Musical Strings and Sound Board Materials – New Exercises for Materials Engineering

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Abstract - **Two years ago, students in Introduction to Materials Engineering began studying basic subject areas within the course in the broad context of musical instrument design. Results from the initial assessment data show that the students enjoy the course more and score higher, as a group, on certain examination questions. For example, a classic set of problems involves calculating stress, strain, yield, and the elastic constant given load and elongation data. The new way to introduce these same concepts is to use the tuning and design process for a stringed instrument. While many students are unaware that objects strain under load, they do know that musical strings change pitch as the load is changed during tuning. Once the students understand the underlying concepts based on idealized musical strings, they more easily transition to classical problems. This paper describes the new exercises and design problems that were developed; it also gives the data needed to develop many additional exercises. Lectures and data sets will be available on a CD. The paper concludes with the initial assessment data and goals for changes in the course.**

Index Terms - Active learning principles, Design of stringed musical instruments, Musical strings, and Teaching materials science in context.

INTRODUCTION

Introductory Materials Engineering courses are often viewed by students as difficult and abstract. It is the first course in which they must integrate what they have learned in their basic science and mathematics courses to solve introductory problems in materials science and design engineering. Since the course is often taught at the freshman or sophomore level, students often search for a context for their studies. Even though they are surrounded by common objects made from a wide variety of innovative materials, few students have thought much about why the products are made from those materials or how the product engineers went about selecting the materials from which the products were made. Similarly, it is difficult for the students to comprehend the complex interaction between engineering design and materials engineering and selection since they come to the course with almost no background knowledge. It is easy to understand why they struggle with these issues. Simply stated, a design engineer has to know a great deal about engineering materials and the behavior of those materials in service to select from the appropriate class of engineering materials for a particular application. Engineers work in teams work to out an appropriate selection set of materials for particular applications. Thus, it makes sense that freshman and sophomore level students often feel overwhelmed by the large amount of information they must assimilate in this course for them to be successful.

The basic premise then of this paper is to describe a new approach to classic materials science problems that may lead to better student learning because the problems are placed in a context that students have some knowledge of, and perhaps interest in, when entering the class – music and musical instruments. For example, a classic set of problems encountered in a basic materials science course covers calculating the tensile stress resulting from particular loads and geometries, calculating the elastic constant and yield from stress/strain data, and calculating elongation/strain under loading conditions. The new way to introduce these same concepts to the students is to use the tuning and, subsequently, the design process for a guitar or violin. While many introductory students are unaware that any object strains under a given load, they all already know that a musical string changes pitch as the load is changed during the tuning process.

Although it is always difficult to measure improved student learning, there are a number of measures that indicate more active student learning and more active engagement in the course. For example, the number of after-class interactions with students seeking additional information regarding in-class learning increased a full 25% since the stress/strain type problems were introduced in context and, similarly, scores on conventional stress/strain problems on exams improved by 20%. Additional measures will be given later in the paper.

NEW CONTEXT FOR MATERIALS SCIENCE

The following section describes the specific in-context exercises that have been added to the basic Materials Engineering course at Western Washington University. First, it gives the specific materials property data and equations that are needed to create stress/strain problems in the context of musical strings. Then, specific homework problems and design problems are identified. Finally, the anisotropic nature of sound boards (tone woods) is used to introduce non-isotropic behavior of materials. Again, specific materials properties and design guidelines are given so that other instructors may use this technique in their courses. A comprehensive CD will be available at the conference with additional materials data sets and several PowerPoint presentations covering the materials needed to introduce all the essential concepts quickly in-class.

First, the instructor should give the students a quick overview of the operation of a musical instrument. "The amount of energy which passes from the string through the bridge to the body depends on how much the body is able to vibrate resonantly at that frequency. The body also takes the energy at each harmonic frequency in proportion to the size of the harmonic in the string vibration. The sound produced at any one level of bowing contains each string harmonic, its size adjusted by the body resonance at each frequency" [3]. Finally, the sound passes out of the resonating chambers through holes which are circular in guitars and are called f-holes in violins. The transition of air from the hole should be as smooth as possible. The effect of varnish on the overall sound of the instrument is too complex and controversial to be covered in class. Limit the students to understanding the basics and don't get distracted with side issues. Music is a subject with many distractions and there is not time to cover them all in the class.

The second concept that students must know to do stress/strain problems in the context of violin and guitar strings is IDEAL STRING BEHAVIOR. The equation that describes the behavior of an ideal string has been is known for many years (Mersenne, 1636 [1]) and is:

$$f = \frac{\sqrt{\frac{T}{m/L}}}{2L} \qquad (1)$$

where f = Desired String Frequency (in Hertz),
T = String Tension (in N),
m = String Mass (in Kg), and
L = String Length (in m).

The students should be made aware that this is certainly the IDEAL equation and there are certain conditions under which this equation is valid. The first is that the mass/Length (m/L) is perfectly uniform over the length of an ideal string. This is a fairly good approximation in modern music strings for the violin and the guitar. Gut music strings (for baroque instruments, for example) are still the most difficult to control with respect to diameter and that means it would be difficult to assume a constant m/L. Modern strings that the students are likely to encounter are quite uniform. The second condition is that the string has zero stiffness (zero for E) and is completely flexible (no damping). The third condition is that the string would have infinitely high tensile strength [22]. Even though the all these things would have to be true for the equation to give exact results, the equation is quite useful to materials science students. Calculations with it give results very close to those measured in experiments. The violin steel E string comes closest to ideal theoretical string and will be used here for an example.

The frequencies of all the stings will be needed for the calculations. For the four violin strings, they are [6]:

E_5	659 Hertz (highest)
A_4	440 Hertz
D_4	294 Hertz
G_3	196 Hertz

Similarly, the frequencies of the six guitar strings are [6]:

E_4	330 Hertz (highest)
B_3	247 Hertz
G_3	196 Hertz
D_3	147 Hertz
A_2	110 Hertz
E_2	82 Hertz

The free lengths (L) will also be needed. There is some variation in what is listed for this data in the literature, but the following work well for in-class exercises. Reference 24 contains an interesting discussion and good data of the resultant forces on violin strings by position and placement of the bridge.

The vibrating free lengths for the string family and the guitar are [2,4,6,24]:

Violin	328 mm (some use 325 mm)
Viola	360 mm, 377 mm or 380 mm [24]
Cello	700 mm
Bass	1100 mm and
Guitar	650 mm.

The approximate densities of common string materials are [2,5,15,21]:

Tungsten	19.3 g/cm^3
Silver	10.5 g/cm^3
Steel	7.85 g/cm^3
Aluminum	2.77 g/cm^3 (Alloy 2024)
Gut	1.3 g/cm^3
Silk	1.3 g/cm^3 and
Nylon	1.12 g/cm^3 – 1.14 g/cm^3.

The approximate E values of common string materials are [2,6]:

Steel (music wire)	220	GPa
Gut	5.5 – 6.5	GPa
Silk	5.0 – 6.0	GPa
Nylon	4.5 – 5.5	GPa (high)

The tensile limit for silk and gut strings varies 140 - 340 MPa [7,47], although others sources list it considerably lower. "The highest pitch string usually is subjected to the highest tension, so that diameter and stiffness are minimized" [47].

Measured Mass/Length of violin strings [2]:

E_5	0.381 - 0.443 g/m
A_4	0.579 - 0.752 g/m
D_4	0.924 - 1.641 g/m
G_3	2.115 - 2.700 g/m

Measured Mass/Length of guitar strings [2]:

E_4	.417 g/m

B_3	.892 g/m
G_3	1.03 g/m
D_3	2.04 g/m
A_2	3.45 g/m
E_2	5.33 g/m

Measured diameters of violin strings [2]:

E_5	0.249 mm - 0.265 mm
A_4	0.452 mm - 0.701 mm
D_4	0.671 mm - 0.914 mm
G_3	0.790 mm - 0.833 mm

Measured diameters of guitar strings [2]:

E_4	0.70 mm
B_3	0.83 mm
G_3	1.03 mm
D_4	0.75 mm
A_2	0.93 mm
E_2	1.07 mm

There are a number of interesting assignments that you can create for the students with this data. Obvious assignments include simple tensile stress values for each string, finding the mass/length from size and density data, comparing the theoretical data for mass/length with measured mass/length, and calculating the required string tension for a particular frequency from the ideal string equation (1), and comparing the calculated string tensions in N with the measured values.

An example problem would be to calculate the tension needed for a Violin E string given that the free length is 0.325 m and the mass/length (from the measured values in Table 1) is 0.381 x 10^{-3} Kg/m. Rearranging equation (1):

$$T = [f^*(2L)]^2(m/L)$$

$$T = [659 \text{ hertz}(2^*.325\text{m})]^2(0.381 \times 10^{-3} \text{ Kg/m})$$

$$T = 69.9 \text{ N}$$

Using the larger measured value (0.443 x 10^{-3} Kg/m) gives a required Tension of 81 N. The faculty member should go over the units used in equation (1) since the students are usually not familiar with using them in this context.

These calculated values can be compared to measured values found in the literature:

Measured Tension of violin strings [2]:

E_5	64.0 N - 72.3 N
A_4	48.9 N - 63.5 N
D_4	34.8 N - 61.7 N
G_3	35.4 N - 49.9 N

Measured tensions of guitar strings [2]:

E_4	64.4 N
B_3	58.4 N
G_3	70.4 N
D_3	72.8 N
A_2	78.6 N
E_2	70.0 N

Examining results for other studies show similar results with regard to tension. In guitars, the string tensions are roughly between 60 N and 80 N [1-9]. In violins, the results vary somewhat from string to string, but are roughly between 35 N and 60 N, except for the high E string which is usually 70 N to 80 N [1-9]. The students can calculate the stress on each of the strings for another active in-class learning exercise. The results for the Violin E string reveal that a material with a very high yield is needed for this string (more than 1400 MPa). In our course, the students are asked to choose a material using their text or the free access area in http://www.matweb.com. Of course, most of the students do not have the background to choose correctly, but listing their choices provides the perfect opportunity to discuss the pros and cons of each selection and then to actually discuss a material that will do quite nicely, ASTM 228 (which happens to be music wire). This also leads to an opportunity to discuss materials standards and why the ASTM standards are different from the AISI standards.

The data presented here give the instructor an opportunity to have the students calculate the mass/length values from fundamental principles using the density of the material and the approximation that the string is really just a long cylinder. The students can also calculate the resulting strain in the string and the elongation needed in the string that is needed to produce a frequency shift (tuning) that the instructor specifies.

Perhaps the most interesting problem that can be given to the students after they do all these short exercises is to have them DESIGN a stringed musical instrument. The hypothetical goal will be to keep the tensions in the strings as uniform as possible across the instrument given the available materials (metals need to be able to have enough ductility to be wound, for example). Have the students examine what materials are available today for real instruments. Tensions for cellos range between 120 N and 150 N, while tensions in basses are very high between 300 N to 450 N. The students need to first fix the frequencies of the notes. The violin is tuned in 5ths between notes and this implies that the lowest string will need more than 11 times the mass of the highest string. The guitar is strung in fourths. While it is preferred that the students design the strings for a real musical instrument, they can design new instruments as long as they justify their solutions. While the students are designing the strings for their instruments, they should begin to think about what materials that might be used for the body of their instruments and for their sound boards. The solutions to these questions are interesting from a materials science standpoint.

Another design issue that makes a motivating in-class demonstration and/or discussion is that violin strings are meant to damp the vibration as the string must follow the bowing action of the player. This means low damping actually interferes with the production of the necessary sustained, forced vibrations [4,8]. On the other hand, guitar strings are meant to sustain the note. Thus, gut and nylon cores (or multi-fiber cores simulating gut) are used for violin strings. For example, a steel violin string as thick as a gut A string would be too stiff and could not be bowed effectively. "An ideal (violin) string material has a high ratio of tensile strength to density" [8]. Thus, there is always a compromise between diameter and tension. There is also a compromise between loudness and timbre as stiff strings are louder, but perhaps not as rich in timbre [24]. Also, steel has little internal damping when compared to gut or nylon. Sometimes string manufacturers will use multi-stranded steel cores to reduce the stiffness. Solid nylon or other synthetic strings have been very successful on acoustic guitars. Multi-stranded nylon cores strings closely mimic gut core violin strings, although players can feel and hear the difference when playing them. Stranded cores lack good torsional stiffness and numerous clever manufacturing techniques have been developed to give them the required torsional stiffness. Aluminum, copper, nickel, and silver are often used for winding violin strings as are iron alloys, chromium and tungsten. Kevlar has a very high elastic modulus, but the individual strands of a core break if wrapped around a tuning peg as they are too thin to secure at the ends easily [4,8,46].

The sound boards of most stringed musical instruments are made from spruce wood with particular characteristics. The backs of violins and guitars are usually made from hardwoods (curly maple, for violins) and are mostly chosen for aesthetic and strength reasons. It is the sound board that must be able to resonate at all the important frequencies of an instrument (including the harmonics) and it is the sound board that really makes the characteristic sound of the instrument. Both the guitar and the violin use stiffeners to alter the intensities of their vibrating sound boards. The violin has fixed positions for both the sound post (high frequencies) and the bass bar stiffeners (low frequencies), while there are many competing stiffener designs for guitars, with each producing a characteristic sound. The "greatest" instruments produce rich resonances at the highest overtones and have a wide range of frequency responses without any overwhelming resonances at any particular frequency. The bottom line in sound board design is that the stiffness/mass controls the highest resonances. Low frequencies tend to be controlled by the stiffening scheme. Musical instrument makers long ago chose naturally aged Norway spruce from high Alpine regions for their finest instruments. As is turns out, naturally aged old Alpine Norway spruce has a superior stiffness verses strength value. It also has uniform grain and has small differences between spring and fall growth because of the harsh growing conditions high in the Alps. Here, of course, is where the realities of real (not ideal) strings play a key role in the sound of a real instrument. Metal strings have an appreciable bending stiffness, which produces unwanted and not harmonic high upper partials. It is fortunate that the upper partials from the steel violin E string are not within the hearing range of humans.

Woods are orthotropic materials and make for interesting comparisons with steels (metals) for materials science students. The very fact that the sound board materials are chosen as sound board materials for their anisotropic nature makes a meaningful introduction to the concept of using an anisotropic material purposely in engineering design. By this point in the course, the students have seen microstructures of different steels. Showing them the microstructure of both softwoods (spruce) and hardwoods (maple) provides a way to illustrate how anisotropic structures might be deliberately produced in metals and in composites.

The students should be reminded that the spruce top for a violin is only 3 mm thick. If the students have already had their strength of materials class, additional calculation opportunities abound here. Guitar tops and backs are usually approximately 2.5 mm thick [6].

Materials properties (measured) for sound board spruce from the literature follows [10]:

- ☐ Elastic Constants - MPa
  - ■ $E_1 = 13000$, $E_2 = 890$, $E_3 = 649$
- ☐ Shear Moduli - MPa
  - ■ $G_1 = 1015$, $G_2 = 715$, $G_3 = 416$
- ☐ Poisson's Ratio
  - ■ $\mu_{12} = .375$, $\mu_{13} = .436$, $\mu_{23} = .468$
  - ■ $\mu_{32} = .248$, $\mu_{21} = .034$, $\mu_{31} = .022$
- ☐ Density (g/cm^3) = 0.46

Materials properties (measured) for maple [10]:

- ☐ Elastic Constants - MPa
  - ■ $E_1 = 17000$, $E_2 = 1564$, $E_3 = 731$
- ☐ Shear Moduli - MPa
  - ■ $G_1 = 1275$, $G_2 = 1173$, $G_3 = 187$
- ☐ Poisson's Ratio
  - ■ $\mu_{12} = .318$, $\mu_{13} = .392$, $\mu_{23} = .703$
  - ■ $\mu_{32} = .329$, $\mu_{21} = .030$, $\mu_{31} = .019$
- ☐ Density (g/cm^3) = 0.8

Finally, materials properties (measured) for guitar back materials are as follows [11]:

- ☐ Brazilian Rosewood
  - ■ Density (g/cm^3) = 0.83
  - ■ $E_1 = 16000$ MPa, $E_2 = 2800$ MPa
- ☐ Indian Rosewood
  - ■ Density (g/cm^3) = 0.73
  - ■ $E_1 = 12375$ MPa, $E_2 = 2200$ MPa
- ☐ African Mahogany
  - ■ Density (g/cm^3) = 0.54
  - ■ $E_1 = 12000$ MPa, $E_2 = 930$ MPa

Differences in sound board spruce [12]:

Norway Spruce - Density (g/cm^3) = 0.460 [±.051]
$E_1 = 15000$ [±2100] MPa, $E_2 = 760$ [±260] MPa

Sitka Spruce - Density (g/cm^3) = 0.460 [±.050]
$E_1 = 13000$ [±2500] MPa, $E_2 = 890$ [±240] MPa

The parameters that should be given to the students are from Hutchins' work [9], "the desirable ratio of Young's modulus [E] along the grain to the Young's modulus across the grain the spruce for violin tops is about 10:1, and in curly maple for violin backs is 5:3." Other literature sources place the ratio between 8 and 12 (for tops). So, any student work that produces values within the literature values would be acceptable. The value that is stated most often for the E ratio on guitars is more on the order of 20. The values range quite a bit for guitars since there is more than one sound that is acceptable for a guitar. The violin is, perhaps, the instrument with the most fixed sound expectations.

Guitars are instruments where low damping is important because of the long sustain valued in these instruments. Thus, the choice for guitar backs is usually rosewood. Cedar and redwood may be used for sound boards of guitars to increase the sustain of the instrument. Rosewood and curly maple are aesthetically beautiful and make beautiful backs for any instrument. Martin Guitar and Gibson Guitar web sites [43] have musicians' descriptions of the wood used to produce a particular tone for a high quality guitar. The sound board woods are only varieties of spruce that are grown at altitude, but the side and back woods are chosen both for sound and for beauty of the wood. Rosewood, mahogany, and maple predominate for guitar luthiers. The students seem happy to investigate interesting materials (mostly based on aesthetics) for backs and sides, but spruce is always the "safe choice" for sound boards. Occasionally, a student will have a passion for a particular sound board for a guitar. Debating the points of the sound produced from that guitar and the "why" that might be with the students can be quite lively.

The design choices you should specify to the students should be limited to resonating instruments, meaning those with strings, bridge, sound board, and finally sound box (body). Designing an electric guitar, for example, is not very challenging from a materials science perspective. In that case, string vibrations are just amplified and there is no consideration of sound board or resonating body.

IMPROVED STUDENT LEARNING

It is difficult to measure with any degree of certainty improved student learning over the short term. However, it is known that if students are more engaged in their own learning and if students are more interested in the subject, that learning is likely improved. One measure of student engagement is how many times the students stay after class to learn something more about what was covered in class on any particular day. These informal interactions with students have increased 25 percent since we have been discussing musical instruments, strings and sound board materials. Visits to my office (which is now across campus and in a hard to find location) has increased about the same (20%). The overall student satisfaction with the course has also risen. Students come to my office to chat about the "why" of musical instruments, bring me instruments, or show me things that they have seen or share stories. One student brought a CD with his playing of two different guitars (remembering to use the same set of strings) and went on for quite a long time about why he thought they sounded so differently. Students talk with me about this subject in other classes. Also, the context of musical strings/sound boards gives an instructor numerous opportunities to do more active learning in the lecture sessions. The ideal string equation with a database of materials properties and instrument properties can provide several in-class, quick calculation and discussion type active learning sessions. Fully, fifteen percent of the class wrote about some aspect of materials and music for their research paper. This is a about the same percentage that write about materials used in cars [the class has many Vehicle Design majors]. This approach seems to reach out to a different student population. Thus, the students seem to be more engaged in the class. Since I have taught the class in different styles previously, I do have reasonably good benchmarks. I have NOT changed the wording of the stress/strain, elastic constant, design, and elongation problems on the exams purposely. I wanted to see if the students scored better on conventional problems and they did. In general, the scores improved by 17% (plus or minus 5%) on these conventional problems. It is possible that the active learning accounts for these differences too. Regardless, once the context is provided, the students seem to be able to complete conventionally worded problems more effectively since they seem to understand the basics better and seem more engaged in the course.

CONCLUSIONS AND GOALS

In appears that students who are presented with a contextual base for some of the basics principles in materials science are somewhat more engaged in the course and score somewhat better on conventional problems on exams. The same material that is used to present the course in context can be used to provide more active student learning opportunities. Once the practical data are gathered, the students can do basic design problems further enhancing their education in basic materials selection issues. However, the course is still a difficult one and now there is really more material that the students must grasp in order to successfully complete the course. Two other major areas remain to be placed in context for this course are atomic structures and phase diagrams. The materials used for strings may be helpful for the atomic structures context and lectures are currently under development. For example, Kevlar has a superior strength to weight performance, but is so stiff that it does not easily bend about the pegs of an instrument. A question that could be posed is what is happening with materials on the atomic structure level that makes gut, nylon and steel the choices for musical strings. Another goal for the course is to find active learning opportunities for every class session. Currently, no more than half the lectures have any meaningful active learning exercises. Overall, the purpose will be to place every major topic in the course into a context where they bring some knowledge with them. In this way, the students will be able to retain more, because as the education literature shows, they retain more in long-term memory when they can make connections to previously learned material. Hopefully, active and engaged students will leave the course with a more comprehensive knowledge of the subject.

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