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The sound of music

Determining Young's modulus using a guitar string

Pols, Freek

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The sound of music: determining Young's modulus using a guitar string

Freek Pols* 

Science Education and Communication, University of Technology Delft, Delft, The Netherlands

E-mail: c.f.j.pols@tudelft.nl



Abstract

When a new topic is introduced in the curriculum, teachers seek various ways to teach students the related concepts. For the novel topic 'materials' in the revised Dutch curriculum, I developed an experiment in which students determine Young's modulus using a guitar string. The experiment not only covers several concepts related to 'materials' it also provides a clear link to the physics of music and illustrates to students, aged 16, why the topic 'materials' could be of interest.

Keywords: practical work, materials, experiment

1. The challenge of the topic 'materials' in the novel curriculum

Recently the topic 'materials' was introduced in the Dutch Secondary Physics curriculum. Although this broad topic covers many concepts, the curriculum specifies that students should be able to: *interpret stress–strain diagrams in terms of elastic and plastic deformations and calculate elastic deformations using the formulas: $E = \sigma/\epsilon$ (Young's modulus), $\sigma = F/A$ (stress) and*

$\epsilon = \Delta l/l_0$ (strain) [1]. In essence, this implies that students understand that a material stretches when a force F is applied to a cross sectional area A , see figure 1. The strain is the relative elongation of the material. In the elastic region, implying that the material recovers its original shape when the external force is removed, Hooke's law of elasticity holds. Students should be able to, e.g. calculate the strain using Young's modulus which is a material property.

With the introduction of a new topic in the curriculum, teachers have the challenge to develop teaching materials which are interesting to and understandable by students (aged 16). For the topic 'materials', presentations, assignments, test questions and movie clips were already available as the topic is covered at academic level as well. However, affordable experiments, most

* Author to whom any correspondence should be addressed.



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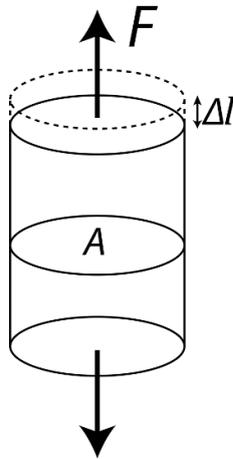


Figure 1. A material deforms when a force acts on it. In the elastic region, the change in length can be calculated using Hooke's law of elasticity.

welcomed by students, were not available at the time.

The idea of *Physics of stringed instruments* came to mind. This idea links two different topics in physics: Music and Materials. Engaging students hands- and minds on makes the topic of stress and strain more tangible. An experiment in which students investigate the physics in an instrument could also illustrate why this specific topic is of interest to them, especially since students at this age are often interested in playing music.

2. The physics of tuning a guitar

Guitar strings produce their sound by transverse resonant standing waves [2]. The natural frequency of a guitar string depends on the wavelength and the wave velocity: $f_0 = v/\lambda_0$ with $\lambda_0 = 2L$ where L is the length of the string. The wave velocity v is dependent on the string's tension and material: $v = \sqrt{F/\mu}$ where μ is the mass per unit length ($\mu = m/L$).

As every guitar player knows, changing the tension of the string, changes the frequency (tuning). One increases the tension by twisting the tuning knob which effectively stretches the string. The change in tension can be calculated using: $F = \sigma A = E\varepsilon A$, with E the Young's modulus and ε the strain. Rearranging these formulas, relates the



Figure 2. The experimental set up consists of a sonometer with an adjusted tuning knob.

frequency produced by the string with the change in length:

$$f^2 = \frac{EA}{4\mu L^3} \Delta l + f_0^2 \quad (1a)$$

or written as:

$$f^2 = \frac{E}{4\rho L^3} \Delta l + f_0^2. \quad (1b)$$

Assuming that the dissectional area A and the mass per unit length do not change when tuning, we can measure the frequency as function of the change in length Δl . This allows us to determine the Young's modulus of a guitar string [3].

The derivation of equation (1a) shows that this single experiment covers the formulas specified in the Dutch physics curriculum.

3. The experiment

In the designed experiment, the frequency as function of the increased length of a guitar string is determined. To do so, a sonometer was used, where one fixed end is replaced by a 'tuning' knob (dovetail translation stage) obtained from an optical equipment company, see figure 2. This tuning knob, in combination with a nonius scale, allows to accurately alter the length of the string (0.05 mm), see figure 3. The produced frequency is measured using a mobile phone, with either a guitar tuning app such as gStrings or the physics app Phyphox [4]. The guitar string can easily be replaced with strings of different thickness or materials, offered by any music instrument shop.

4. Experimental results

For the purpose of this paper, I did two different measurements. Figure 4 shows the results of the measurements of a (0.33 ± 0.01) mm thick

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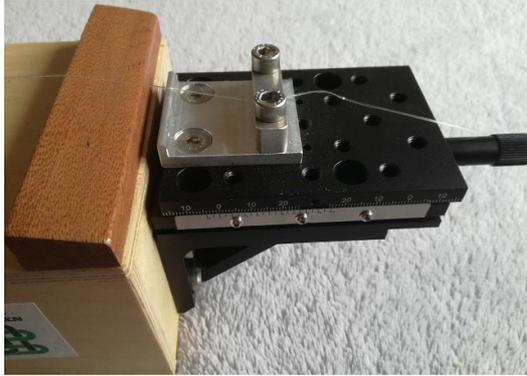


Figure 3. The tuning knob allows one to adjust the length of the string with a 0.05 mm accuracy.

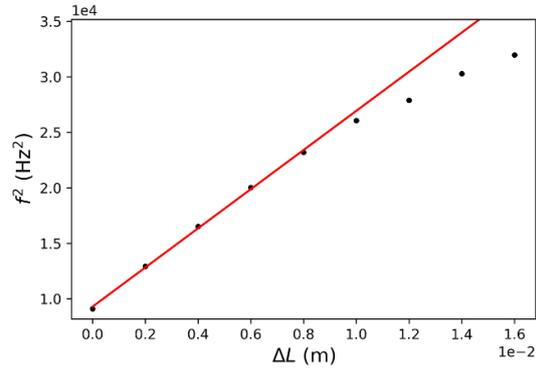


Figure 5. The experimental results with the Nylon guitar string are interesting since plastic deformation occurred.

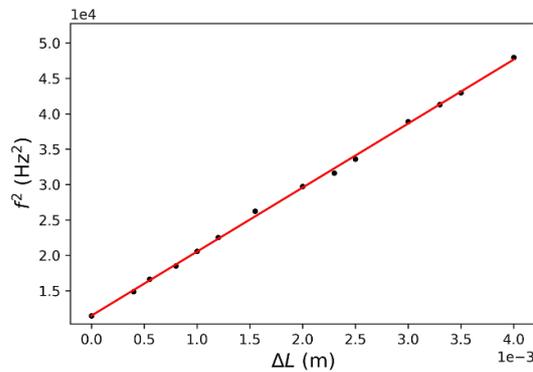


Figure 4. The experimental results with the assumed steel guitar string. Although the results are in accord with the theoretical model, the determined Young's modulus (146 ± 2 GPa) does not accord with the theoretical value (210 GPa).

steel string. These results are in accord with the theoretical model presented in equation (1). The determined Young's modulus was 146 ± 2 GPa which is not in accord with the theoretical value of 210 GPa. Considering that the determined value deviates from the theoretical value, that the thickness of the string is not in agreement with the specs given by the seller and the fact that the advertisement stated three plain strings and three wound strings (a string consisting of a core often made of steel and an overwinding string made of a different material) would be included, though two plain strings and four wound strings were received, leaves us to conclude that the seller is



Figure 6. Plastic deformation occurred when the Nylon string was stretched too far.

not selling what is offered. It would be interesting to see whether students would reach the same conclusion.

If one is really interested in the Young's modulus of steel, the advice is to go to the local construction market and buy steel wire (which can be expected to be cheaper as well).

Figure 5 shows the results of a (0.58 ± 0.01) mm thick Nylon guitar string. It is interesting to see that the first five measurements are in accord with theory, $E = (4.1 \pm 0.1)$ GPa. However, when the guitar string is stretched too far, plastic deformation occurs. This effect was already audible during the measurements: the frequency decreased notably after the string was plucked. A more close look, see figure 6, revealed the plastic deformation explaining why the theoretical model does not hold.

5. Experience

As can be expected of students this age, they had difficulty in deriving equation (1) on their own. Although a single set up was available, collecting data did not take much time. When analysing and presenting the results, students had difficulties using coordinate transformation. This part of data-analysis was taught at the start of the year, but not practiced frequently (in following year we helped students with the coordinate transformation using an excel file). However, with a little help every student was able to determine the Young's modulus of either steel or nylon. They appreciated the connection with the daily life topic 'instruments'. The experiment was re-used when the topic *physics of sound and music* was taught.

6. In conclusion

This experiment, earlier presented in the Dutch Science Teacher Magazine [5], connects the abstract topic 'materials' with a daily live phenomenon: tuning a guitar string. As part of a novel topic in the Dutch physics curriculum, it was received with praise by several physics teachers. Multiple experimental setups have been made by our University and are loaned to secondary schools. Various school science technicians have build less sophisticated but successful, versions ever since.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iD

Freek Pols  <https://orcid.org/0000-0002-4690-6460>

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Freek Pols has been a secondary school physics teacher for ten years. He is a researcher focussing on practical work in physics and teaching scientific inquiry. He recently started working as head of the first year practical course in applied physics, TU Delft.