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Board 252: Developing Optical Laboratories for Teaching Engineering and Physics

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Developing optical laboratories for teaching engineering and physics

Introduction

Project-based learning (PjBL) is an excellent framework for undergraduate engineering education, as it provides benefits to learners from different learning styles while building communication and critical thinking skills [1]. A recent study with high school students found that PjBL was especially beneficial to the lowest-performing students, enabling them to improve their mathematics test scores more than middle- and high-achieving students [2]. At the same time, PjBL places additional burdens on instructors, lab spaces, and departmental budgets, particularly when a hardware component is involved. To aid in the deployment of PjBL at our university and others with similar interests, we are developing a series of optical tools and laboratories that can be easily implemented for low cost, in small spaces, and without dedicated infrastructure such as vibration-free optical tables. To date, we have reported on a schlieren imaging system for convective flows using a smart phone as the light source and imager [3]; a simple laser communication system using two lasers and a LabVIEW^{TM} script [4]; and a digital holography apparatus capable of imaging the deformation of a loaded mechanical beam [4]. In this work, we are providing updates to the digital holography technique, specifically regarding different types of motions (deformation, rotation, and torsion) and boundary conditions (supported vs. clamped), and are introducing a new tool for teaching principles of feedback control, namely a diode laser with optical detector capable of producing a constant optical power when provided with an appropriate feedback signal. Below, we describe these systems and how they will be implemented at small, private, liberal arts college with a combined physics and engineering department. Typical class sizes for teaching with these optical tools are 18-28 students. The tools are designed for teaching upper-division mechanical engineering, electrical engineering, applied physics, and physics majors.

Methods and Results

First, we describe additional investigations into the digital holography apparatus. The layout of the system is shown in Figure 1. Holograms acquired by the camera are processed in a MATLAB^{TM} script. Comparing holograms without and with a force load applied to the metal beam reveals interference fringes as shown in Figure 2. This lab was taught in Spring 2022 to approximately 25 students in a mechanical measurements course for juniors and seniors in mechanical engineering. Typically, this content would be taught alongside strain gauges, which represent a more traditional measurement of mechanical strain. In our course, strain gauges were introduced theoretically only due to a lack of supply. Students were tasked with acquiring holograms of different metals (aluminum, steel, brass) and under different point loads (ranging from 10s to 100s of grams). By counting the number and location of fringes, much like reading a contour or topography map, students could then plot out the deformation along the position of the beam, assuming there was no deformation at the boundary. After analyzing the data, the Young’s modulus of the metal samples could be determined; typically, this was accurate to within about 25-50%. We found that the clamping force, which was provided by a small thumb screw, was inadequate to assume a perfectly rigid clamped boundary condition and that the actual deformation was somewhere between the limiting cases of simply supported and perfectly clamped. Following the lab, students were asked to reflect on their experience and to answer some qualitative questions about the system. Students reported excitement at the extreme precision of the optical technique, but also some frustration that they were not able to reproduce the Young's modulus exactly.

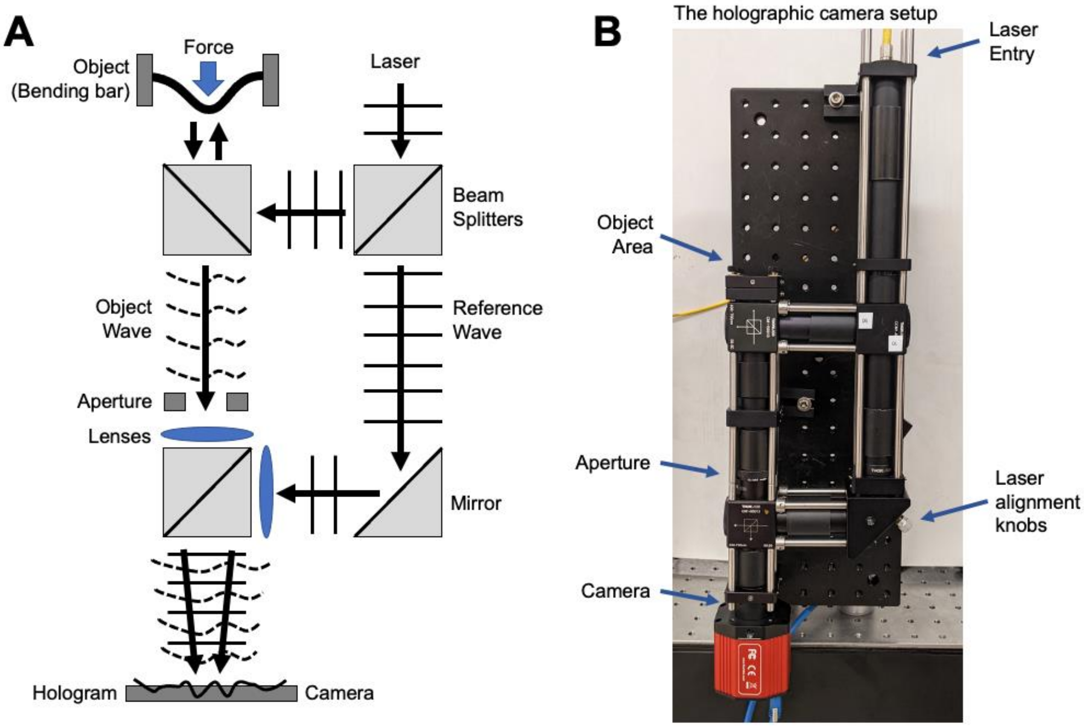

Figure 1: diagram (A) and photo (B) of the holography apparatus.

After successfully teaching this lab for the first time, we wanted to further investigate the system's sensitivity to torsions and rotations. A few different experiments were tried and are summarized here. First, as shown in the middle panel of Figure 2, we introduced only a vertical rotation of the metal beam by clamping it in the middle and applying a point load to the end. Rotation is not something a strain gauge can sense, since it uses the deformation of a metal foil to generate its signal (namely, a changed electrical resistance). In this setup, the small rotation is readily determined, and produces evenly spaced and perfectly vertical fringes. With 4 fringes across the 10 mm of beam in the viewing area, the rotation is on the order of 100 µrad and is easily resolved. Note that both a deformation and a rotation can be induced simultaneously, and they can be distinguished in the data, since the rotation produces a linear fringe spacing, whereas the strain would be quadratic or cubic as a function of position. Second, as shown in the bottom panel of Figure 2, we introduced torsion by applying the point load away from the center of the beam, and by having one side clamped and one side simply supported. Note that the fringes represent equal elevations (or, equivalently, equal distances from the camera). The sensitivity to torsion adds another interesting feature to this lab; however, it may be simpler to remove that sensitivity when using the lab to teach about mechanical measurements. To remove the possibility of torsion, it would be necessary to increase the clamping forces and to ensure excellent centering of the point load. We will investigate those upgrades in the coming year.

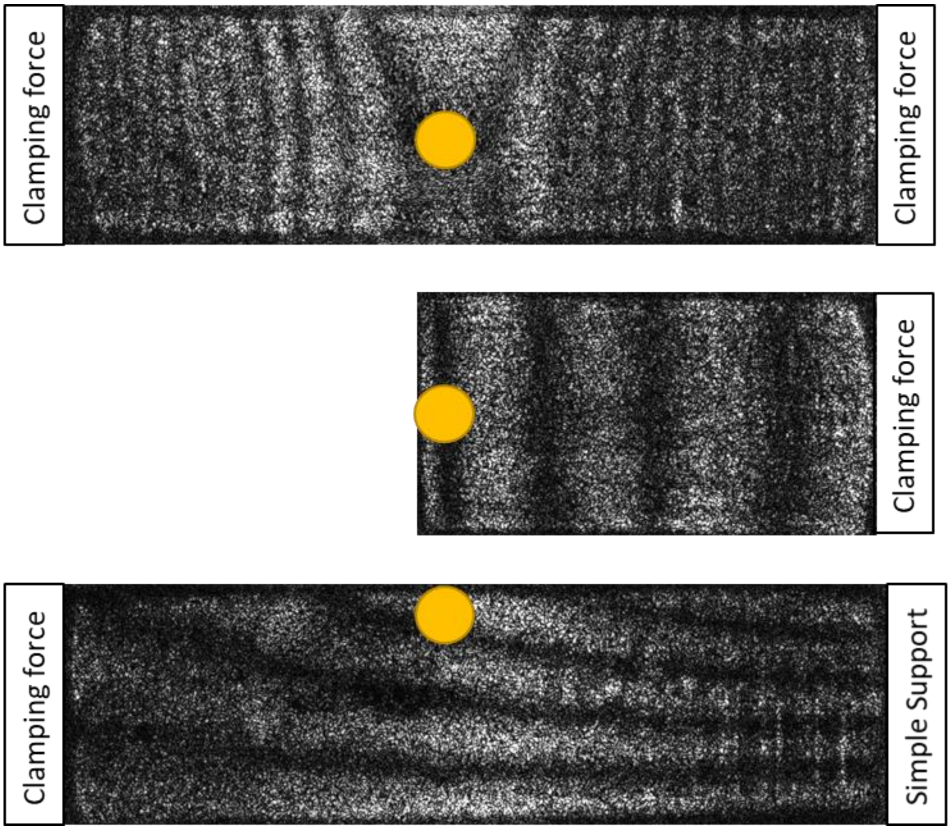

Figure 2: Sample holograms. The yellow dot provides the location of the point load. Each bright-dark fringe pair indicates a displacement of 316 nm. The metal beam in each case is aluminum (6 mm x 25 mm). In the top panel, the beam is clamped on both ends, inducing deformation through the Young's modulus; however, fringes are not perfectly vertical, indicating torsion may also be present. In the middle panel, the beam is slid over to the right and clamped in its center; the point load then induces a rotation rather than a deformation, and the fringes are observed to be equally spaced and vertical. In the bottom panel, a torsion was intentionally introduced by only clamping the beam at the right, and applying an off-center point load.

Second, we will describe the construction and upcoming implementation of a new lab system for a feedback control course. The purpose of this apparatus is to build a full feedback control system including the "plant" (a diode laser's optical power), the sensor (a photodiode onto which the laser beam impinges), the controller (either a digital or analog feedback loop servo), and feedback mechanism (varying the current that drives the diode laser). To keep the cost of producing the apparatus low, we utilize 3D printing as much as possible, and build (rather than purchase) the circuitry, which has led to a prototype printed circuit board. The current system is shown in Figure 3.

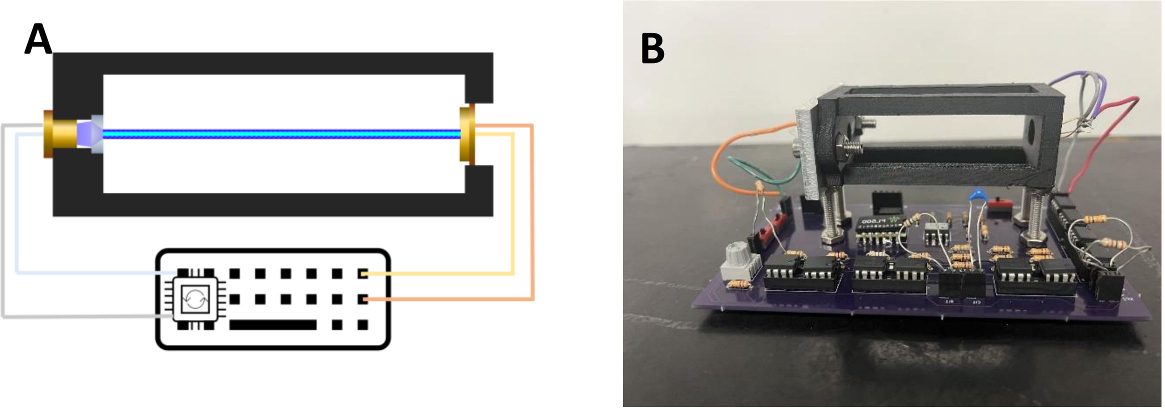

Figure 3. (A): Schematic of the laser power feedback system. The blue laser leaves the laser diode and passes through a lens to collimate it into a beam. The beam propagates a distance and strikes a photodiode, generating a signal that can be read by the electrical control unit, which then adjusts the laser power by changing the drive current, so as to produce a constant signal on the photodiode. (B): Photo of the apparatus. A printed circuit board with screw holes provides the base of the system and houses all electronic components. Screws rise up to attach to a 3D-printed mount (black cage), which on one end (right side) houses the laser diode, and on the other (left side) the photodiode. An aluminum plate sits behind the laser diode to help with heat spreading and dissipation. A lens sits in front of the laser diode to collimate the light. A polarizing filter can be held anywhere between the photodiode and laser diode to drastically change the signal on the photodiode, simulating a step change in the system and allowing the measurement of its impulse response function.

For the laser diode, we selected a blue light source, though the system functions with any color and either polarity of laser diode within a 3-12 V supply range. The photodiode was selected because it has a large area and low cost. A lens collimates the laser diode to produce a pencil-like beam, and for cost reduction a plastic molded lens (as opposed to glass) was chosen. All of the electronic chips used in the feedback circuitry are standard op-amps with the exception of the current driver, which was purchased from Wavelength Electronics (FL500) for approximately $50 per unit. Overall, the cost of each setup is between $100 and $150. We are in the process of preparing a parts list and suite of all files (include 3D printer, printed circuit board, and CNC mill for the aluminum heat spreader) to share with the community.

In spring 2023, students will use this setup as follows. First, they will turn it on and observe the physical layout. Second, they will design a feedback circuit of a prescribed type that stabilizes the laser power. Practically, this means wiring up between two and four op-amps (provided on the printed circuit board, but not connected to the feedback chain without external wiring) and choosing resistor values to set the gain coefficients for the type of feedback circuit prescribed. Throughout the semester, different types (i.e. proportional-integral, proportional-derivative, leadlag, etc.) of feedback will be taught, and the students will use this system to implement that type. The students will also have a more traditional (i.e. servo motor) control lab apparatus to use, but because the servo motor actually uses digital controls, it is expected that the analog feedback to the laser will better match the Laplace-transform-based theory the students will be learning. There will be opportunities for investigators to study the learning process by looking at quizzes and lab reports related to both the servo motor and the laser power feedback apparatus.

Conclusions

We preparing a suite of optical tools to share with the community for implemented as guided labs and projects for teaching engineering. Emphases of this effort include simplicity, low cost and 3D printed apparatus wherever possible, and the opportunity for students to explore something outside of the traditional lab curriculum.

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