure 2: Example figures from written reports submitted by students in 2016

Project Assessment

The main deliverables for this project are a working electric guitar, two working effects pedal circuits (one simple and one more ambitious), and a written report describing the design of the guitar and the analog effects pedal circuit. In this report, students must defend their choice of emphasis or compromise with respect to visual aesthetics vs. acoustical resonance vs. structural integrity vs. manufacturability of their guitar's shape (though admittedly not all of these perfectly counter each other) and discuss any discrepancies between their Multisim computer simulation and sound/signals that were actually created from their circuit prototype. Students then present their guitars to the rest of the class, demonstrate the sounds of their custom effects pedal circuits, and explain exactly what they learned while exploring analog circuitry in the context of this project.

Evolution of the Project

Over the years, this project has adapted as new tools have been acquired, new technologies arisen, and new low-cost products have become available. Originally, with the exception of the tuners, fretwire, and strings, each guitar was constructed completely from scratch. Due to the size constraints of the original CNC router (a Roland MX-650), the first few years of guitars were made out of two pieces of wood (inexpensive yellow pine) with 2x12s for the bodies and the necks all made identically and cut from pine 2x4s. Later when a 4ft x 8ft Shopbot CNC router was acquired, the guitars (body and neck) were all made out of a single piece of high quality (no knots) Douglas fir 2x12s.

Constructing guitar fretboards has been the most difficult part of this project for students to master, and guitars made from scratch that play all of their notes perfectly have been very rare. Fretboard fabrication involves carefully cutting slots for the frets at precisely measured distances, carefully embedding the fret-wire using a hammer or fret press (there is really only one shot to get each one perfect), and then meticulously filing the frets to ensure that they are the perfect height to change a string's length when fretted with a finger while not allowing the string to buzz against other frets. Few students were ever able to get this right on their first try. Since fretboard construction was more a matter craftsmanship skill than of engineering design, last year, when Amazon.com started carrying pre-made electric guitar necks constructed out of high-quality maple and including a built-in truss rod (which allows one to re-straighten a neck as the wood warps and bows over time) all for around $30, these were simply incorporated into most of the guitars. [5] As a result, for the first time, all of last year's guitars were 100% perfectly playable. Student were still left with enough agency in the design and fabrication of their guitars' bodies to fulfill all of the original learning objectives. The premade necks simply saved a lot of time and frustration and allowed more time to be spent on other design projects in this course.

The electromagnetic pickups that transduce the mechanical vibrations of the strings into electrical oscillations were originally created using six iron nails sandwiched between two pieces of polycarbonate. This created a sort of rectangular spool around which a few hundred turns of 30 gauge magnet wire could be wrapped. An electric motor was usually attached to this spool to make winding easier. When professional grade 3D printers became available to the students, they started printing their pickup spools out of ABS plastic. Recently, inexpensive electric guitar pickups, containing thousands of windings of much thinner wire, have become available for under $10 and which also include pre-wired volume (voltage divider circuit) and tone knob (RC low-pass circuit) potentiometers.[5] These have been used for the past few years with much better sounding results. Again, this is a concession in favor of speed and simplicity.

Figure 3: The author holding a special electric guitar shaped like the University of Virginia's iconic Rotunda building, which he and his students designed and made out of mahogany wood to celebrate the 175th anniversary of UVA's Engineering School in 2011

Outcomes and Conclusions

Over the past nine years, this project has proved to be extremely popular among Mechanical Engineering students at the University of Virginia. For most of them, constructing this electric guitar is their first, real, hands-on experience with engineering design. As a result, many mistakes are typically made, which leads to even more learning and growth. Immediately after this project's initial implementation in 2008, it instantly caught the general public's attention when National Public Radio broadcasted a story about it.[6] It helped people to understand and appreciate exactly what engineers do in the context of such an iconic musical instrument.

This project also provides an undeniably fun way for mechanical engineers to experiment with analog circuitry. The excitement that students exhibit while working on this project (rather than the fear of the possibility of getting a poor grade) leads them to spend countless hours working around the clock on this project. They seem to enjoy the opportunity to be creative with their designs and to take pride in their work along the way. This motivation seems to have nothing to do with grades. In fact, many students have continued to work on perfecting their guitars and effects pedal circuits after the project is officially over and has already been graded.

This project provides a perfect opportunity for students to hone their engineering design skills. The experience students gain with CAD, CAM, FEA, and CNC machining during this project, both through their successes and failures along the way, prepares them for a better chance at success while working on other projects in this course and in their capstone design projects, and, of course, after graduation and throughout their careers as engineers.

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