Work in Progress: Kinesthetic Learning of Network Mechanics using Force Feedback Technology

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Abstract

Recent advancements in haptic force feedback technologies enable novel opportunities for the teaching of science and engineering by augmenting classical laboratory experiments with haptic experiences that provide deeper insight into the connections between theory and experiment. This contribution describes the development and implementation of a 'kinesthetic teaching toolkit' for the particular purpose of teaching mechanical properties of polymer networks. In the first part the background of 'network mechanics' is introduced at a level consistent with undergraduate and graduate courses on Polymer Science and Engineering that are being offered at Carnegie Mellon University. The challenges associated with the design of hands-on experiences to support the teaching of 'mechanical properties of polymer networks' are described to illustrate the opportunities for force-feedback technologies.

In the second part, this paper describes the process of adopting low-cost force feedback joysticks for the emulation of a 'rubber extension' experiment. The opportunities for students to explore material property changes in response to defined microstructural changes are described. Finally, we elaborate the implementation of the device in a laboratory course on Colloids, Polymers and Surfaces that is being offered at the Chemical Engineering Department at Carnegie Mellon University.

Introduction

When selecting materials for engineering applications, considerations of 'mechanical properties' typically play an important role. Teaching of the 'Mechanical Properties of Materials' is thus a topic that is of fundamental importance to all engineering disciplines. The discussion typically starts with the consideration of the materials microstructure and an analysis of how structure relates to the material's mechanical response behavior. This often requires the application of complex models. Hands-on experiments are ideal to illustrate these challenging concepts and thus constitute an integral part of the science and engineering curriculum. An ideal experiment involving a system in which responses depend on multiple parameters should be constructed such that individual components can be altered arbitrarily to understand their significance to the response of the system. Unfortunately, such experiments are often not realizable in classroom or even laboratory settings. Computer simulations can remediate some of the problems associated with the visualization of complex processes; however, do not provide tactile feedback that is the most relevant mode of interaction to facilitate conceptualization. The recent advancement of educational robotics and in particular the emergence of computer controlled kinesthetic force feedback devices hold the promise of revolutionary progress in the field of 'educational haptics' and provide new opportunities to address the above-mentioned challenges. Haptic (from the Greek '*haptikos*' meaning 'able to touch' and '*haptesthai*', meaning 'able to lay hold of') educational devices provide force and tactile feedback for a user while interacting with a virtual environment. Among the key application areas for haptic technologies has been motor skill training - such as surgical simulations – for which high-fidelity, multi-degree-of-freedom haptic interfaces have been developed [1]. Because of cost consideration, these technologies have only found sporadic use in educational research, for example, to demonstrate concepts in electromagnetism [2]. However,

progress in the electronics and entertainment industry has led to the emergence of low-cost haptic technologies such as 3D force feedback joysticks that are commercially available for about $300. With force capabilities exceeding 2 lbs and a refresh rate exceeding 1 kHz, these devices provide adequate performance to explore the application for educational purposes [3].

Polymer science provides a particularly suitable context for the application of force feedback technologies to improve learning. Polymer materials – when measured in terms of volume – represent the most relevant class of engineering materials today. Major challenges in the teaching of the mechanical properties of polymers arise because many of the fundamental characteristics of polymer materials – such as the 'random coil nature' of flexible polymer chains – manifest themselves in mechanical responses that defy the rules that are applicable to other types of materials. One example is the well-known 'entropy spring behavior' that gives rise to the stiffening of polymer materials at elevated temperatures which is in contrast to the softening that is observed for inorganic solids which often serves as reference point for students. Teaching of the 'mechanical properties of polymers' often starts with the discussion of network elasticity that directly deals with the elastic response of rubbers [4]. Network elasticity is also relevant to interpret the mechanical properties of many semi-crystalline polymers, thermoplastic elastomers, polymer melts as well as gel- and hydrogel-based materials. Unfortunately, experimental demonstrations of how the structure of networks relates to their properties are elaborate and often not practical in classroom or laboratory settings. This is because the relevant experimental parameters (such as temperature, degree of polymerization, chain stiffness, crosslink density and relaxation time) cannot be varied individually. Hence, classical laboratory experiments do not allow the differentiation of how particular parameters affect the response of, for instance, crosslinked polymers. This limits the ability of experiments to illustrate cause-effect relations and hence the intellectual merits of hands-on experimentation in teaching, a critical aspect of polymer science. The objective of this project is to establish a visuo-haptic experiment using the Novint Falcon 3D Touch Controller (dubbed the 'Rubber Emulator') that allows students to explore the effect of select variation of individual external or structural parameters (such as temperature, crosslink density, and swelling ratio) on a rubber's tensile behavior. The goal is to develop an interface that allows students to select the respective material properties, perform a 'haptic tensile stretch experiment' that emulates the response behavior of a 'real rubber material' and finally to export the data obtained from the deformation experiment for subsequent analysis and interpretation. The 'Rubber Emulator' is to be implemented and evaluated in undergraduate laboratory courses that is being taught by the authors. In the following, the basic approach and theoretical concepts underlying the emulation of network elasticity are being described and the application of the device is being demonstrated. Future work will involve the implementation of the 'Rubber Emulator' in undergraduate laboratory courses taught by the authors and the evaluation of its impact on student learning.

Background 'Mechanical properties of materials' is a summative term that is used to describe the response behavior of materials to an arbitrary loading condition. Because engineering applications of materials generally involve the exposure of materials to stresses – either as part of the primary function such as load bearing structures, or as a consequence of secondary effects such as thermal stresses that arise during heating and cooling of integrated circuits – the subject of 'mechanical properties' constitutes an integral element across engineering curricula. A common feature of engineering materials (with the exception perhaps of artificially engineered 'metamaterials' that are outside the scope of this discussion) is that acting force and deformation are linearly related in

the limit of small deformations. This so-called 'elastic regime' is amenable to quantitative physical description. In the elastic regime the response of a material is characterized by its elastic modulus (or Young's modulus) that is a measure for the resistance of a material to elastic deformation. Young's modulus is commonly measured as the slope of stress-strain curves in tensile deformation experiments. For most engineering materials (such as ceramics and metals as well as some polymeric solids) the elastic modulus is related to the cohesive energy density and hence to the number and strength of bonds. Qualitatively, the geometric extension of a material can be thought to translate into an equivalent extension of chemical bonds, the restoring forces resulting from this 'stretching of chemical bonds' give rise to the macroscopic elastic modulus. On a more fundamental level the elastic modulus is proportional to the change in free energy G of deformation. Hence,

$$\text{Young's Modulus} \sim (\mathrm{d}G/\mathrm{d}l) = (\mathrm{d}H/\mathrm{d}l) - T(\mathrm{d}S/\mathrm{d}l)$$

where l denotes the length of the sample, T is the (absolute) temperature and H and S refer to enthalpy and entropy, respectively [5]. If Young's modulus is determined by the cohesive energy density of materials then the effect of entropic forces can be neglected and thus Young's Modulus ~ ($\mathrm{d}H/\mathrm{d}l$). Metals and ceramics are thus also called 'enthalpy elastic'.

Rubbers, defined as weakly crosslinked amorphous polymers above the glass transition temperature, defy this trend. Rubbers are an important class of polymer materials that are widely used for their low modulus and large strain elasticity, most importantly in tire applications. In 2019, the word demand of rubber materials was estimated to about 32 million metric tons. Besides their technological relevance, rubbers have also become important as model systems to understand the mechanical properties of polymer networks in general. The latter are encountered in materials as diverse as hydrogels, tissue or thermoplastic elastomers. Network elasticity therefore is an important subject in the polymer engineering curriculum. The challenge for students when encountering this subject is that the origin of elastic restoring forces in rubbers (and related polymer network structures) is of entropic origin, i.e., it is related to the change in chain conformational entropy associated with the deformation of the network. Thus, for rubber materials, Young's Modulus ~ $-T(\mathrm{d}S/\mathrm{d}l)$. Entropy elasticity gives rise to a number of 'distinctive' behaviors of network polymers. For example, the modulus of rubbers increases with temperature whereas in enthalpy-elastic materials, such as ceramics or metals, the modulus generally shows the opposite trend. Because traditional engineering curricula tend to emphasize inorganic materials, students find the features of network polymers often 'non-intuitive'.

Discussion of rubber elasticity in polymer engineering courses is generally based on the 'Statistical Theory of Network Elasticity' that was first developed by Kuhn, Flory, Wall, James, Guth and Treolar. The model is based on the assumption of ideal Gaussian chain statistics for network chains and affine deformation. Under these constraints, the theory predicts the Young's modulus of a network polymer as Young's modulus = $3\, n_S\, k_B T$, with k_B denoting the Boltzmann constant and n_S denoting the density of segments of the network. Despite its simplifying assumptions, the model is widely used because of its simplicity and ability to correctly predict trends. However, experiments have shown this model to be valid only in the limit of small extensions (its applicability is somewhat more robust for compression). At larger extension, deviations from the predicted linear stress-strain behavior are observed that sensitively depend on the composition and molecular architecture of the rubber.

A variety of more advanced theoretical models have been proposed to more accurately describe the deformation behavior of rubber materials. A well-known and extensions of the network model is the hyper-elastic constitutive model by Arruda and Boyce (also known as Arruda-Boyce model) [6]. The model is based on the assumption of eight network strands emanating per junction and applies a statistical mechanical approach to calculate the strain energy function of a rubber from which the deformation behavior is predicted. A detailed discussion of the Arruda-Boyce model is given in the literature; here we note that formulations for the stress-strain response are available in the literature for a variety of loading conditions. The Arruda-Boyce model has been shown to semi-quantitatively capture the nonlinear response of rubber deformation. By altering suitable parameters in the model one can thus predict the effect of select variation of temperature or crosslink density on the global deformation behavior of a rubber. In this project, the Arruda-Boyce model was used to program the response characteristics of a NOVINT Falcon® force feedback joystick to emulate the deformation behavior of a rubber material.

Approach

A low-cost 3D force-feedback joystick (Novint Falcon®, Novint Technologies Inc.) that was developed for gaming applications was chosen as testbed to emulate the response behavior of rubbers. This device was chosen because of its force resolution and modest costs (approximately $200 per device on Ebay) that should benefit its more widespread application. Installers for the device are currently available through a public google drive under Noncommercial Software Developer Kit License Agreement (https://drive.google.com/drive/folders/0B4w9Giv8WXqoZ1hJZjBmRmNUMU0). The Polymer Emulator program was written in C++ and uses SDL2 for graphics rendering and SDL2_ttf for text rendering. Several online resources provide information about the process of programming the Falcon device. The Polymer Emulator program contains two loops, one for the graphical user interface (GUI) and one for the haptic program. Information about the development of haptic programs for the Falcon device can be found at online resources such as https://www.ms.mff.cuni.cz/~kadlp7am/has-dev.html. For the present project a program was made available by Prof Hong Tan at Purdue University and was modified for the particular purpose of emulating the response of rubber materials. A GUI was developed to enable students the selection of the rubber crosslink density, the degree of solvent swelling and temperature. The device then allows displacement of the joystick with a force-extension relation that is scaled according to the Arruda-Boyce model predictions. A degree of polymerization of polymer segments of $N = 64$ is chosen as default, however, this value can also be defined by the user. A data visualization window provides live display of the force feedback of the Falcon device in form of a load-deformation diagram similar to a classical tensile test. The plots of the preceding run's curve remain displayed so the student can compare between runs and see the difference in the curves as a result of the change in the conditions. Data generated from these emulated force-extension are saved as ASCII data. A data export function allows students to ‘retrieve’ the data obtained from the ‘Polymer Emulator’ and to analyze the data in common data analysis software such as Microsoft Excel®.

Results and Discussion

The Polymer Emulator has been completed and installed. Figure 1 (see Appendix) shows the operation of the Novint Falcon® device. Figure 2 (see Appendix) displays screen snapshots of the different operational steps of the Polymer Emulator: initiation and parameter selection (Figure 2, left) and force-extension curve emulation (Figure 2, right).

Before performing the 'Rubber Emulator' experiment, students are provided a summary of network elasticity, including a discussion of the challenges of the original statistical model of network elasticity. Following the experiment, students are required to write a report summarizing and interpreting their findings in analogy of a regular laboratory experiment. This includes the interpretation of the observed effect of parameter changes (such as crosslink density, solvent swelling ratio, temperature) and the comparison with theoretical predictions. Students are also asked to replot the data obtained from the Polymer Emulator, to compare the results with predictions based on the theory learned in class and to discuss the impact of molecular parameters on the validity of the statistical network elasticity model.

The Polymer Emulator has been installed in Undergraduate Research Laboratories in the home departments of the principal investigators. The original plan was to implement the Polymer Emulator in the module on 'Network Polymers' that is being taught as part of the Colloids, Polymers and Surfaces Laboratory class (06-802/39-802) that is offered in the Spring 2020. Due to recent events and University closure, a testing of the device in class was not possible. We plan to implement the device as part of the next occurrence of the class in the Spring 2021 semester.

Assessment of Impact on Learning Outcomes The authors are working with assessment experts at the Eberly Teaching Center to devise rubrics for assessing the impact of the Polymer Emulator on student learning. Preliminary assessment of the impact of the Polymer Emulator on the students understanding of the concepts of rubber elasticity will be performed by using both direct and indirect methods. First, quiz questions will evaluate student's understanding of the role of physical parameter variation on the properties of network polymers. The quiz questions will build on questions that are currently being provided to students of 06-802. Comparison of student responses to those in previous years will allow at least a semi-quantitative analysis of trends. Example questions are

(1) How does the value of the modulus for un-swollen rubber which you obtained from the tensile data compare with the ones you calculated from the crosslink density determined by swelling? Which is in better agreement? Discuss your answer.

(2) Hooke's law predicts that graph 1 should be a straight line. How do you account for the deviation from the law shown by rubber?

(3) What change would you make in the apparatus if you wished to measure the modulus G by tensile tests of swollen specimens?

(4) How could you increase the modulus of a rubber?

In addition to direct assessment of student performance we will administer surveys among student to inquire about their perceived level of confidence to explain to their peers the physical driving forces that underlie elastic responses in polymer networks.

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Appendix: Figures 1 and 2.

Figure 1. Operation of the Novint Falcon® based Rubber Emulator.

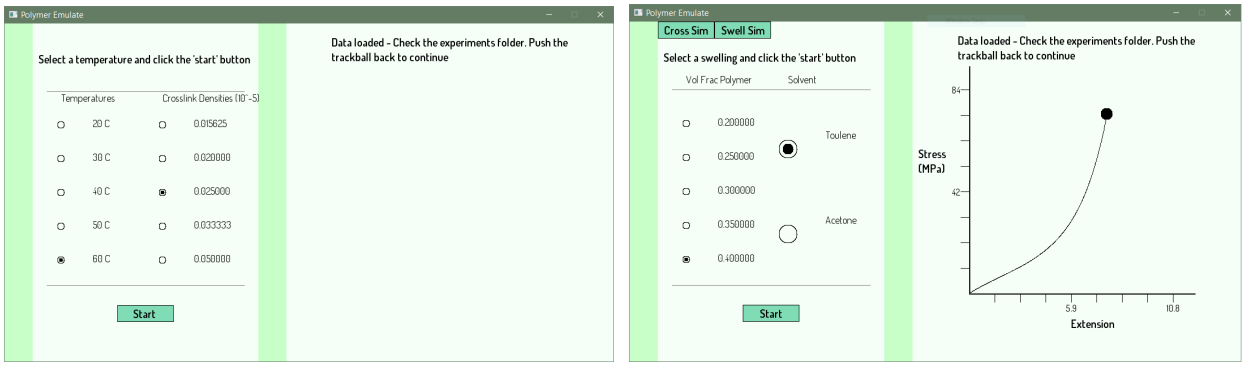

Figure 2. (left) Screenshot displaying initiation screen. The temperature and crosslink density of the rubber is defined. (right) Interface for exploration of the effect of solvent swelling on the elasticity of a rubber. Image on the right is normalized force (stress) extension diagram. Output data is scaled to be consistent with the stress-strain behavior of typical natural rubber.