AC 2010-1762: SYSTEM DYNAMICS AND CONTROL TAKE-HOME EXPERIMENTS

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System Dynamics and Control Take-Home Experiments

Abstract

Most Mechanical Engineering curricula include courses in system dynamics, controls, mechatronics, and vibrations. At most schools, these courses do not have a laboratory component. Even at schools that have such a component, laboratory access is often limited, and thus there is a need to increase students' laboratory experience. This paper addresses the development of instructional material in the form of take-home software and hardware kits that can be used to perform laboratory experiments and measurements at home to illustrate system dynamics and control concepts. Rather than having students perform an experiment in the university laboratory, the students are given a compact, low cost software and hardware kit with which they can perform an experiment at home using only their PC. The kits are designed so that the experiments can be conducted on the provided experimental apparatus. The take-home kit consists of three components. The first is a hardware interface board that is built around a PIC18F4550 microcontroller which interfaces with the student's PC and with the experiment hardware. The second component is a Windows-based user interface program that is loaded on the student's PC and is used to run the experiment and collect data. The third component is the actual experimental setup or the sensor system to perform the measurement. Four experimental setups have been developed. These are a DC motor/tachometer system, a heater/temperature sensor system, a vibrating cantilever beam, and a temperature measurement system. The paper focuses on two of these experimental setups and their testing in two different undergraduate mechanical engineering courses.

Introduction

Providing engaging laboratory experience is one of several challenges to effective undergraduate education in STEM disciplines as reported by The National Research Council (NRC) [1]. There is also need for more laboratory experience in system dynamics and control courses. To make the teaching of dynamic systems concepts more engaging and interesting to students, we have developed take-home software and hardware kits that can be used to perform laboratory experiments and measurements at home. Since almost all students have home PC's (either desktops or laptops) that are suitable for take-home experiments, this makes it possible for students to perform an experiment or obtain measurements outside the lab at their own convenient time, as they would with a homework assignment. Rather than having students perform an experiment in the university laboratory, the students are given a compact, low cost kit with which they can perform an experiment at home using their own PC.

Several educators have developed educational material to perform measurements and experimentation in engineering programs outside of the traditional university laboratory. Scott [2] reported on take-home experiments in fluid mechanics to illustrate basic concepts such as hydrostatics and the Bernoulli equation. Berg and Boughton [3] reported on the use of commercially available attaché cases or electronic trainers that cost in the $200 to $350 range for conducting experiments at home in lower division electronic laboratory courses. Durfee, Li and Waletzko [4] were funded by NSF to develop take home experimental setups. They developed two setups, a fourth order, linear mass spring-damper-system for frequency response and system identification, and an analog filtering system that uses music and synthetic sound as an input. Wang, Lacombe, and Rogers [5] discuss the use of the LEGO programmable brick as a portable data acquisition system to conduct personal engineering experiments at home that can be used to illustrate engineering concepts that are covered in sophomore or junior-level laboratory courses. A challenge in performing experiments at home is developing low cost experimental setups that are rugged, easy to set up and use by the students, and also at the same time produce meaningful results and opportunities for testing of theory.

Take-Home Laboratory Kit

The take-home kit consists of three components. The first component is a hardware interface board that interfaces with the student's PC and with the experiment's hardware. The second component is the User-Interface Program that is loaded on the student's PC and is used to run the experiment and collect data. The third component is the actual experimental setup or the sensor system to perform the measurement.

Hardware Interface Board

The hardware interface board houses all the components that perform measurement, actuation, control, and communication. The hardware interface board was custom-designed and was built around a PIC18F4550 microcontroller from Microchip Technology, Inc. A photo of the developed board is shown in Figure 1. The board is mounted inside a plastic enclosure with opening at both ends. The openings are designed to allow cables and connectors to be easily attached to the board.

Fig. 1 Hardware interface board

To use the hardware-interface board, the student simply connects the output of the provided 12-volt power supply adapter to the board. The student needs also to connect the serial/USB interface cable from the PC to the board, and the cable for the specific experiment to be performed. With these connections, the experimental hardware is ready. Powering the board causes the loaded program inside the microcontroller to run. The program waits for user input from the User-Interface Program.

User-Interface Program

A screen shot of the developed Windows-based User-Interface Program is shown in Fig. 2. The User-Interface Program was designed to serve as the user-interface for all the experiments that are planned to be performed in this project. The User-Interface Program was developed in Visual Basic Express 2008, and it communicates with the embedded program on the PIC18F4550 microcontroller through either a serial or USB connection. The embedded program was developed in C using PICC compiler from CCS, Inc. The User-Interface Program transfers the experiment settings to the PIC microcontroller, provides monitoring and control of the experiment progress, retrieves the data collected after the experiment is completed, and performs saving of the collected data to a file. The User-Interface Program does not perform any measurement or feedback control activities. All measurement, timing, actuation, control and data storage activities are performed by the PIC microcontroller while an experiment is running.

To use the User-Interface Program, the student first selects the *Set-Up* command to set the parameters for the particular experiment. These include the selection of the type of experiment such as temperature measurement or motor speed control, the test duration time, the sampling time to record the data, and, if applicable for the particular experiment, the feedback control parameters. Once the experimental parameters are selected, the user checks the *Setup Done* check box. This disables all the *Set-Up* menus and enables the *Start* command, which upon pressing it, the experiment starts. The experiment progress is indicated by a progress bar, but the user can abort an experiment by pressing the *Abort Test* command. When the experiment is completed, the *Save Data* is enabled, which upon pressing it allows the user to store the collected data into a file. The collected data can then be imported into plotting software such as Excel.

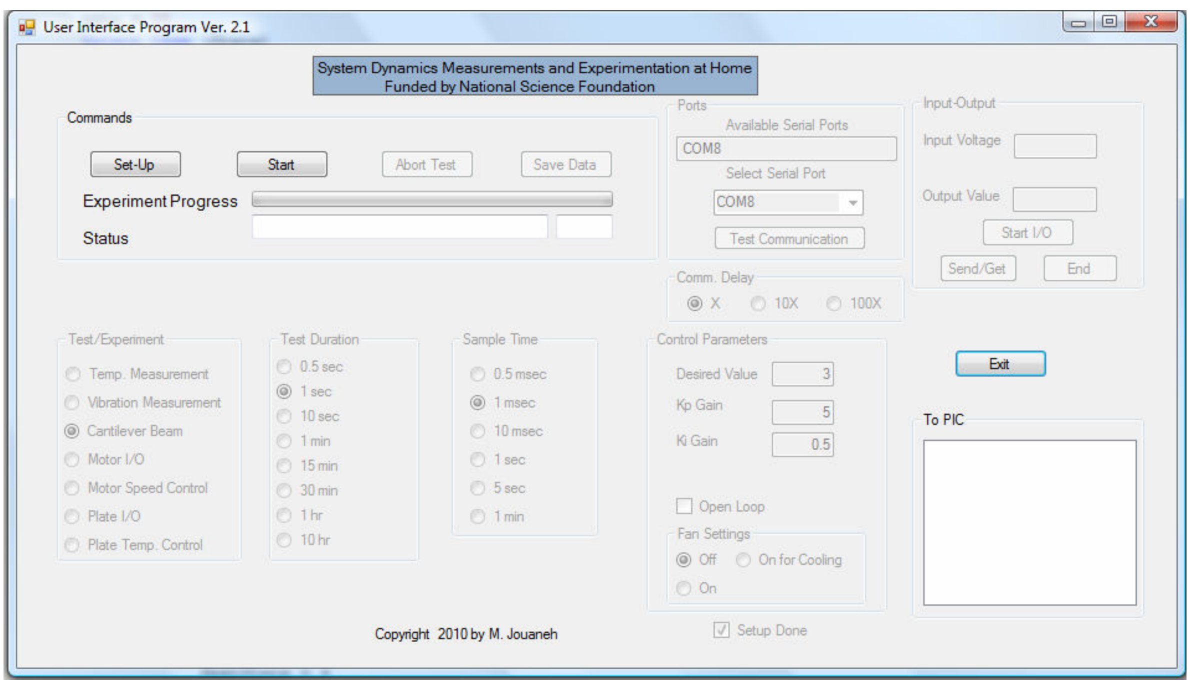

Fig. 2 A screen-shot of the User-Interface Program

Experimental Setups

In this project, we are developing four experimental setups that will be tested in various courses in the mechanical engineering curriculum at the University of Rhode Island. These are a DC motor/tachometer system, a heater/temperature sensor system, a vibrating cantilever beam, and a temperature measurement system. In this paper, we will focus on two setups that were used in the Fall 2009 semester. These are a plate with heater/temperature sensor, and a vibrating beam with accelerometer. A brief outline of the other two experimental setups is given a latter section.

Control of Plate Temperature

MCE433 Mechatronics is a senior elective in mechanical engineering. In the Fall 2009 semester the 10 students in that class used the take-home kit to perform control of the plate temperature. The students first collected data on the open loop response of the system. Then they used this data to design and test a closed-loop PI controller to control the temperature of the plate.

The Hardware The experimental hardware (see Figure 3) consists of a small rectangular (50.8 mm x 38.1 mm x 12.7 mm) copper plate heated by a 10-W flexible silicone-rubber heat strip that is glued to the bottom of the plate. The plate is mounted horizontally on a 76.2 mm x 102 mm polycarbonate base that acts an insulator. A small hole is drilled into one side of the plate, and a thermo-transistor temperature sensor (LM35C plastic package from National Semiconductor) is inserted into the plate to read to read the temperature of the plate. The temperature sensor has a sensitivity of 10 mV/°C, and a measurement range of -10 to 110 °C. A small brushless DC fan is attached to the base to provide optional cooling (not demonstrated here). The control input to the heater is supplied from the PWM output of the micro controller through the H-Bridge amplifier on the Interface Board. The temperature is measured using the 10-bit A/D converter on the micro controller. With a voltage reference of 2.5 volts for the A/D, the temperature measurement resolution is 0.244 °C. The heat output rate q from the heater is directly proportional to the heater voltage v: $q = Kv$, where K = 10/12 W/V.

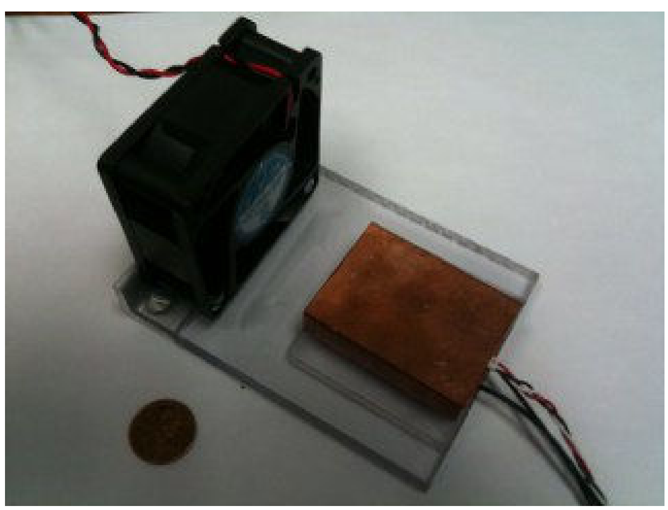

Fig. 3 Plate and heater experimental setup

The Experiment The students were asked to the following in this experiment:

a. Collect the open loop temperature response of the plate over 1 hour when subjected to two different input voltage levels such as 6 volts and 9 volts.
b. Use the open loop data to obtain a dynamic model of the heated plate.
c. Through analysis, or simulation of the model in MATLAB or Excel, select appropriate control gains to control the temperature of the plate.
d. Test the selected gains by running a closed loop control test over 30 minutes/1 hour with a desired temperature of 50 C.

The students were asked to collect two open loop response plots to check the linearity of the system and to average the parameters obtained from these two plots. Figure 4 shows the results for a test in which the heater output was 7.5 W (9v input).

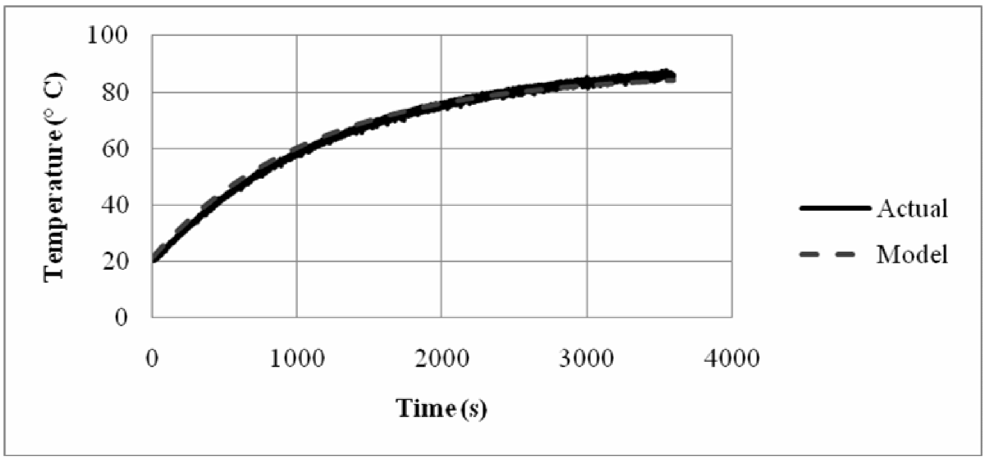

Fig. 4 Open loop response of the plate/heater system with q = 7.5 W

The Analysis A basic model of the copper plate excluding radiation effects is:

$$RC\frac{dT}{dt} = T_a - T + Rq$$

Where T = plate temperature, T_a = ambient temperature, q = heater output (W), C = thermal capacitance, and R = convective resistance.

The solution is (assuming that $T(0) = T_a$):

$$T(t) = T_a + Rq(1 - e^{-t/RC})$$

The parameter R and C can be determined experimentally from analyzing the open-loop temperature response of the plate to a given heat input. For example, using the data in Figure 4, *R* is 8.66 °C/W and the time constant τ is 1100 s. The figure also shows the solution of the model. The model agrees well enough with the data to be useful for designing the control algorithm.

The model was used to design a PI controller. The PI gains were selected to give a closed loop system with a damping ratio of $\zeta = 1$ and a desired closed-loop time constant τ_d.

The Results Since the heater voltage is limited to 12 V, if τ_d is selected too small, the heater will saturate. A Simulink model was constructed to investigate how small τ_d could be made without causing saturation. It was found that τ_d close to 550 s was the smallest possible value. Figure 5 shows the experimental results using the calculated gains (Kp = 0.40 and Ki = 4.8 x 10^{-4}) for ζ = 1 and τ_d =566 s. Obviously the agreement between the data and the model is very good.

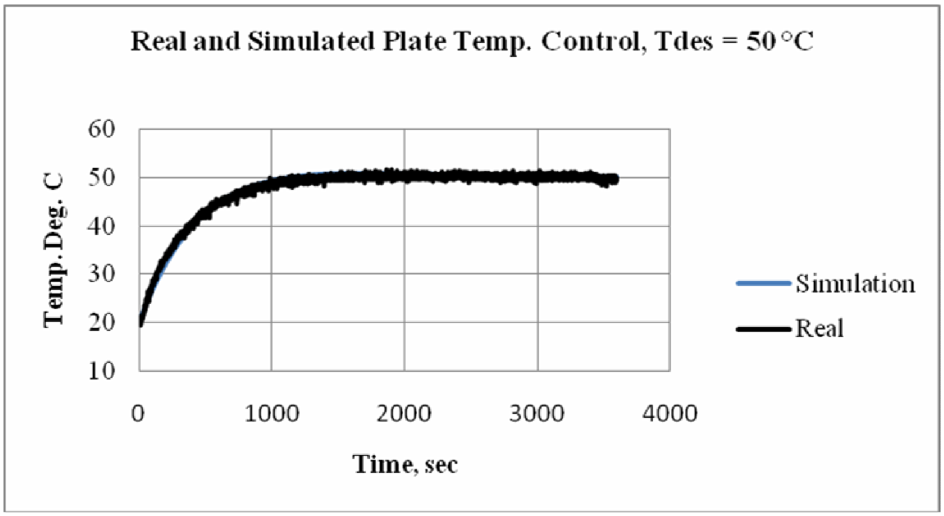

Fig. 5 Experimental and simulated data for the plate setup

The Assessment The major benefit of this experiment is that it gives the students an opportunity to conduct a control experiment on their own. They saw the effects of control gains on changing the time constant of a system.

The theory in this experiment is covered in class before the experiment is conducted, and it is rather simple. The dynamic model of the plate and heater is derived in class, and the relationship between the control gains and the performance parameters such as damping ratio and time constant were also discussed. The students were given two quizzes on this topic, one just before the experiment was given, and the other after the experiment was given. The class average on the second quiz improved by 28% indicating that the take-home experiment has helped in their understanding of the material related to this topic.

In a survey given to the class after the project report was turned in, 50% of the students answered that they were comfortable and 50% reported that they were somewhat comfortable with performing an unsupervised experiment at home. About 90% reported that the hardware was easy to set up. When asked if the experiment contributed to their learning of model development from time-dependent data, calculation of heater time constant from data, and calculation of gains for temperature control, 23% answered that it greatly contributed to their learning and 48% answered that it contributed somewhat.

Vibration of a Cantilever Beam

MCE464 Vibrations is a senior elective in mechanical engineering. In the Fall 2009 semester the 12 students in that class used the take-home kit to perform measurements on a cantilever beam. The data was used to determine the natural period of vibration of the beam and to compare the results with those predicted by beam theory.

The Hardware In addition to the basic kit components, the hardware for the vibration experiment included an accelerometer with a twisted three-wire cable, a beam made of a steel strip, and a C-clamp for fastening the steel strip to a solid surface to make a cantilever beam. We used three beam lengths, 5”, 6”, and 7” from the tip of the beam to the support.

The accelerometer (Model MMA1250KEG from Freescale Semiconductor) is silicon capacitive micromachined accelerometer. The accelerometer has a measurement range of +/- 5g and a sensitivity of about 400 mV/g. The accelerometer surface mount chip was mounted on a 23.8 mm x 16.5 mm custom-fabricated circuit board. The accelerometer circuit board is attached to the free end of the beam with double sided tape. Optionally the accelerometer wire may be taped to the beam or left free. We choose to tape the wire to the beam, thus making it part of the beam. If left free, the wire’s unmodeled dynamics could complicate the analysis. Figure 6 shows the beam setup with the attached accelerometer.

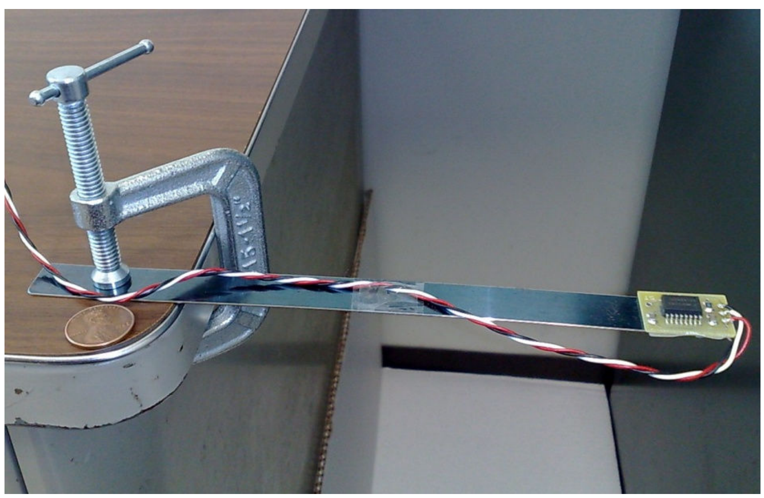

Fig. 6 Photo of the beam setup with the attached accelerometer

The Experiment After choosing a test duration of 1 s and a sample time of 10 ms, the student gently flicks the end of the beam to start it vibrating, then clicks the Start button. If the beam is flicked too hard, the displacement and thus the acceleration amplitudes will cause the accelerometer output to saturate and give meaningless data (this is due to the usable voltage range of the A/D converter).

After the run, the data is saved, imported into Excel, and plotted. The cursor can be used to select from the plot the peak times corresponding to a span of several periods. The average period is then calculated by dividing this time span by the number of cycles. This is done for each of the three beam lengths. Figure 7 shows the plotted data for the 7 inch case. The oscillations are centered about 2.625 V, which is the zero-displacement output of the A/D converter.

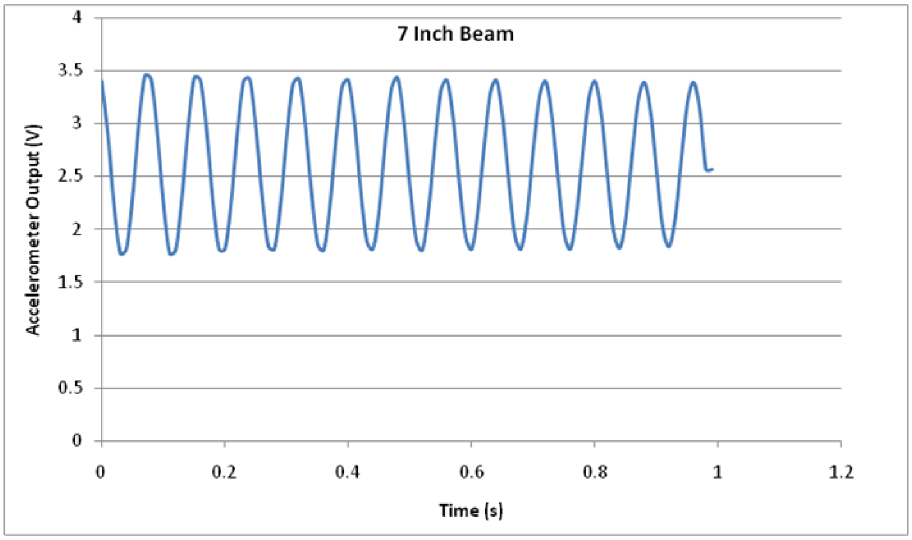

Fig. 7 Vibration data for the 7 inch beam

The Analysis From cantilever beam theory, assuming that the lowest vibration mode shape is the same as the static deflection curve, we find that the effective mass of a cantilever beam is 23% of the beam mass [6]. Since the sensor wire is taped to the beam, we also include 23% of its mass. We modeled the sensor as a mass concentrated at the tip of the beam. Thus the equivalent system mass m_e is given by:

$$m_e = 0.23(m_b + m_w) + m_s$$

where m_b is the beam mass, m_w is the sensor wire mass, and m_s is the sensor mass. The beam data is given in Table 1. The mass data is given in Table 2, and the system model formulas are given in Table 3.

Table 1. Beam Data	
Mass density (Steel), ρ	7800 kg/m^3
Young's modulus, E	2×10^{11} N/m^2
Width, w	1.59×10^{-2} m
Thickness, h	6.35×10^{-4} m

Table 2. Mass Data	
Sensor mass, m_s	1.5×10^{-3} kg
Sensor wire mass, m_w	5.9×10^{-2} L kg (L = beam length in meters)
Beam mass, m	ρwhL = 7.88×10^{-2}L kg

Table 3. System Model Formulas	
System equivalent mass, m_e	$0.23(m + m_w) + m_s$
Stiffness, k	$k = \frac{Ewh^3}{4L^3}$
Natural period, P_n	$P_n = 2\pi\sqrt{\frac{m_e}{k}}$

The Results Table 4 shows the calculations based on the theory and the measured results. In each of the three cases, the percent error was positive, which indicates that the calculated period was higher than the measured period. An explanation for this discrepancy lies in the fact that the sensor wire, when taped to the beam, added stiffness to the system. Since the stiffness k appears in the denominator of the expression for the period, an increased stiffness value would result in a smaller value for the calculated period, thus making it closer to the measured period.

Table 4. Calculations and data			
Beam lengths	L = 5 in. (0.127 m)	L = 6 in. (0.152 m)	L = 7 in. (0.178 m)
Sensor wire mass, m_w (kg)	0.0075	0.009	0.0105
Beam mass, m (kg)	0.01	0.012	0.014
System equivalent mass, m_e (kg)	0.0055	0.0063	0.0071
Stiffness, k (N/m)	99.38	57.96	36.09
Calculated period, P_c (s)	0.047	0.066	0.088
Measured period, P_m (s)	0.044	0.062	0.082
Percent error, $100(P_c - P_m)/P_c$	7 %	6%	7%

Assessment The major benefit of this experiment is that it gives the students an opportunity to conduct a vibrations experiment on their own. They saw the effects of A/D converter saturation when they flicked the beam too hard. They also saw the results of making a proper choice of a sampling time when measuring an oscillating signal.

The theory in this experiment is covered in class before the experiment is conducted, and it is rather simple. The equivalent mass formula is derived in class, and the stiffness formula is shown to arise from the mechanics of materials course the students took in their sophomore year. This helps the student to see the connections between the various subjects. In the final exam the students were given the problem of calculating the equivalent mass and stiffness of a simply supported beam, rather than a cantilever beam. The class average on that problem was 90%, thus indicating that the students were able to transfer the concepts to a somewhat different application.

In a survey given to the class after the project report was turned in, 25% of the students answered that they were very comfortable and 45% answered that they were somewhat comfortable with performing an unsupervised experiment at home. 70% reported that the hardware was easy to set up. When asked if the experiment contributed to their learning of calculating natural frequencies from data, comparison of data with beam theory, and the concept of equivalent mass, 21% answered that it greatly contributed to their learning and 60% answered that it contributed somewhat.

Earlier Work

One advantage of the kit and its software is its versatility. It can be used with a variety of sensors and actuators. In two previous papers [7,8] we reported on two experimental setups that were used with the kit in the Spring 2009 semester. One was a speed control experiment; the actuator is a dc motor and the sensor is a tachometer. In the second experiment the students measured the temperature of hot water as it cooled. The experiment used a different temperature sensor than the one used in the heated plate experiment. What follows is a brief summary of those experiments.

Speed Control Experiment

The hardware consists of a small DC motor (Transicoil 1121-110 DC Servo Motor Tachometer from Servo Systems, Inc.) with a built in tachometer (see Figure 8). The control input to the motor is supplied from the PWM output of the micro controller through the H-Bridge amplifier. The speed of the motor is measured from the tachometer using the 10-bit A/D converter on the micro controller. Using the User-Interface Program, the students first performed a calibration test to relate the steady state speed of the motor to the input voltage. This is done be selecting the *Motor I/O* experiment from the experiment list. This test will reveal any nonlinearities in the response such as those caused by friction.

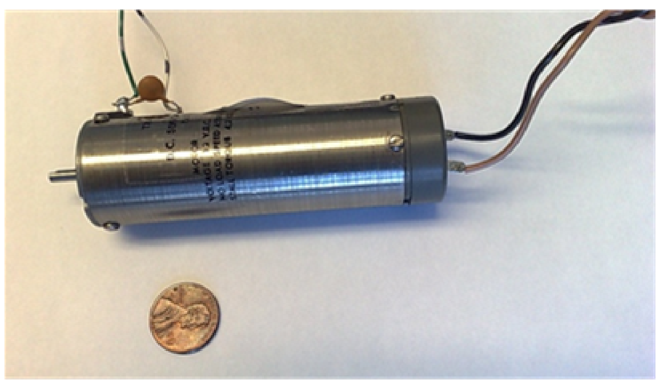

Fig. 8 The motor-tachometer

The students then performed an open-loop step response of the motor-tachometer system using different voltage inputs. From the data, the students obtained the parameters of a first order model of the system. The model was then used to compute the PI gains K_P and K_I necessary to achieve a desired time constant and damping ratio for the closed loop system. Finally they ran the experiment with the computed gain values and compared the data with simulation results. Figure 9 shows a plot of the simulation and the experimental data for a particular motor. The command input was 4 V, and the PI gains were 0.61 and 20, respectively. For the open-loop plant model given in the figure, a 4 V input would result in a steady-state output of 4(0.3075) = 1.23 V. However, the figure shows that the closed-loop system produces a steady-state output of 4 V, so the steady-state error is zero. The closed-loop time constant is less than 0.1, and the damping ratio is greater than 0.707, as required.

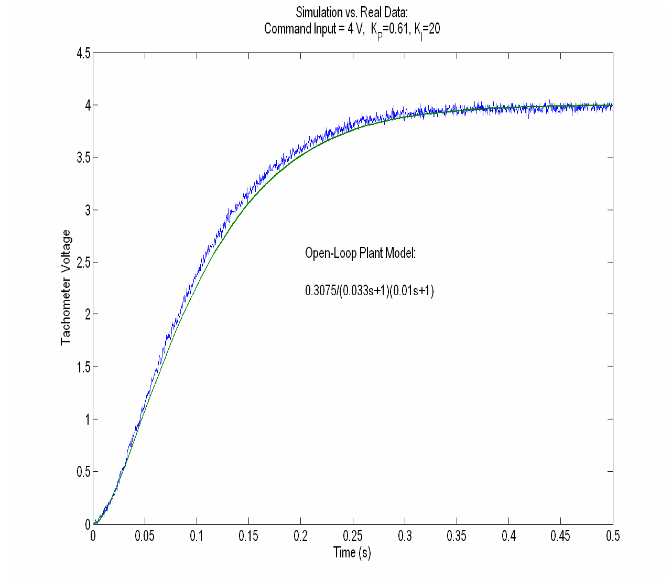

Fig. 9 Data and simulation results for closed-loop speed control

Temperature Measurement Experiment

This experiment uses the same temperature sensor that was used in the heated plate experiment but in the metal package form. The sensor was enclosed it in a protective sealed casing (see Figure 10) so that it can be used to measure the temperature in different environments such as air and in liquids. Using this setup, the student will be able to perform timed measurements on the response of many engineering systems that are available in the home such as heated/cooled fluids, and heating/cooling systems.

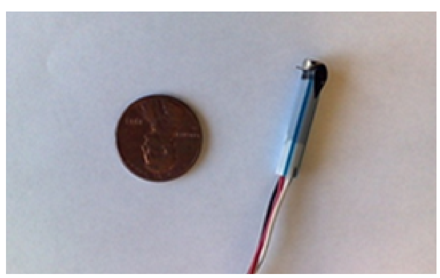

Fig. 10 Photo of the temperature sensor

The students were given a 16 oz plastic cup. They measured the temperature of hot water as it cooled, in two tests: one with the cup containing 100 ml of water, and the second with the cup containing 395 ml. They wrote a MATLAB program to fit an exponential function of the form $\Delta T = be^{t/\tau}$ to the data, where $\Delta T = T - T_o$, T is the water temperature, and T_o is the constant ambient temperature. They then used the model with each data set to compute the time constant τ and to predict how long it will take for the water temperature to decay to 5°C above the ambient temperature. They then compared the ratio of the two time constants with the theory. A plot of the temperature of water measured by the take-home kit is shown in Figure 11, along with the fitted model.

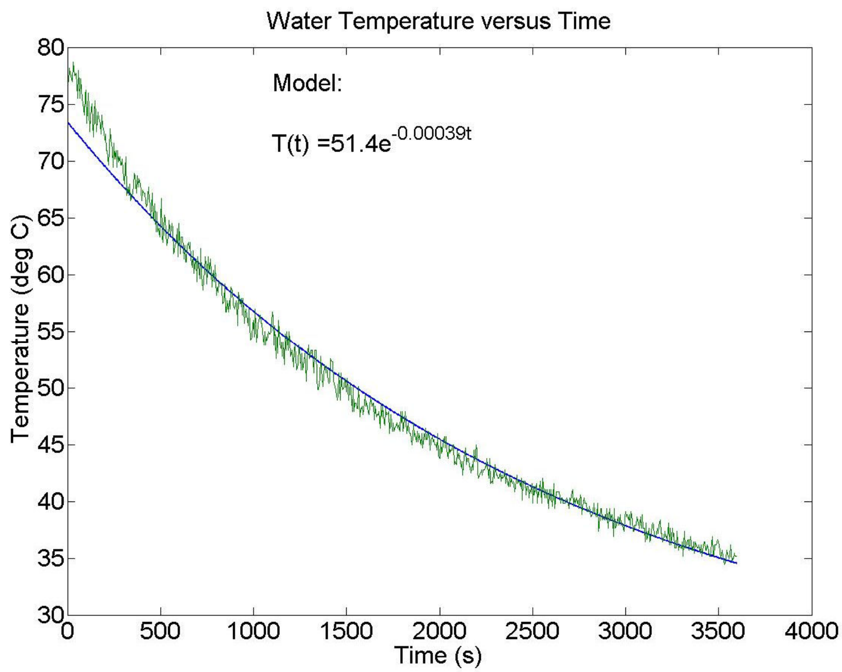

Fig. 11 Temperature of water in Styrofoam cup obtained by the take-home kit

Conclusions

We have developed low-cost take-home kits that can be used to perform laboratory experiments and measurements at home to illustrate system dynamics concepts. These concepts include: modeling using simple first and second order lumped-parameter models, stability of closed loop systems, and response time as indicated by the time constant. We have used the kits in four different courses in the mechanical engineering curriculum, and more usage of the kits is planned in the spring and fall 2010 semesters. The applications included thermal systems, electro-mechanical systems, and mechanical vibrations. Assessment of the effectiveness of the kits in illustrating system dynamics concepts was positive. The assessments were obtained by pre and post testing on course exams, and by questionnaires.

Acknowledgments

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