Dynamic Balancing System with 3D-Printed Components

Dr. James J. Scire Jr., New York Institute of Technology

Dr. Scire is an Assistant Professor of Mechanical Engineering at New York Institute of Technology (NYIT). He received his bachelors degree in Mechanical Engineering from The Cooper Union for the Advancement of Science and Art, and his masters and Ph.D. degrees in Mechanical and Aerospace Engineering from Princeton University. After completing his Ph.D., Dr. Scire worked for Advanced Fuel Research, Inc., a small business in East Hartford, CT. There he developed optical diagnostics and imaging systems for the company's Combustion Monitoring and Control Group. Dr. Scire joined NYIT in 2013. His research interests include optical sensors, combustion, numerical simulation, and optimization.

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Abstract

This paper describes a project in which students designed, built, and used a small dynamic balancing machine with 3D-printed components. This project was found to be very effective in keeping its student designers engaged and invested. They immediately understood the need for balancing, and they had an opportunity to apply simple concepts from mechanical vibrations, linear algebra, and electronic circuits to complete this task. Construction details and the results of balancing a small rotor are presented.

Keywords

student projects, dynamic balancing, 3D printing

Introduction

Design projects are an important part of an engineering education. In particular, projects that extend beyond paper designs to the actual construction of a device allow students to see, firsthand, how things that they conceived actually work. The literature of engineering education therefore rightly includes numerous examples of effective design projects alongside more abstract discussions of educational practices and assessment methods.

For example, Petroski[1] devised a clever way to involve freshman engineering students in design through the design/redesign of paper clips. Using minimal resources and with minimal prerequisites, students were exposed to the compromises involved in the design of a real product[1]. In another example, Latcha and Oakley[2] describe a Capstone course where students design and construct toys or games. This course exposes students to the severe economic constraints on effective toys and gives them the opportunity to have their designs presented to industry.

Both of these project examples involve teaching practices that are recognized throughout the greater community of educators as high-impact practices[3]. Design project work, especially with construction, requires that students devote considerable time and effort to “purposeful tasks”[3]. The work requires a series of decisions that deepen students’ investment in the project[3]. Finally, the work involves frequent interaction and feedback from faculty. Each of these aspects of the project work has been found to increase retention of the lessons involved[3].

This paper describes the design, construction, and use of a dynamic balancing system made primarily from 3D-printed components. The author found that, like the examples above, this project was very effective in keeping its student designers engaged and invested, for a number of reasons. First, since rotating machines are ubiquitous, students are likely to have an intuitive feel for balance and imbalance. Cell phones vibrate by rotating an unbalanced mass. Students working with rotating machines quickly recognize that balancing is often necessary. In fact, this

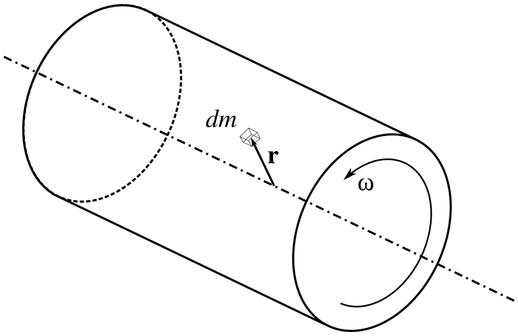

Figure 1: Rigid rotor with notation for balancing discussion.

project was undertaken in order to balance a small, high-speed rotor that the students were developing with the author as part of a separate research project.

A second reason for the effectiveness of this project is that balancing involves a number of relatively simple and understandable concepts and technologies to which the students have already been exposed. Here, students applied their knowledge of mechanical vibrations, linear algebra, electronic circuits, and data acquisition techniques to develop a capable balancing system and its associated software.

Finally, a third reason for the project's effectiveness is that balancing is an inherently satisfying activity. After carefully machining and assembling the high-speed rotor mentioned above, the author and his students found an alarming degree of imbalance when the rotor was spun up. The detour to build the balancing system was taken reluctantly. However, the first time the small corrective test masses were taped to the rotor and it spun up smoothly, we could all see and feel that this was a worthwhile endeavor.

This work was made possible by the availability of low-cost 3D printers. The author previously described his experiences in using 3D printing to involve undergraduates in the design of optical instruments[4], and that work led to an additional publication[5] with the student researchers. Manufacturing by 3D printing allows designs to be quickly implemented with minimal resources, thereby increasing engagement.

Balancing

Balancing of rotating machinery is a well established practice and there are many texts covering the practice in detail[6,7]. Here we briefly describe the problem to fix notation. We consider the balancing of rigid rotor. Following the notation shown in Figure 1, we denote an element of mass in the rotor by dm and the vector measuring the displacement of the mass from the axis of rotation by $\mathbf{r}$. We assume a constant angular velocity given by ω. Since the rotor is assumed to be rigid, the mass traces a circular path. The centripetal acceleration is given by $r\omega^2$. The rotor therefore provides an inward force to maintain the mass on its circular path. The reaction force on the rotor is

$$d\mathbf{F} = \mathbf{r}\omega^2\, dm \tag{1}$$

Integrating over all of the mass in the rotor gives the net instantaneous force vector that must be borne due to imbalance. In addition, distribution of the force along the axis of rotation may lead to moments perpendicular to the axis. For a perfectly symmetrical and uniform rotor, the force and moment would be zero. In practice, eccentricity from machining tolerances and material variations lead to imbalances that must be corrected if the resulting force or moment is unacceptable for the application. From the squared angular velocity in equation (1) it is clear that balancing becomes more important for higher rotational speeds.

Balancing is accomplished by removing or adding mass to reduce the imbalance in the rotor (the quantity mr for the correction is called the *unbalance*). A simple approach to eliminating the *net force* due to imbalance is to add or remove mass to move the center of mass of the rotor closer to the axis of rotation. This can be accomplished statically – if the imbalance is sufficient to overcome friction, a horizontal rotor will turn until its center of mass sits directly below the axis of rotation. This approach does not, however, give any guidance on how to eliminate any couples that are produced when the shaft is rotated. That is, two identical masses reflected through the center of mass do not alter this center but do produce a moment when the rotor rotates if they are at different axial positions. To eliminate these couples the rotor must be balanced dynamically.

In a dynamic balancing system, measurements are taken during rotation to determine what corrections must be made to eliminate both the imbalance force and moment. Generally, corrections must be made at two separate planes along the axis of the rotor. Masses added off axis at either plane could correct the force, but adding appropriate masses in two separate planes also allows any moment perpendicular to the axis to be canceled.

The system developed in this work is a soft-bearing balancing machine. In these machines, the rotor is run in a suspension that allows it to move when it has any imbalance. Measurements of the movement are then used to determine the appropriate correction for the imbalance. In another type of balancing machine, called a hard-bearing machine, the mounting is relatively stiff and forces transmitted through the mounting are used to determine the appropriate correction.

As mentioned above, the balancing of rotating machinery is a regular and necessary practice throughout industry. There are commercial balancing machines available to handle systems over a range of sizes from the very small to the very large (including the tiny turbines in dental drills). These balancing machines are a welcome and useful addition to student laboratories at engineering schools. That being said, the author believes that it is usually more useful for students to see how a particular machine or device is put together than to simply learn how to use it. Often, however, it simply takes too much time to go this route. For a small dynamic-balancing machine, this work shows that students can rapidly design and construct such a system. The balancing system developed in this work is now described.

Student-Developed Balancing Machine

A photograph of the balancing system is shown in Figure 2. The soft-bearing suspension consists of a rotor platform mounted on four flexible columns. The rotor/bearing assembly (not shown) is securely bolted to the platform through holes near its center. The rotor axis runs above the platform, centered between the mounting holes and parallel to the leftmost edge of the platform as seen in the figure. The flexible columns, platform, and base form a flexure that allows the platform to shift and twist horizontally but restricts vertical movement. These components are

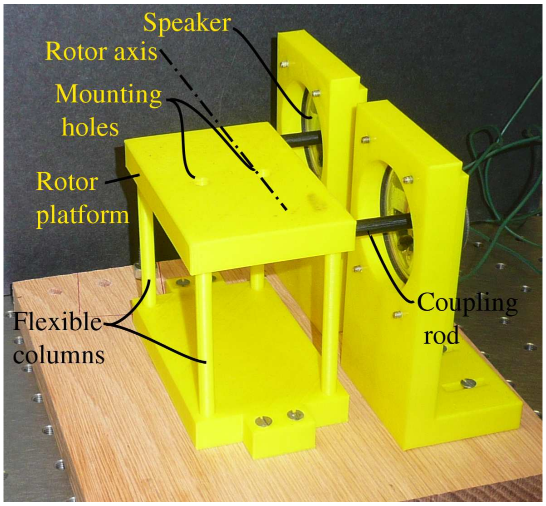

Figure 2: Balancing System.

made of (yellow) ABS plastic that has been 3D printed using a Makerbot Replicator 2X printer. The columns and platform are printed as a single piece, while the base is a separate part into which the columns are press-fit.

The flexure assembly can by readily modified to accommodate different types of rotors. The rotor for which this version was developed consists of a 4 in-diameter flywheel and an air turbine, mounted together on a 3.5 in-long shaft. The rotor assembly was balanced in its own mount, which has a 3.5 in-by-2 in footprint.

The motion of the platform is measured by attaching it to a pair of 2.25 in-diameter speakers. Each speaker is attached to the edge of the platform adjacent to one of the flexible columns. The attachment is made using a 3D-printed coupling rod that is attached to the platform on one end and to the center of the speaker cone on the other end. The speakers themselves therefore add additional resistance to the motion of the platform as they deflect.

The speakers are each mounted in a 3D-printed bracket. The two speaker brackets and the rotor flexure are secured to a wooden base that is clamped to a heavy table during use.

The two speakers measure the combined in-plane linear and rotational motion of the rotor platform. In addition, a tachometer (once-per-revolution) signal is needed from the rotor. The tachometer signal was obtained optically. A diode laser was reflected from the edge of the flywheel and detected using a photodiode. A stripe was added to vary the reflectivity and thereby mark the zero-angle location in the tachometer signal. The laser and detector were mounted together in another 3D-printed bracket that was mounted to the wooden base.

Each speaker signal is amplified and then filtered to prevent aliasing. The tachometer signal is also amplified and filtered. All circuitry was constructed on a solderless breadboard. The three signals are digitized at 8192 Hz using a National Instruments USB-9215A 16-bit data acquisition module that we had available. This module is the most expensive part of the balancer, but given the modest performance demands here it could be replaced with a less expensive model.

The tachometer signal is used to help extract magnitude and phase signals from the two speakers at the current rotational frequency of the rotor. One-second chunks of data from each channel are apodized with a Hamming window and then padded with zeros out to four seconds. This padding gives interpolated signals in the frequency domain, thereby making it easier to extract the signals at the rotor frequency. The rotor frequency is determined from its frequency domain signal and the corresponding frequency components for each of the speakers are determined. The phase for each speaker is calculated relative to the recorded tachometer phase.

Balancing Procedure

The rotor tested here includes an air turbine, so the rotor was driven using compressed air directed downward against the turbine blades. The rotor was spun up to about 3500 rpm and then allowed to spin down freely for the balancing measurements. Data were collected between 2500 rpm and 1000 rpm. The balancing calculations were performed near 1750 rpm.

The mass corrections could be made most easily on the flywheel and on a retaining collar at the opposite end of the shaft. To calibrate the system, data were recorded first for the unbalanced rotor, second with a test mass on the flywheel, and third with a test mass on the retaining collar. The locations of the masses, in radius and angle relative to the tachometer stripe, were carefully measured using paper strips to transfer measurements from the rotor to a caliper. Masses were determined using a small digital balance with a reported accuracy of $\pm 5\,\mathrm{mg}$.

The calibration is calculated by assuming that the complex speaker voltages (with magnitude and phase) are linear combinations of the complex unbalance in each of the planes. Subtracting the unbalanced-rotor results from the two test-mass cases, we find a complex two-by-two matrix representing the calibration. Then, the matrix is used with the unbalanced-rotor results to solve for the unbalance for that case. The complex unbalance gives us the angle and the mr product for the mass that we need to cancel in each plane.

Results

Figure 3 shows the magnitude of the two speaker signals (simply labeled A and B) at the rotor speed before and after balancing. The initial curves show strong resonances associated with the soft-bearing mount at 1250 rpm and beyond 2500 rpm. The test point at 1750 rpm, between the two resonances, shows significant vibration in both speakers, with the two magnitudes about equal. After balancing, the signal at speaker A has been reduced by a factor of 34 and the signal at speaker B has been reduced by a factor of 18.

Conclusions and Future Work

This work demonstrates that the design and construction of a small balancing machine makes an excellent project to engage undergraduate engineering students while also producing a fully functional and useful instrument. Furthermore, the project could be extended by asking the students to optimize the soft-bearing design to move resonances by employing computational tools such as finite-element analysis.

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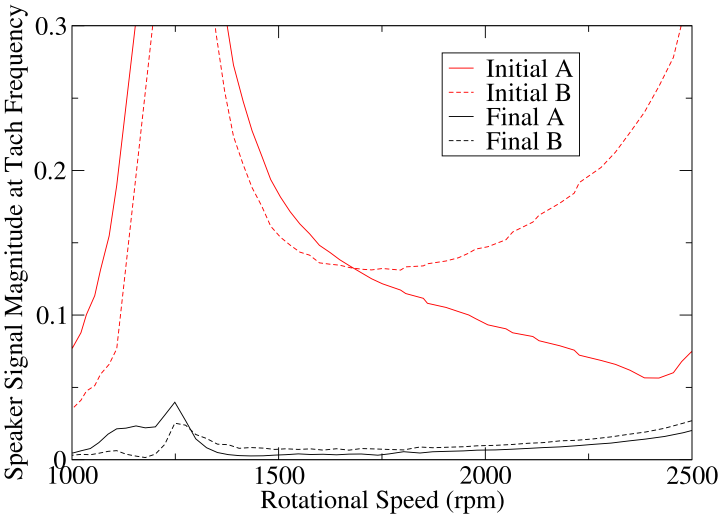

Figure 3: Signal magnitude (uncalibrated units) for speakers A and B before and after the rotor was balanced.

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