Vibrations and Control Lab Equipment Design

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Abstract

Take home lab equipment and hands-on learning tools are still in demand for control theory and vibrations courses. The existing equipment are extremely expensive and require wide lab space. The aim of this research is to build mechanical and electrical systems that are compact, modular and small scale so that each student can work on their setup and take it home if necessary. For this purpose, in this study, we designed several mechanisms to be utilized in systems control and vibrations courses which would enhance the understanding of students by using experimental demonstration of the theoretical systems taught in class. The superiority of the designs over commercially available equipment are their low cost and simplicity. The designs include modeling a crank attached to a stepper motor, and a dual parallel arm mechanism consist of flexible links that are driven by a dwell typed cam. The mechanisms are designed in Solidworks and the prototypes are built using 3D printer and machining. The mathematical models of each systems are obtained using Euler's equations. The simulations are performed using Matlab Simulink and Simmechanics. The prototypes are made available to vibrations and control lab students and their feedback will be collected through a survey and the mechanisms will be modified based on their suggestions.

Keywords

Vibrations and control lab equipment, design

Introduction

Students who pursue an undergraduate degree in engineering learn lumped parameter modeling and analysis of single degree and two degrees of freedom mechanical, electrical and multi energy systems in dynamics, vibrations and control theory courses. Once a student establishes a solid foundation in dynamics which is related to the motion of rigid bodies under external forces, the latter courses such as machine dynamics, vibrations and control theory provide thorough understanding to more complex real-life applications. However, the laboratory components for these courses is often limited as the equipment are expensive, few in numbers and bulky. Furthermore, the labs associated with the courses are taken at different semesters, making the transition from concepts learned during lectures to real world application difficult. In many cases matching concepts from lecture to experiments are difficult since there are usually only a few lab setups for each experiment due to the propriety nature of the equipment. While increased time in the lab is preferred, students taking these upper level courses may not have time for laboratory session due to time commitment in work or other classes.

The objective of this study is to design a take home lab equipment for the system dynamics, vibrations and control design classroom. The design limitation is to build mechanical and electrical systems that are compact, modular, and small scale so that a student can work on their setup and take it home if necessary.

The price of translational and rotational turnkey apparatuses commonly used in labs vary between $5000 to $18000. For this reason, affordable and portable control lab kit design is still popular. Reck et all. developed a low cost ($150) Raspberry Pi controlled motors and sensors in replacement of an existing equipment cost about $15000[1]. Grosch et all. designed a low cost lab kit consisting of DC motor, driver, microcontroller, and embedded software using an open Application Programming Interface (API)[2]. Feedback control demonstration with motorized pendulum complete with circuit board to control the motor is investigated by Enikov and Giampiero[3]. Leva and Shiavo utilized LEGO components in tandem with motors and analog electronic components to build a lab kit[4]. The novelty of the proposed designs in this paper are their simplicity, single piece production using 3D printing and consisting flexible members.

Mechanism Designs and Implementation

Three mechanisms which would enhance students' comprehension by using experimental demonstration of the theoretical systems are proposed. The superiority of the three designs are their simplicity by means of their assembly and reduced cost compared to their commercially available counterparts.

The first design is an electromechanical system as shown in Figure 1. Quanser servo motors are commonly used to demonstrate and study the modeling of a motor and a crank link along with the position and speed control mostly in control theory labs. Although these motors are robust and give students a better understanding of the effects of the controller coefficients and modeling, they are expensive. We designed a very simple and cost-effective mechanism which consists of a step motor, driver, crank and a pencil gripper to study the position of the pencil tip. In this mechanism, the crank and the pencil gripper parts are 3D printed.

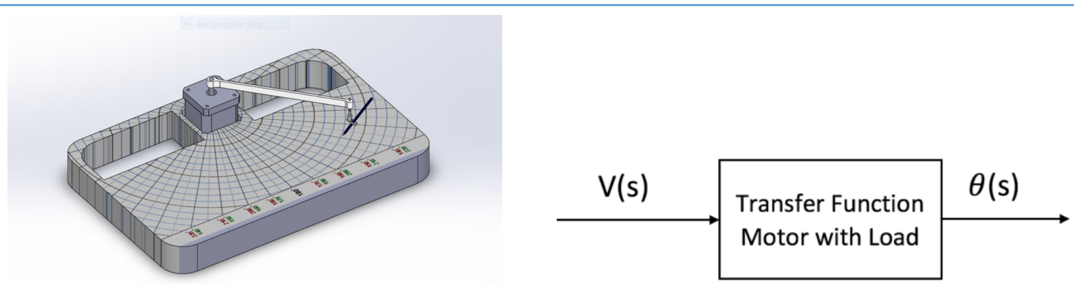


Figure 1. Step motor with a pencil holder (left) and open loop system block diagram

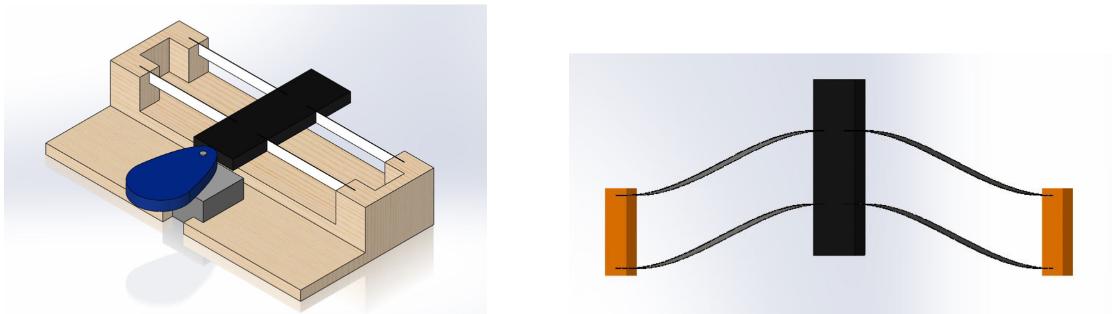
For this lab, students are asked to create input-output model of the motor in Matlab Simulink as in Fig. 1b using the below equation:

$$\frac{\theta(s)}{V(s)} = \frac{k_m}{(J_{eq}s^2+C_{eq}s+k_{eq})(R+Ls)} \quad \text{(Eq.1)}$$

where θ is the crank angle, V is the input voltage, k_m is the motor constant, R is the resistance of the coils, L is the inductance of the coils, J_{eq}, C_{eq} and k_{eq} are the equivalent inertia, damping and stiffness of the motor respectively[5,6]. The motor parameters are obtained from manufacturer's user manual. The equivalent inertia of the model is the sum of the inertia of the motor and the crank. Since the crank is 3D printed, the material, density and dimensions are all known values so that the inertia can be easily calculated or can be provided by the instructor. As an input voltage supplied to the stepper motor, the crank together with the pencil holder will start rotating. Students attain the angular displacement since the pencil tip draws arcs on the grid paper as crank rotates. Matlab Simulink model output and the actual angular displacement from the experimental system can be compared to validate the mathematical model. With this lab, students will have the ability to model an electromechanical system using the motor parameters in Matlab Simulink, and compare the experimental and theoretical outputs.

The second mechanism is a flexible double arm translational system which consists of 4 flexible links attached to a sliding mass as seen in Figure 2. This mechanism can be thought of a replacement to a traditional slider crank mechanism. The translational double arm mechanism is designed to study vibration analysis and finding equivalent mass-spring-damper models that's

been taught in Machine Dynamics and Vibrations class. A dual arm design helps the slider only slide back and forth along the horizontal axis.
The objective of this lab is finding the equivalent mass spring damper model of the system. As seen from Fig. 2, although this mechanism does not literally have springs, the flexible members act like springs when loaded. As the crank rotates, the fixed-fixed flexible links deflect (Fig. 2b) letting the slider move forward and backward.



(a) (b)

Figure 2. (a) Flexible double arm as alternative to rigid slider crank mechanism, (b) The deflected configuration of the flexible beams

If an accelerometer is attached to the mass, and a load sensor is placed between the cam and the slider, and both sensors are connected to the external data acquisition card (DAQ) with connecting cables, the acceleration and the force data can be recorded either using LabVIEW or Matlab. First, students are requested to find the natural frequency of the system by replacing the slider forward by hand without applying any external force and then releasing. The students can read the natural frequency of the system from the power spectrum of the acceleration data that is related to the mass and the equivalent stiffness. Since the mass is already known, the equivalent stiffness can be calculated. In order to find the damping of the system, the position vs time is plotted by integrating the acceleration data in time domain, or by simply dividing the acceleration by the negative of the square of the natural frequency in frequency domain[2]. The damping ratio can be obtained by utilizing the logarithmic decrement calculated from position vs time graph[7]. Using the calculated parameters, the transfer function of the system can be written as in Eq. 2.

$$\frac{X(s)}{F(s)} = \frac{1/m}{s^2+\frac{c}{m}s+k/m} \qquad \text{(Eq.2)}$$

where X is the displacement, F is the force, m is the mass, c is the damping and k is the stiffness. Students will create Matlab Simulink model of the system first by giving it an initial position to compare the natural frequency and then applying the same force data from force sensor to compare the position data from simulation model and the experimental data.

Conclusion

Two small scale, low cost and simple mechanical systems are designed to be utilized in machine dynamics, vibrations and control theory courses. The mathematical model of each system and Matlab Simulink model are obtained and experimental results are compared with the theoretical analysis. These two implementations help students apply the theories they learned in the courses.

References

1 Reck, Rebecca M., and Ramavarapu S. Sreenivas. “Developing a New Affordable DC Motor LaboratoryKit for an Existing Undergraduate Controls Course.” *2015 American Control Conference (ACC)*, 2015, doi:10.1109/acc.2015.7171159.
2 Grosch, Theodore, and Hai Ho. “Low Cost Motor Control Systems Laboratory Kit for Distance Learning Courses.” *2016 International Conference on Computational Science and Computational Intelligence (CSCI)*, 2016, doi:10.1109/csci.2016.0074.
3 Enikov, Eniko T., and Giampiero Campa. “Mechatronic Aeropendulum: Demonstration of Linear and Nonlinear Feedback Control Principles With MATLAB/Simulink Real-Time Windows Target.” *IEEE Transactions on Education*, vol. 55, no. 4, 2012, pp. 538–545., doi:10.1109/te.2012.2195496.
4 Leva, Alberto, and Francesco Schiavo. “Low-Cost Flexible Speed Control Experiments.” *IFAC Proceedings Volumes*, vol. 38, no. 1, 2005, pp. 37–42., doi:10.3182/20050703-6-cz-1902.02279.
5 Morar, Alexandru. "Stepper motor model for dynamic simulation." *Acta Electrotehnica* 44.2 (2003): 117-122.
6 Meirovitch, Leonard. *Methods of analytical dynamics*. Courier Corporation, 2010.
7 Wahab, Dr Magd Abdel. *Dynamics and vibration*. John Wiley & sons Ltd, 2008