Advancing Laboratory Education in Control Engineering with Practical Implementation Approaches

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Abstract: - Some practical approaches have been presented successfully, which can be applied for control engineering education. Compared with conventional lecturing and laboratory exercising, instructing outcomes can be improved significantly. Two independent sets of instruments from Feedback Instruments Limited are selected to conduct experiments on a basis of the fundamental control theories. In particular, the 33-110 servo system is selected, consisting of three components: mechanical unit, analogue unit and digital unit. The 150 servo system contains a number of major discrete component units. Both systems can be used to test the fundamental control principles, such as the PID control. Matlab is employed for data analyzing, simulation, plotting and programming. Simulink is also employed to implement numerical simulations for advanced control practices. For practical control problems in real time, such as robotic control and engine control, Labview can be applied considering its merits of the graphical user interface design and block diagram approach. Some typical examples to improve classes at the system and control laboratory are presented, using software or hardware instructing tools such as the Matlab, Simulink and Labview.

Key-Words: - Engineering Education, Control Laboratories, Control Courses, Matlab, Simulink, Labview

1 Introduction

Electrical engineering education covers numerous undergraduate and graduate courses related to systems and control, optimization, signal processing and image processing. The theoretical part is the primary focus for the classroom instruction. However, the instruction procedure is lack of the hands on experience, thus, practical implementation of control applications is urgently needed. Some methodologies in the area of modeling, control and optimization can be developed to improve control theory instruction and laboratory practices, covering most aspects of classical control, modern control and intelligent control theories [1-3]. The proportional controller is the simplest and most intuitive structure to be implemented in linear control systems, which has been presented to determine the control stability range [4]. The program in MATLAB and Simulink languages, based on various proposed methods, design examples and class assessments, can be widely applied in order to improve the pedagogical issues. The student centered course content becomes more critical, which is suitable for every individual student's direct learning expectation and academic background [5]. Building blocks can be developed by open-source software tools also to be integrated into a

single system for the experimental study. By means of a specific application of the quality philosophy in the development of digital electronics laboratory courses, two main goals can be achieved to provide students with knowledge to analyze and manage problems and then initiate the improving processes [6-7]. The inter-disciplinary nature of the control laboratory courses allows for diverse applications in subjects of various disciplines across electrical, mechanical, automotive and biomedical systems such as robotic control and engine control systems [1-17].

Educational activities should always be integrated with research programs so as to reach student learning objectives. Up-to-date technologies must be developed and employed for the concern of control engineering on laboratory instruction and practical implementation. For instance, modeling can be conducted to show characteristics of the back-EMF and torque constants based on the electromagnetic field theory in the gearless flat-type brushless DC motor control system. To provide the insight and motivation, a course "Fundamentals of ECE" is designed to introduce multiple areas of ECE, emphasizing how to interrelate and contribute to the real-world applications. The course must engage its students who are evaluating

Zhengmao Ye, Habib Mohamadian, Hang Yin,
Guoping Zhang, Su-Seng Pang

ECE as a prospective major and career. To achieve these goals, the course adopts a unifying theme, tightly couples the lecture and laboratory exercises. The interactive classroom lecture and laboratory exercises should be developed iteratively so that many courses will support each other. Decision-making in a field of academic planning involves extensive analysis of large data volumes to ensure that new specializations and programs are adequately supported. Based on specific application of the quality philosophy in development of digital electronics laboratory courses, main goals are achieved to help students to manage the problems independently and to start continuous improvement process. It presents a methodology to assess education and plan utilization. It also serves as a decision support system allowing simulation and evaluating projects and scenarios [8-10].

Some real world interesting engineering topics can be introduced for classroom testing simulation. The interactive graphical software Simulink has been used to model, simulate and analyze the dynamic system. In this way, the rapid prototyping has been utilized to implement the hybrid fuzzy controller so as to control an assembly robot arm. In addition, both adaptive control and neural control strategies for the robotic manipulator with two joints have been proposed to improve performance [11-12]. A model-based feed-forward engine idle control system has been proposed to achieve better fuel economy. Then learning control method is developed and applied to a vehicle to verify improvement in controllability and be robust against aging and environment changes. This topic can also be simulated using Matlab and Simulink [13-14].

In this article, several simple approaches to enhance the student learning in fundamental control laboratory classes have been discussed, which can be easily assessed at electrical engineering at most university campuses. The main instrumentation systems are from Feedback Instruments Limited, namely the integrated 33-110 servo system and the discrete component 150 servo system. For advanced simulation, modeling, optimization and control, Matlab and Simulink have been introduced. For the practical implementation, Labview has also been used to demonstrate the control education practices in real time.

2 Feedback Instrumentation Systems
2.1 Control System Structure
The 33-100 servo system consists of the Digital Unit, Analogue Unit, Mechanical Unit, Oscilloscope and DC Power Supply (±15V, +5V) (Fig. 1). The 150

servo system consists of the Attenuator Unit, Servo Amplifier, Power Supply, DC Motor, Loading Unit, Reduction Gear Unit and Baseplate (Figs. 2-3). The 33-100 servo system provides the magnetic eddy current induced brake to change the level positions representing adjustable torques for different loading levels. The 150 servo system has a similar magnetic brake with the permanent magnet which could be swung over an aluminum disc. When the disc is rotated, eddy currents circulate in the area of the disc within the magnet gap. The current react with the magnet field to produce the torque which opposes rotation. It gives the adjustable torque speed and provides the very convenient load for the motor. The brake is provided in order to show that the steady speed of the motor is ideally proportional to the voltage being applied, less the amount which is directly proportional to load torque. In addition, it helps to learn that the DC tachogenerator provides a signal representing the speed, independent of motor loading. The response of the motor to an input changes is away from immediate, while it is expressed as a time constant (time delay).

Fig. 1 33-100 Servo System Demo: X-Y Display
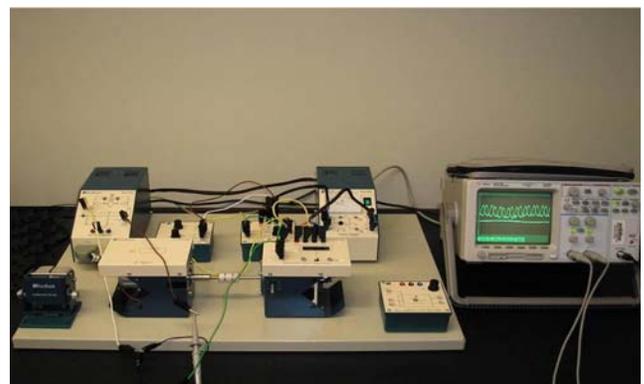
Fig. 2 150 Servo System in V-t Graph Display
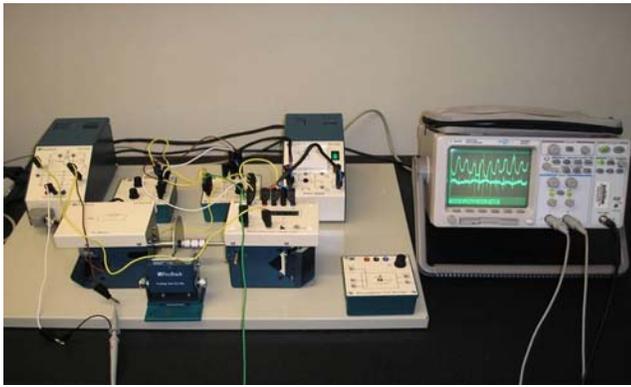
Fig. 3 150 System with Brake in V-t Graph Display

The overall characteristics of a motor may be considered from two aspects: the steady state, which is concerned with constant values or very slow changing operating conditions; the transient state, which is corresponding to sudden changes. Both the steady state and transient state responses are important in control system applications. The main objectives of the velocity control experiments are: to evaluate how a permanent magnet DC motor is controlled by varying magnitude and direction of its armature, to recognize the torque and speed characteristics and to establish the tachogenerator scaling factor.

On the experiments, a permanent magnet type of motor has been selected. When the motor is stationary and the voltage (V_S) is applied, a current flow (I_A) is generated which causes the motor to rotate. As the motor rotates, a back EMF (V_B) occurs. As the motor speeds up, the back EMF increases and I_A drops. For an ideal motor, when the armature current falls to substantially zero, the V_B approximately equals the armature voltage (V_A). Thus, if V_A is varied slowly in either polarity, the motor speed is proportional to V_A. In the 33-100 and 150 servo systems (Figs. 1-3), the armature voltage is provided by a power amplifier. It is necessary because although the voltages in the error channel may be of the same order as V_A, the motor current may be up to 1 A, while the error channel operates with currents of less than 1 mA and could not drive the motor directly. The amplifier has two input sockets, enabling the motor rotation direction to be reversed for a specific input. The tachogenerator is a small, permanent magnet machine and hence it produces an EMF proportional to speed when rotating, which can be used as a measure of the rotation speed. The basic principles for DC motor control without and with load inertia are shown in Fig. 4 and Fig. 5. The permanent magnet DC motor can be controlled by varying the magnitude and direction of its armature current. The motor has the single armature winding, the current flow through the armature is controlled by the power amplifiers.
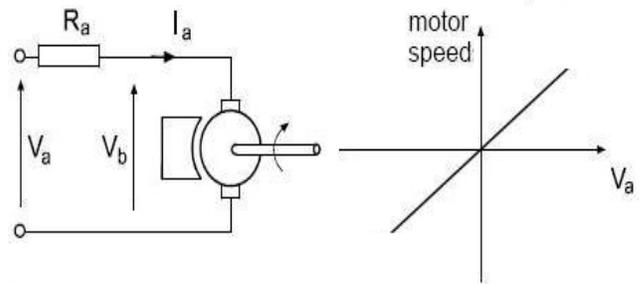
Fig. 4 DC Motor Control Principle without Load
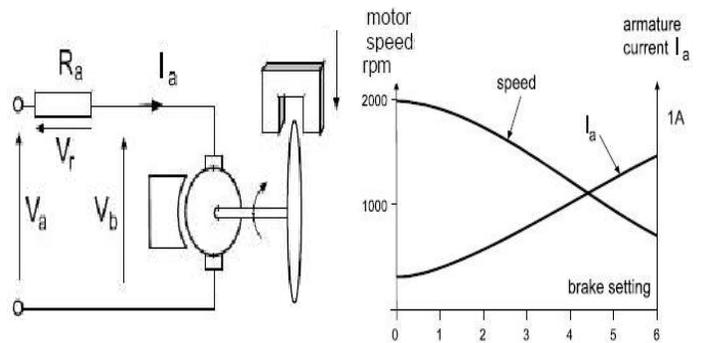
Fig. 5 DC Motor Control Principle with Load

Another typical practice is proportional (P), integral (I) and derivative (D) - PID controller design, where coefficient parameters of three terms can be adjusted arbitrarily using the 33-100 and 150 servo systems on a trial-and-error basis. The dynamic example of the 33-110 servo system using PID control has been shown in Fig. 6. A comparison can be made in terms of testing results on the two speed control experiments.
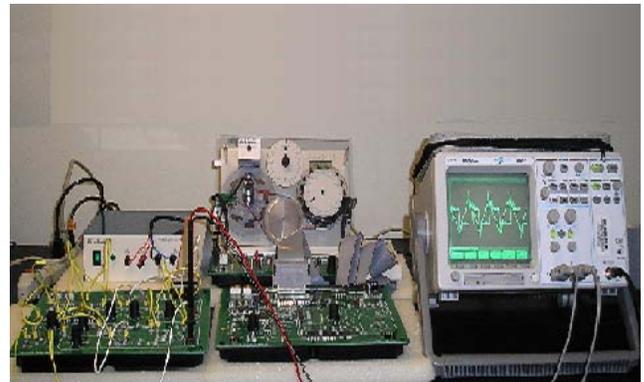
Fig. 6 33-100 Servo System: PID Control

Zhengmao Ye, Habib Mohamadian, Hang Yin,
Guoping Zhang, Su-Seng Pang

2.2 Comparative Analysis of Experiments

2.2.1 33-100 Servo System

The analogue and mechanical units of the 33-100 servo systems are connected by the 34-way ribbon cable. The power supply should be connected by 4mm plug, which gives rise to the +15V, +5V, 0V and -15V sockets at the back of the mechanical unit.

A. Steady State Characteristic Measurement

For steady states, the system gain should be arranged so that a voltage at the range of ±10V is applied to the power amplifier. Switching between DVM and RPM is for voltage and speed measurements, respectively. The DVM is used at the range of ±20V for voltage measurements. The required steady state can be set up for each measurement. By varying the gain, the motor speed curves can be plotted against an amplifier inputs at the range of ±10 V, with the vertical scale unit of 1000 r/min. The tachogenerator characteristics can be plotted by setting the motor speed to various values and then measuring the generated voltage. Thus, the tachogenerator factor can be determined by measuring a change in the generated volts for a speed change of 1000 r/min. When the brake is added, the steady state characteristic changes accordingly. At this time, the gain can be adjusted again and the DVM is used to measure the armature current output. The brake level can be set to each of its six positions. For each setting (load), speed and current curves will be plotted.

B. Transient Characteristic Measurement

For transient states, the system is connected so that it enables the motor to be driven by the square wave input function. It allows the speed to be displayed on the Y axis of an oscilloscope. When the gain is set to zero and the test signal frequency is set to be 0.2 Hz. The power amplifier can be adjusted to run the motor at maximum speed in one direction. Adjust the gain and square-wave signal to speed up or slow down the motor. The gain should be adjusted until the motor is stationary at a half cycle. In this case the oscilloscope displays the speed corresponding to the armature voltage. If the applied voltage is suddenly changed, the motor does not respond instantly. Its time constant is defined as the time it takes to reach its final speed if an initial acceleration is maintained. It can be estimated by considering the initial slope and maximum speed. The motor time constant value can be calculated.

2.2.2 150 Servo System Measurement

In general, the 150 servo system is attached to the baseplate using the magnetic fixings. The aluminum eddy current disc should be placed at the midway in the gap of magnetic brake with its edge flush with the back of the magnet. Both the voltage and speed can be displayed. The magnetic brake is initially set to the unloaded position. Then keep turning a potentiometer until there is a reading of 1V at the voltmeter. Repeat readings with the 2 to 5 volts generator outputs. As a result, a graph of speed against tachogenerator volts can be plotted. The calibration factor is calculated accordingly which is about 2 to 3 volt per 1000 r/min. The slope of the speed v.s. input voltage curve can be recorded at the zero load stage. The next step is to reduce the input voltage until the motor is just turning so as to measure the tachogenerator output voltages. This time the input voltage increases at 1V increment and readings of the input voltages and tachogenerator voltages are collected up to the maximum speed of the motor of 2000 r/min or so. Calculate the slope again. The brake is fixed slowly so that it passes through the eddy current disc smoothly while the motor is running to measure the torque/speed characteristics. The brake is set to be zero and the input voltage is increased until the motor rotates at its maximum speed. Reduce the input voltage via brake settings so that the ammeter is just below 2A up till zero position. Finally the brake is set back to maximum position to reduce the input voltage so that the motor is slowly rotating. Now results of speed against torque (brake levels) under different input voltage values can be plotted.

3 Matlab Application Analysis of Testing Data

3.1 Matlab Analysis of Testing Data

For the 33-110 servo and 150 servo systems, the motor speed is roughly proportional to the applied voltage level when no external load is added. Using the brake to represent the external load, so we have $V_A = V_R + V_B = I_A R_A + V_B$, where V_A is the input voltage, V_B is the back EMF, R_A represents the armature resistance and I_A represents the current at different levels of brake. In Fig. 7, results from the 33-110 and 150 servo systems are shown. The X-Y display of transient response in the 33-110 servo system can also be seen.
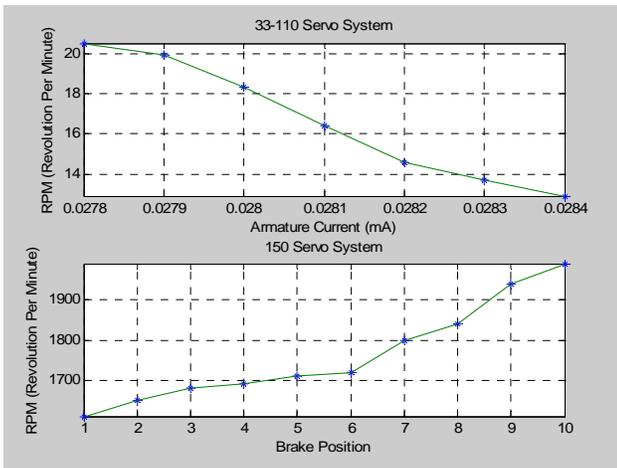
Fig. 7 Two Servo Systems (33-110 and 150)
Experimental Result Plotting Using Matlab

Comparing the 33-110 and 150 servo systems, the 33-110 servo system includes experimental units with compact structure using the integrated type of circuit design. It takes shorter class time for students to conduct the complete experiments. On the other hand, measuring of the steady state and transient state characteristics can be conducted at the same time. The advantage of the 150 servo system is that physical principles can be directly shown from the layout of experimental connections, where every individual system component units are employed. This system also has the flexible loading system to generate the magnetic disc eddy-current and back EMF. It takes a little longer time to instruct students with hands on experience, while the steady state response is the major design in this system. In Fig. 7, for both 33-110 and 150 servo systems, different brake settings result in the variations of armature current, so the output RPM and voltage are changed accordingly.

3.2 Matlab Simulation of DC Motor Control
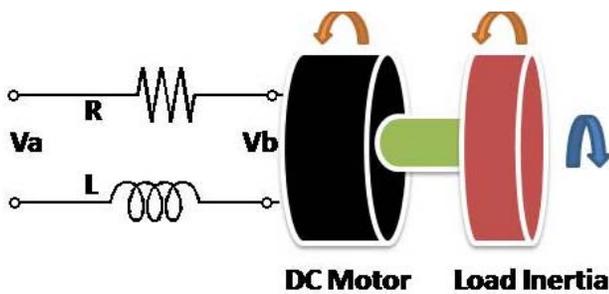
Fig. 8 Simple Illustration of DC Motor Control

The armature controlled DC motor is subject to both load variations and random disturbances. This issue can also be simulated using Matlab programming. The simple illustration of the DC motor control system is shown in Fig. 8, where the torque is used to model load disturbances. To reduce the sensitivity in motor load control, the speed variations should be minimized against various load disturbances. Both feedforward and feedback control methodologies can be selected. To make a comparison between two approaches, at first, the feedforward controller is used to adjust the velocity to a specific value with the feedforward gain; secondly, a feedback controller based on linear quadratic regulator (LQR) is designed, where a cost function is used as a tradeoff of the error signal between actual speed and reference speed. The step responses are simulated with a disturbance load in a time period, with the resistance, inductance, torque and inertia being given, the results from a typical example of feedforward design and linear quadratic regulator design against load disturbance are shown in Fig. 9. It can be shown easily that linear quadratic regulator feedback control provides better disturbance rejection than feedforward control.
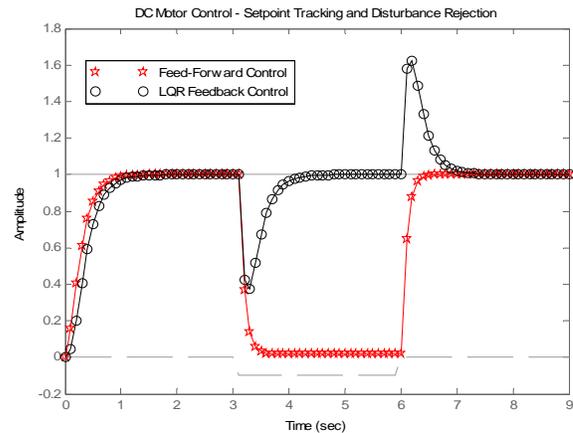
Fig. 9 Two Control Schemes of Disturbance
Rejection for DC Motor Control

4 Simulink Applications

For modeling and control applications at the off-line stage, numerical simulations can be conducted using Matlab and Simulink. MATLAB is one of the most powerful programming languages in disciplines of control, communication, signal processing and image processing. In previous sessions, Matlab programming is used for data analysis to make comparisons between two feedback instrumentation systems. Simulink stems from Matlab with additional graphical block diagram representations. For advanced modern control theories

Zhengmao Ye, Habib Mohamadian, Hang Yin, Guoping Zhang, Su-Seng Pang

and applications under the state space representations, Simulink is an interactive and very effective tool for modeling, simulating, and analyzing. It can be used to build the graphical block diagrams, evaluate system performance, and revise initial design at preliminary stages. Simulink works well for both continuous and discrete time control systems. It provides integration of graphical modeling and animated simulation, which is carried out with specific and practical design for the control systems. In this session, special cases of the Simulink programming are provided to introduce this well designed simulation method with satisfied results.

In Fig. 10, the structure of the inverted pendulum control system is shown. Modeling and control of this pendulum system is conducted, where the Simulink state space model are given in Fig. 11. A frictionless surface is assumed for the pendulum to keep balance which is connected to a moving cart with a hinge. Suppose that all state variables are measurable, and the position and speed of the cart can be observed. Then, this Simulink model with state feedback and full order observer design can be used. In Fig. 12, the two state trajectories for the original system and closed loop control system (with state feedback and full order observer) are plotted. The result shows that feedback control system design performs satisfactory.
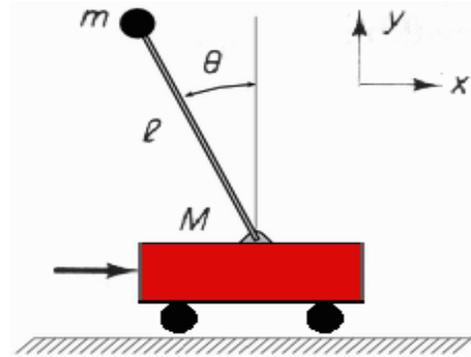
Fig. 10 Inverted Pendulum and Moving Cart System

Another example is also provided to simulate the adaptive control theory, where an adaptive self-tuning regulator (STR) is applied. With the presence of the stochastic disturbances, this adaptive STR controller is employed to adapt to the desired system performance. In Fig. 13, the Simulink graphical program is presented. In Fig. 14, simulation results are shown for this adaptive STR control problem, where both the reference input signal and self-tuning system design against uncertainties and random disturbances have been considered.
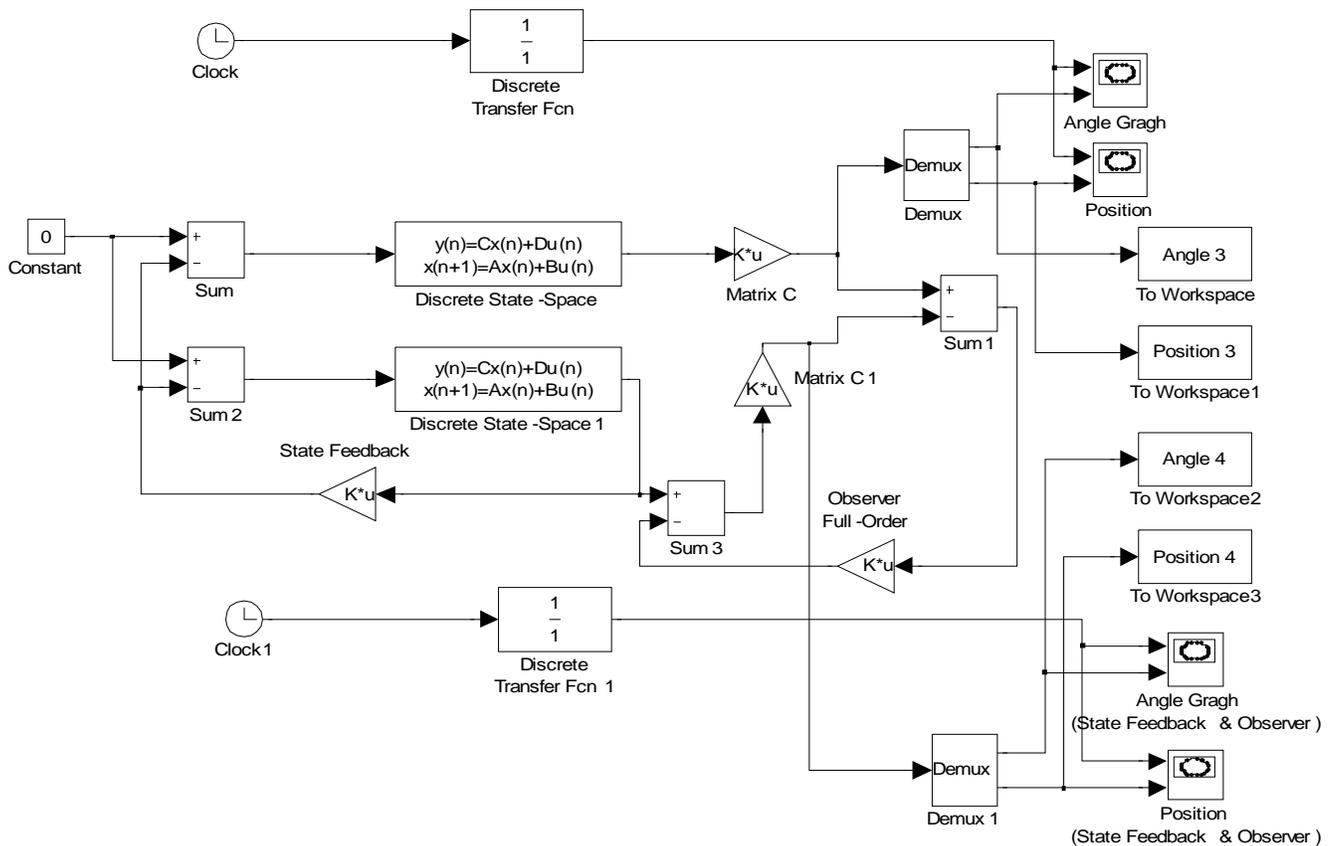
Fig. 11 State Feedback and Full Order Observer Design for Pendulum Control System Using Simulink
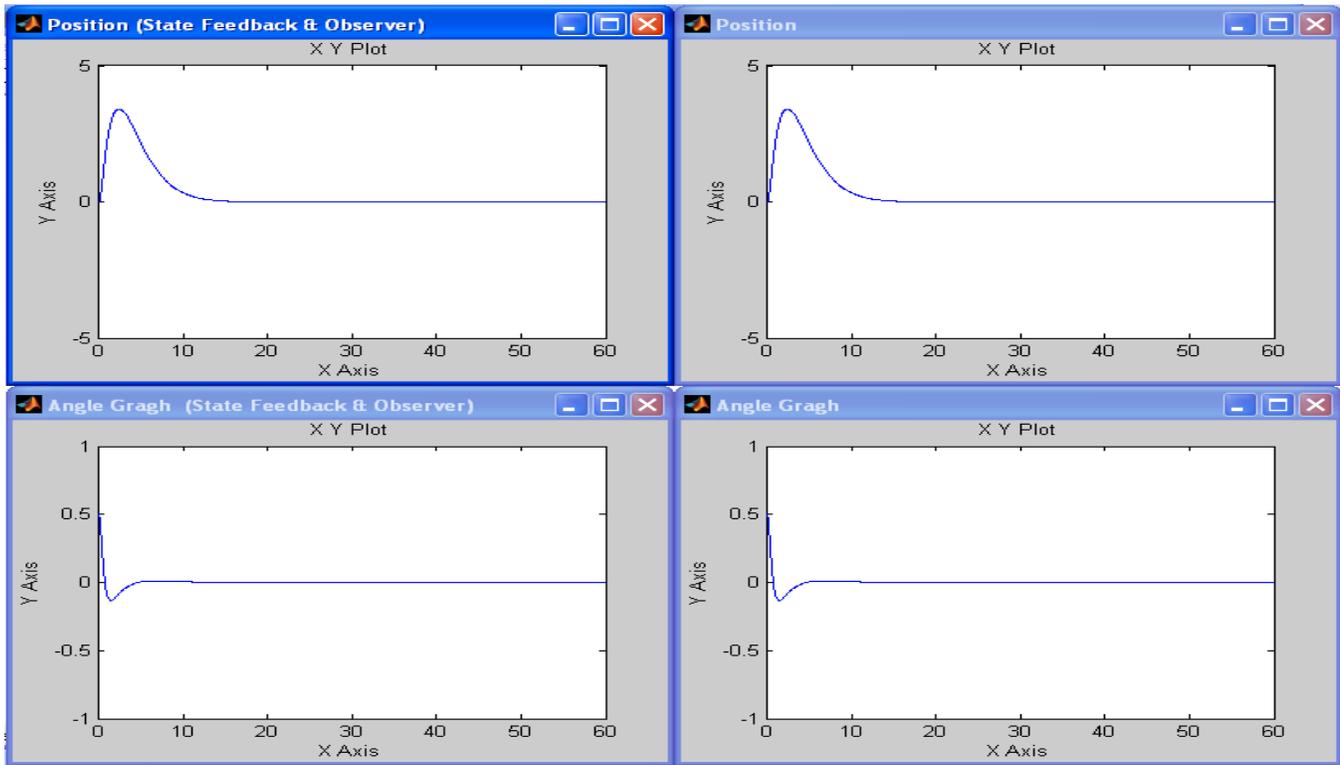
Fig. 12 Simulation Results of State Feedback and Full Order Observer Design for Pendulum Control Systems
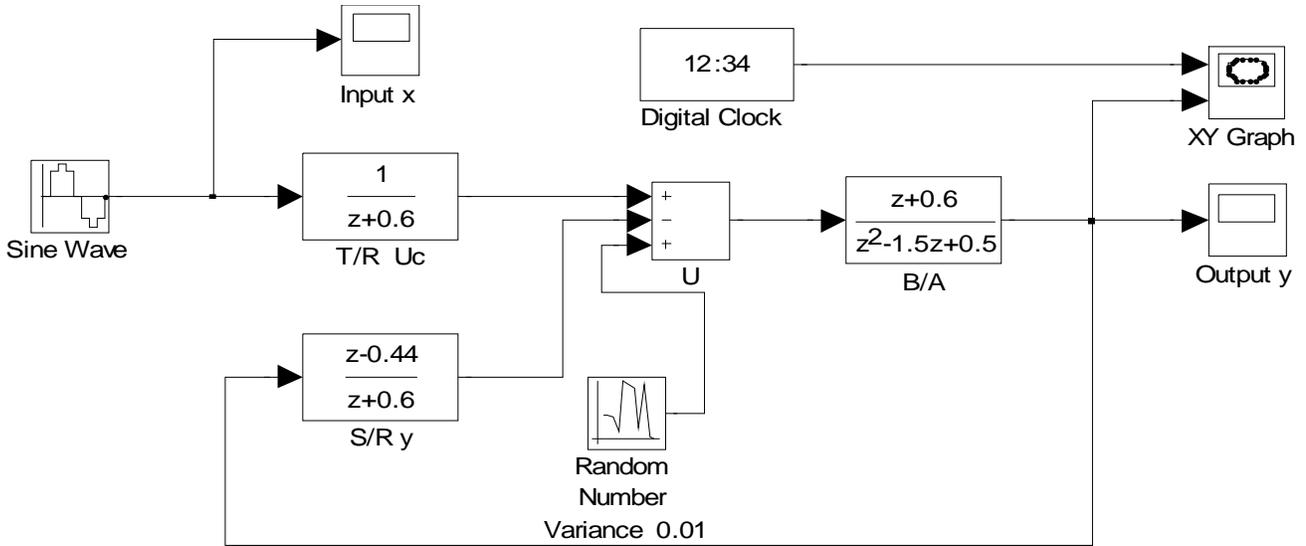
Fig. 13 Stochastic Self-Tuning Regulator Design
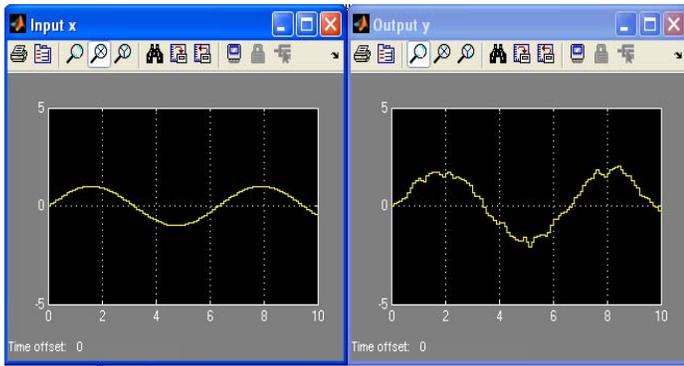
Fig. 14 Input and Output of Self-Tuning Regulators

It is easy to expand Matlab and Simulink applications to numerous practical engineering control issues, such as robotic control systems, automotive control systems and aeronautical control systems. Control engineering education can be greatly enhanced when Matlab and Simulink instruction is included into the pedagogy.

5 Labview Applications

For advanced control education, the real time approach also needs to be developed. LabVIEW is a dominant approach for control applications either off-line or on-line. The user interface and block diagram methods should be instructed for enhancing student learning.
For a simple example in a robotic end effector control system, the human-machine interface can be set up by the LabVIEW software and hardware. Fig. 15 provides the detail information of locations and orientations of the robotic arm and end effector. For advanced robotic control, the visual interface to CCD cameras, head mounted display, 3D monitor) and haptic interface (for pressure sensors, cyberglove, ultrasound array) can be applied to control systems to support real time visual and tactile information acquisition. It will enhance the perceivable capability of the robot manipulators with precise and accurate sensing information. LabVIEW is based on graphical programming. Communication between the hardware and plug-in data acquisition board can be made using various techniques such as serial interface RS-232, GPIB, CAN and Ethernet.

In Figs. 16-17, the block diagram and user interface are designed to real time monitor the cylinder pressure trace, fuel injection pressure trace, heat release trace of combustion processes for the RCM compression ignition engine. The friendly user interface design and its real time control capability have presented Labview with the unique advantage over other programming languages. The multiple channels can be operated simultaneously while experimental results will be displayed easily and then arbitrarily recorded as data files or graphic plots. The graphical design ensures adequate output presentation for decision making by showing significant details of data. On the other hand, the results for different piston speed conditions from Labview are shown using Matlab simulation in Figs. 18-19. Programming systems of Matlab and Labview integrate with each other well in this case.
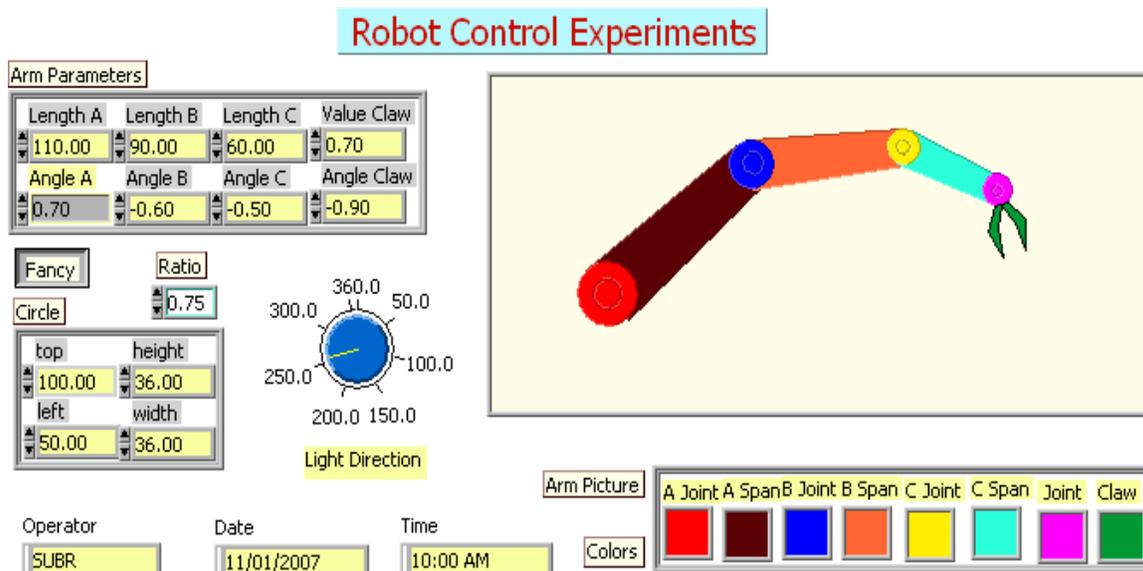
Fig. 15 User Interface for Robotic End Effector Control
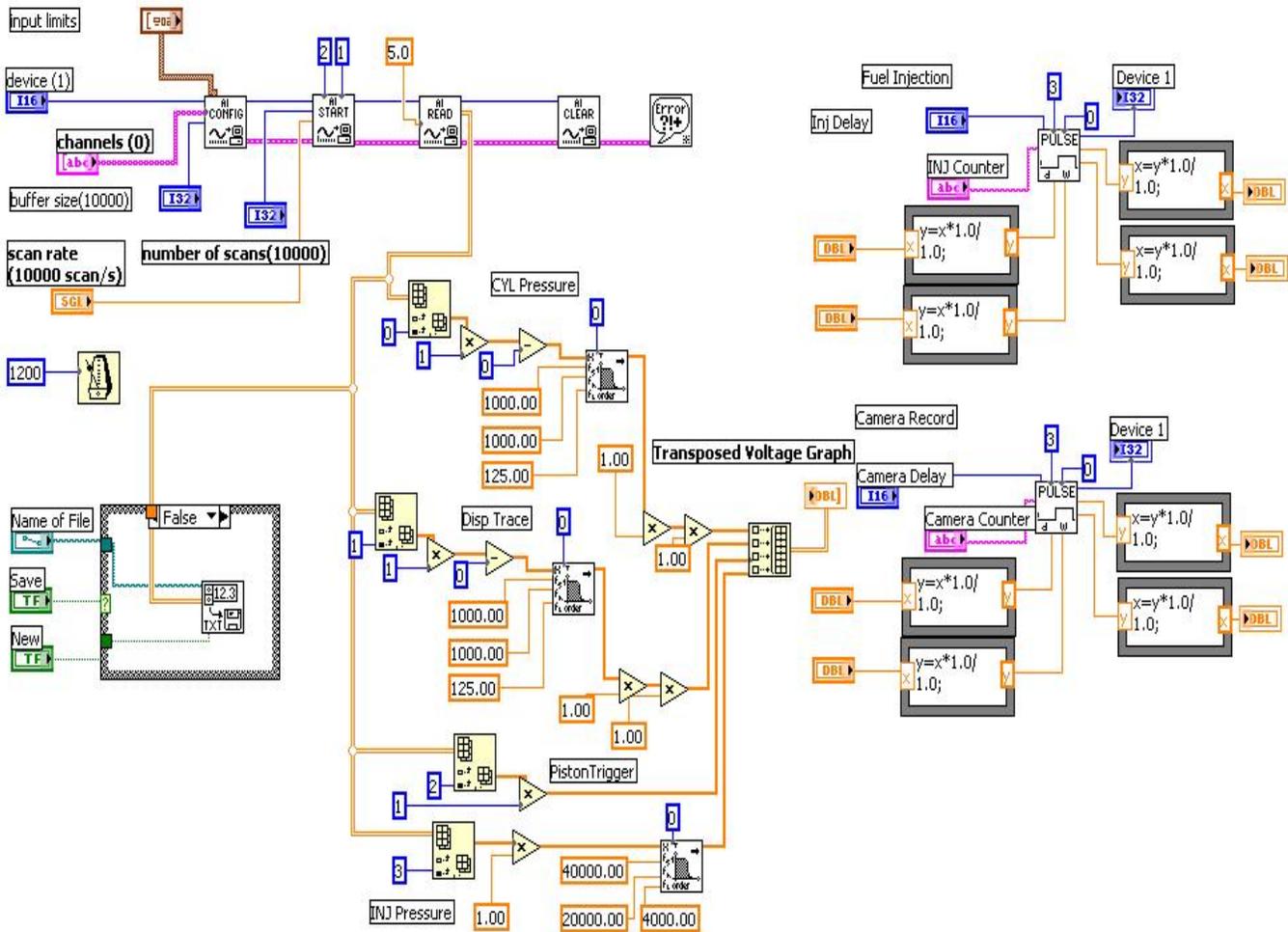
Fig. 16 Block Diagram for Engine Fuel Injection Control Using Labview
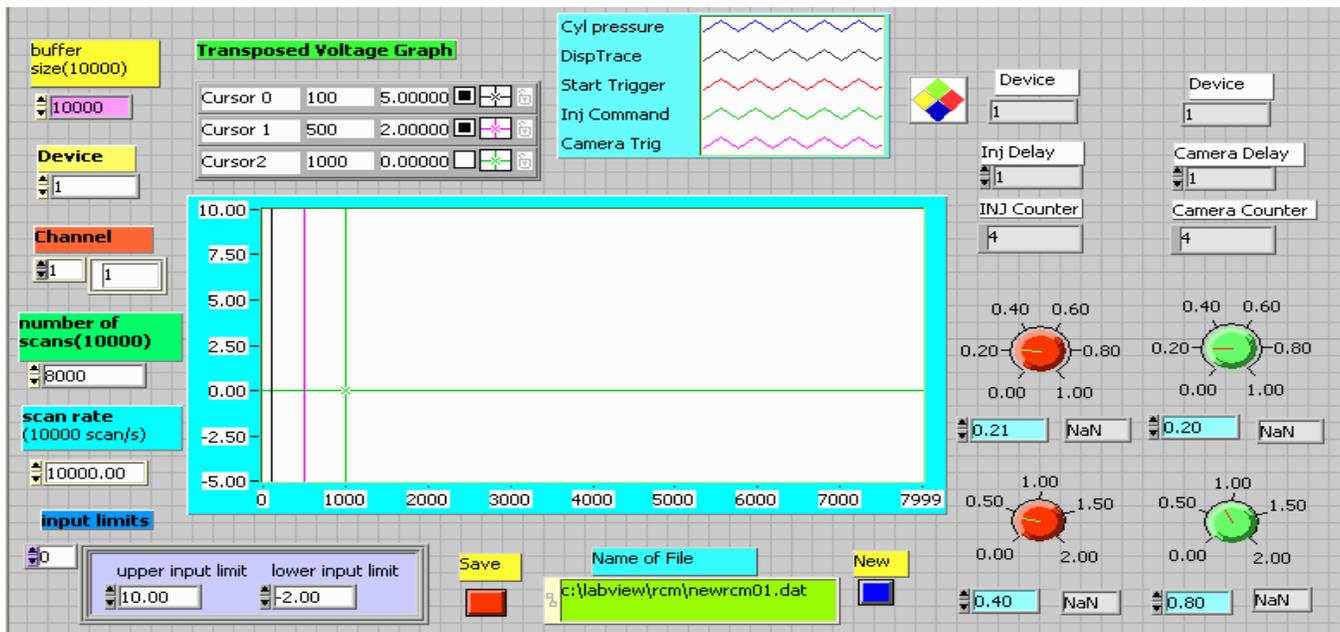
Fig. 17 User Interface for Engine Fuel Injection Control Using Labview

Zhengmao Ye, Habib Mohamadian, Hang Yin,
Guoping Zhang, Su-Seng Pang
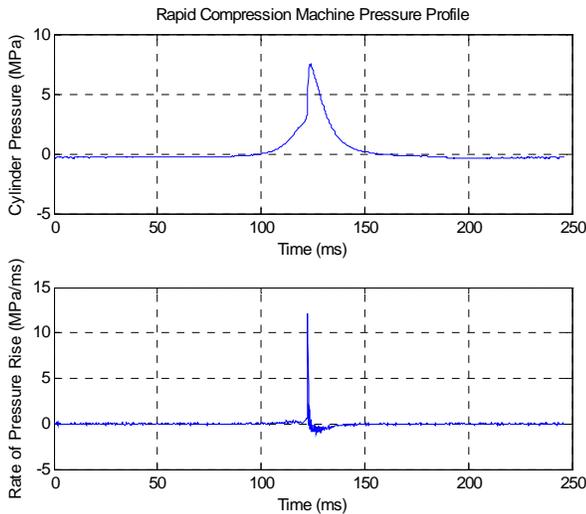
Fig. 18 Simulation of RCM Engine Control
(High Piston Speed)
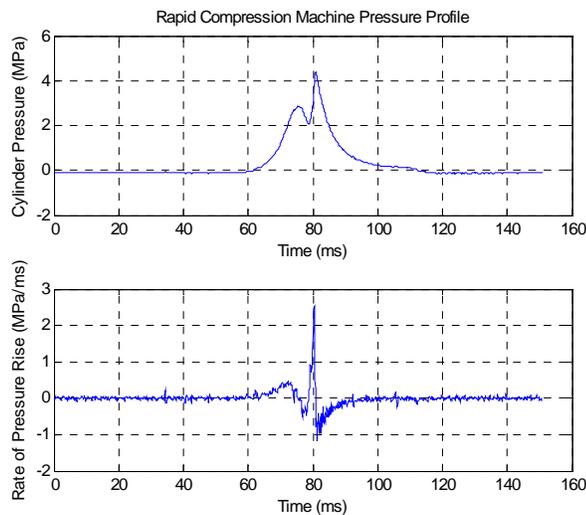
Fig. 19 Simulation of RCM Engine Control
(Low Piston Speed)

6 Conclusion

This paper presents several practical approaches to improve the quality of control laboratory instructing in a series of simple ways. For two servo systems, the armature current increases with the increasing torque, causing a voltage drop in armature resistance. This effectively reduces the applied voltage, causing the speed drop. The magnetic brake provides a torque proportional to speed which depends on the overlap between the magnet and disc. The slowing-up process is associated with the reverse current which takes less time for motors to slow down. With armature control, the negative feedback of the back EMF will oppose the input signal and tend to maintain the steady motor

current across the torque range. To evaluate the system performance, it is appropriate for students to conduct experiments on both systems so as to fully grasp control engineering theories via hands on experience. Simulation of experimental results can be conducted using Matlab. To demonstrate some advanced control theory practices, Simulink has been introduced to conduct various engineering applications, where actual state feedback and full order observer design is made for pendulum modeling and control systems. Another algorithm based on the stochastic self-tuning adaptive control has been demonstrated. For the on-line control implementations in real time, it is suggested that the Labview system should be suitable choices, which include the user friendly block diagram and human machine interface. Typical examples on both robotic control and engine control cases have been presented. All these proposed simple practices have enhanced the quality of control engineering education.

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