International Journal of Engineering Education Vol. 30, No. 3, pp. 729–737, 2014
Printed in Great Britain

0949-149X/91 $3.00+0.00

Impact of Model-Order Reduction of a DC Motor on Control Systems: An Undergraduate Laboratory Module*

RAFFI TOUKHTARIAN and SAMER S. SAAB
Department of Electrical and Computer Engineering, Lebanese American University, P.O. Box 36, Byblos, Lebanon.
E-mail: raffi.toukhtarian@mail.mcgill.ca and ssaab@lau.edu.lb.

The control lab module presented in this paper culminates with a hands-on experience of the basic theory given in an introductory control systems course. This module, which is placed during the last two sessions of an undergraduate control laboratory course, focuses on the modelling of two DC motors with different characteristics, parameter identification, and the impact of different model-order reduction techniques on control design. This module integrates theoretical, numerical and experimental analysis of practical relevance, and redirects students to focus more on performance measures and analysis. This paper details the objectives, equipment needed, laboratory lectures, experimental procedures, and observation and analysis desired for this module. It also includes assessment results pertaining to student learning. In addition, this paper provides a novel condition for neglecting the armature inductance. This condition, which is elaborated theoretically and verified experimentally in this paper, is shown to be more reliable than the two conditions presented in the literature.

Keywords: engineering education; laboratory experiment; experiential learning; DC motor control; modelling; parameter identification

1. Introduction

The first undergraduate control systems course offered in many universities provides students with the understanding and comprehension of the basic theory needed for a control engineer but does not usually focus on practical issues. Introductory courses on control systems typically include mathematical modelling of dynamic systems, transient and steady-state response analyses, root-locus analysis and control system design [1–4]. The skill base of this course includes modelling, relevant performance measures, and control design. Hands-on experience is very important in control theory especially where there is a high level of abstraction. A complementary laboratory work is commonly offered in order to cover the other basic skills needed for a control engineer to analyse and interpret data such as numerical and experimental simulation, and implementation. Such laboratory work can be offered by using: (1) simulated/emulated versions of physical test beds that can be offered as a web-based laboratory or remote laboratory [5, 6]; (2) traditional laboratory equipment provided by educational manufactures [7]; or (3) a locally developed real-time controller targeting a deeper understanding and integration of real-time control systems [8]. However, the choice of experiments and experiment set-ups vary significantly in different universities. The choice of experiments is either guided by the instructors' selection of focuses that they wish to emphasize and/or be guided by the lab manual provided by the manufactures of the lab equipment. However, the main goal behind selected practical experiments is to effectively improve experiential learning and relevant students' skills.

The relatively simple model of DC motors and their wide use in industry makes DC motors an attractive practical example in introductory control systems textbooks [1–4]. Moreover, the wide availability and mass production of DC motors and their accessories has made DC motors the subject of many control systems laboratory experiments [9–13], not to mention that DC motors are still being a topic of interest to control systems scholars around the world [14–16]. Different simplification techniques are implicitly assumed while modelling a DC motor that aims at reducing the complexity of the system. Such simplification techniques may include: neglecting the static friction, relating the frictional torque directly and solely on the angular speed, neglecting the armature reaction and dealing with the resistance and armature inductance as constant quantities [17].

Modelling of a DC motor is typically introduced by applying Kirchhoff's law at the armature circuit and applying Newton's law on the rotor of the motor. This will result in a second-order stable system with angular velocity being the system output and with poles being real. Usually the system order is reduced by neglecting the armature inductance, L_a [2, 4, 18]. The conditions that are used in the literature for neglecting L_a are either based on the magnitude of L_a being negligible [1, 4, 19] or by the condition that the electrical subsystem of the motor is much faster than the mechanical

---

* Accepted 28 December 2013.

subsystem [2, 4, 20]. Another general method for MOR is based on neglecting the non-dominant pole for second-order systems. In other cases the DC motor is considered as a first-order system and the parameters of the reduced system are obtained by using a simple parameter identification technique [21].

A few students ask interesting and critical questions.

1. How small should the armature inductance be in order to neglect it?
2. Since the magnitude of the viscous-friction coefficient is approximately equal to the magnitude of the armature inductance, how come the viscous-friction coefficient is not neglected?
3. Why not neglect the non-dominant pole?
4. Since the root loci of the reduced and nominal systems differ significantly, what would be the impact of using the reduced-order model on controller designs using root-locus analysis?

However, another key concern should be as follows: Since the actual system poles are not only dependent on the electrical or mechanical sub-systems, wouldn't it be necessary to consider also the magnitude of the back EMF constant that actually couples the mechanical and the electrical sub-systems?

Inspired by such critical questions, a dedicated laboratory experiment was designed at the authors' institution where students were able to study and criticize existing conditions and other new conditions needed for reducing the order of a DC motor, as well as their impact on control design. During this laboratory experiment student were exposed to different theoretical and practical principles. Because of our positive experience we thought it would be worthwhile revealing it to a wider audience. This paper presents a proposed laboratory module that reinforces and integrates basic theoretical concepts and skills that are associated with a typical first control systems course. The main goal of the proposed laboratory experiment is to let the students experience basic concepts and skills learned in the first control systems course and other related courses and comprehend how they can be implemented in real life. The proposed module requires two three-hour lab sessions and is better being given towards the end of the lab course. Unlike the existing literature, e.g., [1, 2, 4, 18, 19], which provides inaccurate conditions for neglecting the armature inductance, this paper provides a thorough and novel condition for neglecting the armature inductance. The latter is theoretically elaborated, and experimentally verified within the scope of the proposed module.

The rest of the paper is organized as follows: Section 2 presents the objectives and background information of the proposed module and includes the equipment needed. It also describes the lecture materials, procedure, and expected student observations and analysis. Section 3 includes assessment results, and concluding remarks are included in Section 4.

2. Proposed lab module

2.1 Overview

The main objectives of the module are as follows:

- the ability to comprehend the practical operational concepts of DC motors;
- the ability to relate knowledge acquired in the circuits and control courses to the concepts involved in model-order reduction techniques and parameter identification procedure;
- the ability to comprehend the basic conditions that are needed to reduce the order of a DC that can result in insignificant errors;
- the ability to numerically simulate and analyse different configurations of control systems.

Students follow the control lab course in conjunction with the first control systems course. The proposed module was given towards the end of the semester.

The background needed for this module is not demanding. In particular, the basic theoretical background, which is limited to the Laplace transform, basic circuit analysis and electromechanical concepts (usually covered in an introductory control course) are covered before following this course. The students are also expected to be exposed to a high-level technical computing language (e.g., MATLAB) and elementary laboratory equipment prior to following this course. Other specific concepts such as mathematical modelling of dynamic systems, transient and steady-state response analyses, root-locus analysis, are usually covered a couple of weeks before the end of the course. The aforementioned will not be a problem when the module is given at the end of the semester.

The newly introduced module replaced a DC motor control project, which was given during the last two lab sessions at the end of the semester. The project was about typical DC motor modelling and control. The new module replaced the previous project mainly due to its novel approach and the wider exposure to practical issues. The preceding lab modules include MATLAB programming and simulation techniques relevant to control systems, and PID controllers and their implementations to 1st- and 3rd-order delay systems.

The basic recourses needed for this module are rather generic, except for having two DC motors with different characteristics; in particular, one motor with poles that are relatively distant from one another whereas the other motor has poles that are relatively close to one another – the difference in the characteristics are elaborated further in the next subsection. Students used the available DC motor dedicated for the control lab, the Control Lab Motor, and the other rated DC motor dedicated for the power lab, the Power Lab Motor. The Control Lab Motor is the motor with 'distant' poles, whereas the Power Lab Motor is the motor with 'close' poles.

2.2 *Session 1*

This session mainly deals with the modelling of a DC motor, the relationship between actual system poles and the electrical/mechanical sub-systems poles, model-order reduction techniques, and parameter identification.

2.2.1 *Equipment list*

The equipment list needed for this session is composed of typical accessories needed to operate DC motors. The educational boards used are shown in Fig. 1.

The descriptions of the employed motor and PID boards' components are shown in Fig. 1.

2.2.2 *Lecture*

Session 1 starts with a 45-minute lecture that focuses on the modelling and parameter identification of a DC motor. What follows are the concepts presented to students during the first lecture.

The DC motor's model is introduced by the electric circuit of the armature and the free body diagram of the rotor. Applying Kirchhoff's law at the armature circuit and applying Newton's law on the rotor of the motor the student will end up with the following differential equations:

$$\begin{aligned} u_a(t) &= r_a i_a(t) + L_a \frac{di_a(t)}{dt} + K_a \omega_r(t) \\ J\frac{d\omega_r(t)}{dt} &= K_a i_a - B_m \omega_r(t) - T_L \end{aligned}, \qquad (1)$$

where ω_r is the angular speed, u_a is the armature voltage, i_a is the armature current, T_L is the load, r_a is the armature resistance, B_m is the viscous-friction coefficient, L_a is the armature inductance, J is the equivalent moment of inertia, K_b is the torque constant, and K_a is the back EMF constant. The corresponding transfer function relating the output, $\omega_r(t)$to its input, $u_a(t)$ is:

$$\frac{\Omega_r(s)}{U_a(s)} = \frac{K_a}{K_a^2 + r_a B_m} \frac{s_1 s_2}{(s+s_1)(s+s_2)}. \qquad (2)$$

The uncompensated poles of the nominal system are at

$$-s_{1,2} \equiv \frac{-\left(\frac{B_m}{J} + \frac{r_a}{L_a}\right) \pm \sqrt{\left(\frac{B_m}{J} - \frac{r_a}{L_a}\right)^2 - \frac{4K_a^2}{L_a J}}}{2} \qquad (3)$$

The specific block diagram shown in Fig. 2 highlights the mechanical and electrical sub-systems of a DC motor.

The transfer function of electrical subsystem is

$$H_{elec}(s) = \frac{1}{L_a s + r_a},$$

where its time constant is given by

$$\tau_{elec} = \frac{r_a}{L_a}.$$

The transfer function of the mechanical subsystem is

$$H_{mech}(s) = \frac{1}{Js + B_m},$$

where its time constant is given by

$$\tau_{mech} = \frac{J}{B_m}.$$

Usually $\tau_{mech} >> \tau_{elec}$.

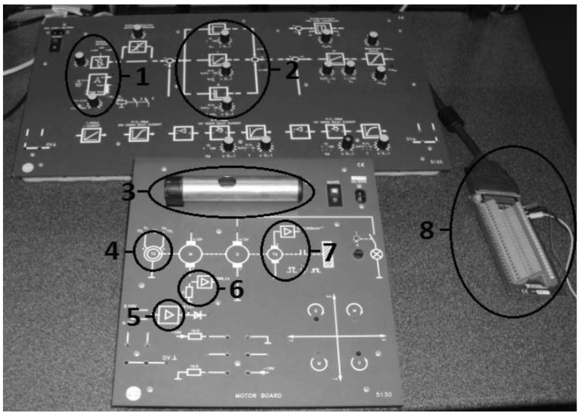

Fig. 1. Control Lab Motor board and PID board: 1- Square wave generator (used for step input); 2- PID board; 3- DC motor; 4- Optical encoder (used for speed measurement); 5- Power op-amp (used as buffer); 6- 1 Ω power resistor used for measuring the current; 7- Tacho-generator (also used for speed measurement); and 8- Data acquisition board.

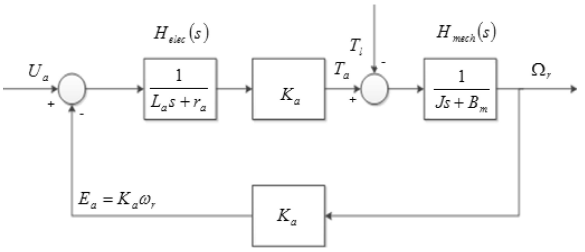

Fig. 2. Block diagram of a DC motor.

2.2.3 Model-Order Reduction (MOR)

Modelling is always a compromise between accuracy and simplicity. MOR techniques aim to reduce complexity while preserving the input–output characteristics. MOR reduces computational time in simulations and may also reduce complication in mathematical proofs and derivations. One of the simplest and most common MOR techniques is Modal Approximation (MA). MA entails removing non-dominant poles that are far in the Left Half Plane (LHP) or have relatively small residues.

Consider the system

$$H(s) = \frac{s_1 s_2}{(s+s_1)(s+s_2)}$$

where s_1 and s_2 are positive and$s_1 > s_2$. The transfer function of the MA system is

$$H_{MA}(s) = \frac{s_1}{s+s_2}.$$

Figure 3 shows the step response of the nominal systems and the step response of the reduced-order system for different values of the non-dominant-to-dominant pole ratio, γ, where $\gamma = \frac{s_2}{s_1}$. As γ increases, the reduced-order system better represents the nominal system.

The modal approximation of the second-order DC motor given in Equation 2 is reduced by the following transfer function:

$$H_{MA}(s) = \frac{K_a}{K_a^2 + r_a B_m} \frac{s_1}{s+s_1} \tag{4}$$

where

$$s_1 \equiv \frac{\left(\frac{B_m}{J} + \frac{r_a}{L_a}\right) - \sqrt{\left(\frac{B_m}{J} - \frac{r_a}{L_a}\right)^2 - \frac{4K_a^2}{L_a J}}}{2}$$

is the system dominant pole (refer to Equation (3).

Another MOR technique particular to DC motors is Neglecting the Armature Inductance (NAI). If the armature inductance is neglected in the system differential equations, Equation 1, the following first-order transfer function is obtained:

$$H_{NAI}(s) = \frac{K_a}{r_a J} \frac{1}{s + \frac{r_a B_m + K_a^2}{r_a J}}. \tag{5}$$

The conditions found in the literature for justifying the reduction of DC motors vary and can be ambiguous. In some cases the condition for neglecting the armature inductance is based on the magnitude of the armature inductance being small [1, 14, 19], and in other cases the electrical time constant is much smaller than the mechanical time constant $\tau_{mech} >> \tau_{elec}$ [2, 4, 20].

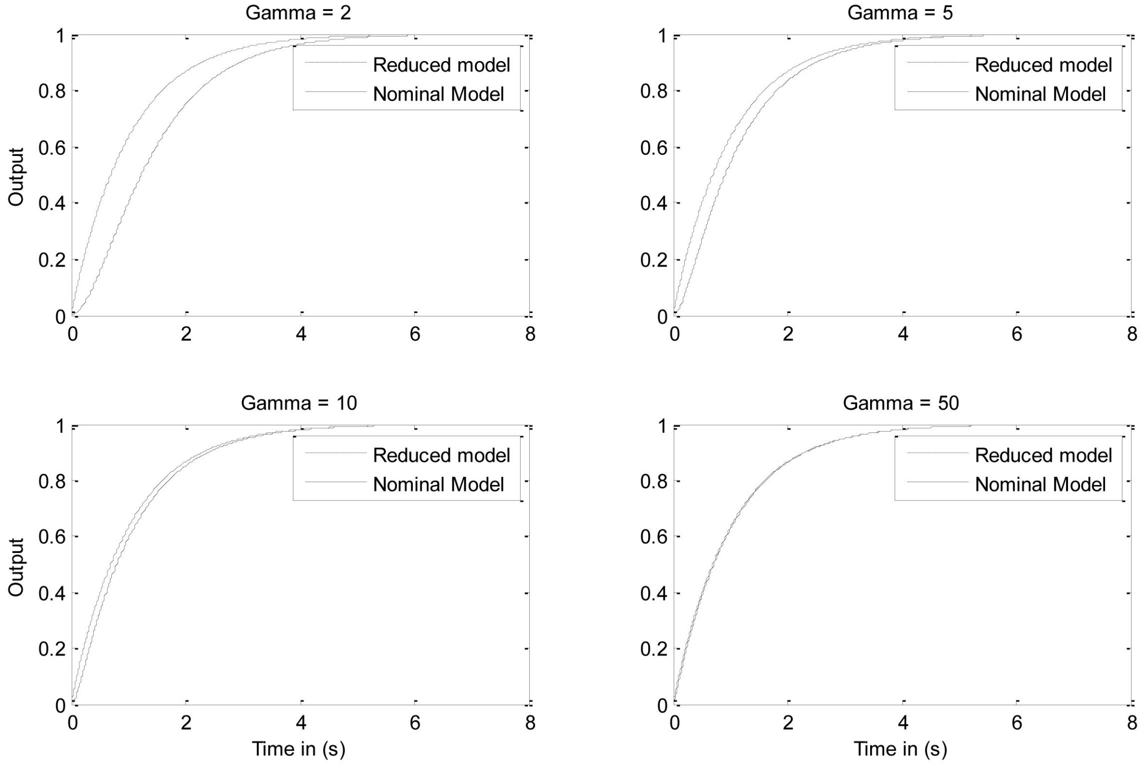

Fig. 3. Step response: nominal versus reduced-order systems.

To justify the MOR for DC motors it is essential to analyse how the different parameters of the DC motor effect the location of the actual system poles. The poles of the DC motor are the roots of its characteristic equation:

$$L_a J x^2 + (L_a B_m + r_a J)x + r_a B_m + K_a^2 = 0 \tag{6}$$

The system's actual poles are at the intersection of the parabola $y_1 = L_a J x^2 + (L_a B_m + r_a J)x + r_a B_m$ and the straight line $y_2 = -K_a^2$ since $y_1 - y_2$ is the characteristic equation given in Equation 6. Figure 4 shows the parabola and straight line using the parameters of the Power Lab Motor.

The parabola intersects the x-axis at

$$-\frac{r_a}{L_a} \equiv -s_{elect} \quad \text{and} \quad -\frac{B_m}{J} \equiv -s_{mech},$$

which are equal to the poles of the electrical and mechanical sub-systems but are different from the system actual poles. The parabola's vertex coordinates:

$$x_v \equiv -\frac{1}{2}\left(\frac{B_m}{J} + \frac{r_a}{L_a}\right) \tag{7}$$

$$y_v \equiv -\frac{1}{4}\left(\frac{r_a}{L_a} - \frac{B_m}{J}\right)(L_a B_m - r_a J) \tag{8}$$

It is worth noting that as y_2 approaches the vertex, the actual poles are brought closer together. If

$$\tau_{mech} = \frac{J}{B_m} >> \tau_{elec} = \frac{L_a}{r_a}, \quad \text{then} \quad \mathrm{y_v} \cong \frac{1}{4}\left(\frac{\mathrm{r_a^2 J}}{\mathrm{L_a}}\right).$$

Consequently, if the value of K_a^2 is close to

$$\frac{1}{4}\left(\frac{r_a^2 J}{L_a}\right),$$

then the system poles become too close together to have the order of the plant reduced.

Examining the system illustrated in Fig. 2 and using root-locus analysis, the electrical and mechanical poles can be considered as open-loop poles. Consequently, as K_a increases, the actual poles, or the closed-loop poles of the system in Fig. 2, approach one another. This phenomenon is also consistent with the analysis associated with Fig. 4.

Rule 1: As a rule of thumb, the ratio $\frac{-y_v}{K_a^2}$ should be larger than five or equivalently the ratio of the non-dominant pole to the dominant pole should be significantly larger than five in order to reduce the order of the plant. In addition, the larger the ratio the more accurate the reduced-order model becomes.

2.2.4 Experimental procedure

The second half of Session 1 involves the experimental part where students identify the parameters of the DC motor and implement a P-type speed controller by following the guidelines below.

Parameter identification

Determining r_a and L_a (Locked Rotor Test): A square wave generator is connected to the power amplifier on the board and then connected to the motor. The motor is connected in series to a 1 Ω resistor so the voltage across the resistor is equal to the current through the motor and resistor. Given a

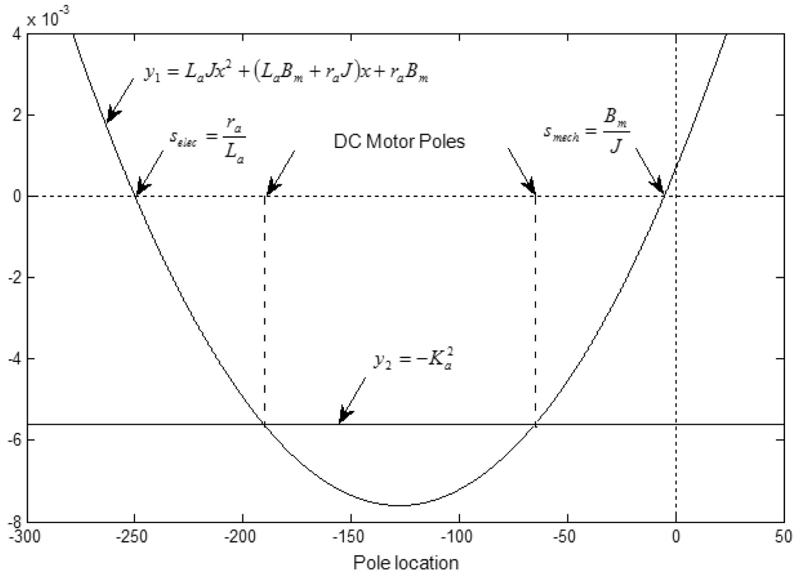

Fig. 4. Relationship of actual poles to electrical/mechanical subsystem poles.

square wave input, and having the angular speed $\omega_r(t) = 0$, the current should reach steady state exponentially. The input voltage and the current are saved using a data acquisition system. Students estimate the time constant, L_a/r_a, and the steady-state gain, $1/r_a$, to calculate r_a and L_a.

Identification of K_a and B_m: After identifying r_a and L_a, B_m and K_a can be identified from the steady-state values of the step response of the motor. During the steady state of a step response of a motor

$$\frac{di_a(t)}{dt} = 0 \quad \text{and} \quad \frac{d\omega_r(t)}{dt} = 0,$$

the angular speed is measured using a tacho-generator, and

$$K_a = \frac{u_a(t) - r_a i_a(t)}{\omega_r(t)} \quad \text{and} \quad B_m = \frac{K_a i_a(t)}{\omega_r(t)}.$$

The current and angular speed are measured for different input voltages. B_m and K_a are calculated for a few different values of $u_a(t)$ and then averaged out.

Identification of J: The last parameter to be identified is the moment of inertia, J, which is basically obtained by a trial-and-error procedure. In particular, the step response of a model reference with adjustable values of J is compared with the step response of the actual motor. If the simulated response is less than the experimental response, then the moment of inertia is increased and vice versa. The student should tune J so that the simulated response is similar to the experimental response.

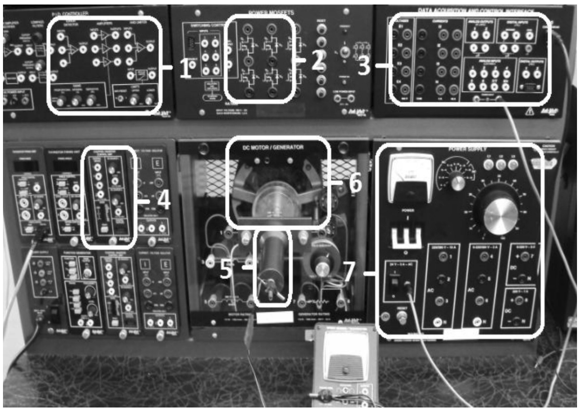

Fig. 5. Power Lab DC motor bench: 1- PID board; 2- Power MOSFETs in an H-bridge configuration (used as a buffer); 3- Data acquisition interface; 4- Chopper/inverter control unit (used to convert analog signal to PWM signal); 5- Tacho-generator; 6- DC motor; and 7- Power supply.

Limitations in the implementation of a P-type controller: Since the plant under consideration is of type zero, in order to decrease the steady-state error, the gain of the P-type should be increased. However, in order to implement a 'robust' closed-loop system, students should observe the response of the system for large values of the P-type gain and also monitor any unexpected behaviours due to disturbances and measurement errors. Students should observe and record the system time constant and steady-state error as the gain of the P-type controller is increased. Students should also record the critical P-type gain at which the response significantly deviates from its theoretical norm. The recorded experimental data will be used in the subsequent session for further analysis.

2.3 Session 2

2.3.1 Equipment list

Another DC motor, with poles that are relatively close, is needed. The employed system components are shown in Fig. 5.

2.3.2 Introduction by lab instructor

The lab instructor introduces the equipment, operation and data acquisition of the system associated with the Power Lab Motor. This part will expose the students to the operation of different systems.

2.3.3 Observations and analysis: power and control lab motors

At this stage, students are ready to use the identified parameters, and the saved experimental responses for the two motors for analysis.

Students are first asked to comment on the open-loop and closed-loop step responses performance of three models by comparing them to the experimental results for the two motors during both the transient period and the steady state. The corresponding analysis entails the following tasks.

1. Using the identified parameters of the Power Lab Motor, students numerically simulate step response as well as implementing a P-type controller for: (1) the second-order (nominal) model, (2) the reduced model obtained by the NAI method, and (3) the reduced model obtained by the MA method. Corresponding numerical and experimental results, involving the step response and the implementation of a P-type controller, are then compared graphically. Students should observe that the second-order model simulates the experimental response with insignificant errors, whereas both MA and NAI reduced models result in a noticeable error during the transient period.

Students should also notice that the reduced-order models cannot result in overshoot (being first-order systems). However, students should notice that the nominal model simulates the physical plant well.

2. The same procedure as that above is repeated for the Control Lab Motor. Students should notice that the simulated responses for all three models simulate the experimental response for the open-loop step response and closed-loop step response.

2.3.4 Observations and analysis: fictitious motor

The following part of the module considers a scenario of a fictitious motor with armature inductance and electric and mechanical poles that are the exactly the same as the Control Lab Motor, except that the value of K_a is significantly different. The value of K_a is chosen such that the ratio $\frac{-y_v}{K_a^2}$ is significantly smaller than 5 as opposed to Rule 1 where y_v is defined in Equation 8.

The corresponding analysis entails the following tasks.

1. Using the parameters of a fictitious model sharing the same parameters as the Control Lab Motor, except for a value of K_a that is 7.5 times larger, students are asked to numerically simulate the step response for the three models.
2. Based on root-locus analysis for the second-order model (nominal) and first-order models (reduced-order models), students are asked to analyse the presence and absence of overshoot while implementing a P-type controller for both motors.

2.3.5 Observations and analysis: wrap-up

1. Based on the numerical and experimental results for both motors and the theoretical results (Fig. 4), students are asked to assess specific conditions for the use of model-order reduction. In particular, students are asked to examine the four conditions, listed in the first row of Table 1, for a reliable employability of the reduced-order models for both motors as well as the fictitious model. The conditions are: (a) L_a being small, (b) the ratio of electrical pole over the mechanical pole being large, (c) the ratio of the vertex (Fig. 4) over K_a^2 being larger than 5 (consistent with Rule 1), and (d) the ratio of actual poles being significantly larger than 5.

Based on numerical and experimental results, and the values listed in Table 1, the students should be able to understand the basic consequences of modelling and model-order reduction and notice that the conditions (a) and (b) can be misleading, whereas conditions (c) and (d) are sound. By the end of the module, the lab instructor goes over the expected results and summarizes relevant analysis.

3. Assessment

Students were exposed to the following theoretical concepts:

1. modelling, model-order reduction, and parameter identification of a dc motor;
2. transient and steady-state response analysis;
3. root locus and controller design.

Students also experienced other practical issues such as:

1. basics of motor operation: students will be exposed to dealing with sensors (e.g., ammeter, tacho-generator and encoder) needed for procedures such as applying a step input and observing its response;
2. different power electronics configurations: students will be made aware of the use of H-bridge and power operational amplifiers;
3. data acquisition: students will use acquisition system(s) needed for interpretation and analysis of data pertaining to relevant measurements.

All the teams ended up successfully experimentally and numerically implementing all the concepts involved in this proposed module. Few students received some guidance from the lab instructor during implementation. Right before taking this module, students did not have any knowledge about parameter identification, different power electronics configurations, or parts of data acquisition. The ability for the students to properly implement and to a certain extent analyse such concepts experimentally and numerically within *two lab modules* is considered sufficient for assessing their actual learning expected from the proposed two modules. However, in order to reflect on the perspective of students pertaining to the objectives of the two new

Table 1. Parametric conditions for MOR: existing (a) and (b) versus proposed (c)

Condition related to the size of:	**(a)** L_a	**(b)** $\frac{s_{elec}}{s_{mech}}$	**(c)** $\frac{-y_v}{K_a^2}$	**(d)** $\frac{s_2}{s_1}$
Power Lab Motor	0.2 mH	232	1.21	2.35
Control Lab Motor	0.06 mH	1535	63.21	216
Fictitious Motor	0.06 mH	1535	1.12	2

Table 2. Questionnaire results on the four objectives

Knowledge Statements	Average Score	Percentage of students choosing A or SA
I was able to comprehend the operational concepts of DC motors.	3.97	77%
I was able to relate my knowledge acquired in the circuits and control courses to the concepts involved in model order reduction techniques and the parameter identification procedure.	3.94	71%
I was able to comprehend the basic conditions that are needed to reduce the order of a DC resulting in insignificant errors.	4.06	74%
I learned how to numerically simulate and analyze different configurations of control systems.	4.48	94%

Table 3. Questionnaire results on knowledge gained

Differential Knowledge Statements	Average score	Percentage of students choosing A or SA
Before going through this module I did not appreciate as much the significance of theoretical concepts and numerical simulation to practical applications.	3.61	72%
Application of my knowledge from the circuits and control systems courses was used significantly more than any other module.	3.89	83%
After completing this module, I am now able to check for the proper conditions needed for model-order reduction of a DC motor more rigorously and comprehensively.	3.83	78%
The module significantly improved my understanding towards the impact of modeling to control design.	3.83	78%
After taking this module, I feel more comfortable with the use of data acquisition and sensors needed for interpretation and analysis of data pertaining to measurements of the input and output of a DC motor.	4.06	94%

modules, an indirect assessment method was performed.

At the end of the module, 31 students completed one questionnaire evaluation survey (Table 2) that directly targets the desired four objectives presented in Section II-A. Eighteen students completed another questionnaire evaluation survey (Table 3) that targeted the knowledge gained during this module after completing the module.

Scores range from 1 to 5 according to how much they agree with the knowledge statements. In particular: 1—Strongly Disagree (SD); 2—Disagree (D); 3—No Opinion (NO); 4—Agree (A); and 5—Strongly Agree (SA).

Remark: Another common approach in assessing the knowledge *gained* during this two-session module is to give the same survey to students before and after the module. However, such an approach can be misleading and biased in this specific study. In particular, when students are asked about the level of knowledge before taking this module, then students may believe that they feel very comfortable and choose 'Strongly Agree', leaving no room for a differential measure. For example, if students are asked about their ability to check for the proper conditions needed for model-order reduction of a DC motor, then based on the concepts presented in a typical control course, students may choose SA without appreciating the practical issues that are presented during this module.

At least 70% of the students Agreed or Strongly Agreed with all the objectives and knowledge 'differential' statements (Tables 2 and 3). Consequently, it may be claimed that student knowledge improved significantly, taking into consideration that this lab module is composed of only two lab sessions.

4. Conclusion

One main goal of the proposed lab module targeted experiential learning, where students were exposed to notions closely related to real-life situations pertaining to classical control systems. This module, which was composed of only two lab sessions, well integrated key theoretical concepts with numerical and experimental analysis. This paper presented a novel concept in model-order reduction of a DC motor. In particular, this paper provided a condition for neglecting the armature inductance and showed that the two corresponding conditions in the existing literature can be misleading. In addition, this module addressed parameter identification, and different measurement techniques and data collection. The equipment needed for this lab consisted of 'generic' equipment existing in typical electrical engineering labs. Based on assessment results, the students successfully acquired in their matriculation through this module all the objectives described in this paper.

References

1. K. Ogata and Y. Yanjuan, *Modern Control Engineering,* 4, Prentice Hall, Upper Saddle River, NJ, 1990.
2. K. Benjamin and F. Golnaraghi, *Automatic Control Systems*, 4, John Wiley & Sons Ltd, 2003.
3. R. H. Bishop and R. C. Dorf, *Modern Control Systems*, Prentice Hall College Division, 2004.
4. R. N. Bateson, *Introduction to Control System Technology*, Prentice Hall , 1999.
5. C. A. Ramos-Paja, J. M. R. Scarpetta and L. Martínez-Salamero, Integrated learning platform for internet-based control-engineering education, *IEEE Transactions on Industrial Electronics*, **57**(10), 2010, pp. 3284–3296.
6. A. M. Borrero and J. M. Andújar, Interaction of real robots with virtual scenarios through augmented reality: application to robotics teaching/learning by means of remote labs, *International Journal of Engineering Education*, **29**(3), 2013, pp. 788–798.
7. R. Patil, J. Wagner, T. Schweisinger, R. Collins, A. Gramopadhye and M. Hanna, A multi-disciplinary mechatronics course with assessment—integrating theory and application through laboratory activities, *International Journal of Engineering Education*, **28**(5), 2012, pp. 1141–1149.
8. D. Ibrahim and J. F. Abu Hasna, Teaching PID auto-tuning using a low-cost control kit, *International Journal of Engineering Education,* **29**(1), 2013, pp. 239–247.
9. M. Gunasekaran and R. Potluri, Low-cost undergraduate control systems experiments using microcontroller-based control of a DC motor, *IEEE Transactions on Education,* **55**(4), 2012, pp. 508–516.
10. O. Bingöl and S. Paçaci, A virtual laboratory for neural network controlled DC motors based on a DC–DC buck converter, *International Journal of Engineering Education*, **28**(3), 2012, pp. 713–723.
11. T. J. Schubert, F. Jacobitz and E. Kim, Exploring the basic principles of electric motors and generators with a low-cost sophomore-level experiment, *IEEE Transactions on Education,* **52**(1), 2009, pp. 57–65.
12. D.-J. Lim, An undergraduate laboratory course in real-time dynamic control, *IEEE Transactions on Education,* **48**(1), February 2005, pp. 105–110.
13. J. Apkarian and K. Åström, A laptop servo for control education, *IEEE Control Systems,* **24**(5), 2004, pp. 70–73.
14. E. Vazquez-Sanchez, J. Gomez-Gil, J. C. Gamazo-Real and J. F. Diez-Higuera, A new method for sensorless estimation of the speed and position in brushed DC motors using support vector machines, *IEEE Transactions on Industrial Electronics*, **59**(3), 2012, pp. 1397–1408.
15. J. Benecke, Impedance and emission optimization of low-voltage DC motors for EMC compliance, *IEEE Transactions on Industrial Electronics*, **58**(9), 2011, pp. 3833–3839.
16. C. E. Castaneda, Alexander G. Loukianov, Edgar N. Sanchez, Bernardino Castillo-Toledo, Discrete-time neural sliding-mode block control for a DC motor with controlled flux, *IEEE Transactions on Industrial Electronics*, **59**(2), 2012, pp. 1194–1207.
17. N. K. Sinha, C. D. Dicenzo and B. Szabados, Modeling of DC motors for control applications, *IEEE Transactions on Industrial Electronics and Control Instrumentation*, **21**(2), 1974, pp. 84–88.
18. R. Kelly and J. Moreno, Learning PID structures in an introductory course of automatic control, *IEEE Transactions on Education,* **44**(4), 2001, pp. 373–376.
19. M. Koksal, F. Yenici and A. Asya, Position control of a permanent magnet DC motor by model reference adaptive control, *IEEE International Symposium on Industrial Electronics*, 2007.
20. Z. Li, J. Chen, G. Zhang and M. Gan, Adaptive robust control for DC motors with input saturation, *Control Theory & Applications, IET*, **5**(16), 2011, pp. 1895–1905.
21. H. Paiva and R. Galvao, Simulation of dynamic systems with output saturation, *IEEE Transactions on Education,* **47**(3), 2004, pp. 385–388.

Raffi Toukhtarian received his BE degree in Electrical Engineering and his MS degree in Computer Engineering from the Lebanese American University, in 2005, and 2013, respectively. He is currently pursuing his Ph.D. degree in Electrical engineering at McGill University. From 2010 to 2013, he worked as an instructor at the Lebanese American University, teaching circuits, electronics and control laboratories. He served as a Research Assistant with the Department of Electrical Engineering at the Lebanese American University. His research interests are in the area of automatic control and circuit simulation.

Samer S. Saab received his BS, MS and Ph.D. in Electrical Engineering in 1988, 1989 and 1992, respectively and an MA in Applied Mathematics in 1990, from the University of Pittsburgh. He joined the faculty of the Lebanese American University (LAU) in 1996. He is a Professor of Electrical Engineering at LAU. He worked for Union Switch and Signal and ABB Daimler-Benz Transportation, Pittsburgh, PA, 1993–1996. He is the recipient of the opening (2007–2008) LAU Best Research Award in engineering and physical sciences. His research interests include iterative learning control, Kalman filtering, navigational positioning systems, and wireless communications. He served on the Editorial Board of the *IEEE Transactions on Control Systems Technology* from 2005 to 2011 and on the Editorial Board of the *IEEE Control Systems Society-C* from 2005 to 2009.