Using Modeling and Simulation Projects to Meet Learning Objectives in an Upper-Level Course in System Dynamics

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Abstract

Modeling and simulation projects in an upper-level system-dynamics course are described with an emphasis on using these projects to support course learning objectives. Course-specific objectives include: modeling engineering systems using Lagrange's equation; using the Dymola software package to solve the resulting nonlinear differential-algebraic equations; and validating simulation results. General educational objectives include: reproducing published work and comparing and interpreting the results; close reading for understanding; critical reading to identify unstated assumptions and incomplete development, and responding to such deficiencies; and developing a project topic, scope of work, and final report consistent with professional standards. The course and projects are described and examples of student work are given. The discussion concludes with a summary of student responses and possible drawbacks to the approach and of how project outcomes support the learning objectives.

1. Introduction

Projects, projects everywhere! Students are doing projects in courses all across the engineering curriculum. Depending on the course level, freshman to graduate, different learning objectives can be met using projects, some relating to the specific content of a course and others relating to broader goals of an engineering education. In upper-level courses, faculty have the opportunity to set high standards for project deliverables, meeting one of the primary goals of an undergraduate engineering education, that of preparing students to enter either engineering practice or graduate school. In either case, the experience of producing project results and reports that are technically thorough and coherently written is a valuable one.

This paper describes modeling and simulation projects in an upper-level mechanical engineering course and the manner in which these projects support a variety of learning objectives.

2. Course description

The course is ME597 Modeling and Simulation of Dynamic Systems, an elective open to graduate and undergraduate students in math, science, and engineering. The course presents a unified approach for modeling and simulating multidisciplinary engineering systems. The text is by Layton [1]. Detailed course information is available at the course website [2] and at the website of a similar course taught at the University of Washington [3]. In both courses, *modeling* is the formulation of mathematical models—sets of linear or nonlinear ordinary differential equations (ODEs) and, if algebraic constraints are present, differential-algebraic equations (DAEs)—based on the physical systems theory developed in [4]. *Simulation* is the numerical solution of these initial-value problems in ODEs and DAEs. Students are assigned projects in modeling and simulation to develop their skills in applying these methods to engineering systems. These projects and their educational objectives are the subject of this paper.

The course objectives are summarized as follows. At the conclusion of the course, students should be able to:

- write expressions to model the energy functions, virtual work, and constraints of multidisciplinary engineering system or components
- using these expressions, apply a differential-algebraic equation (DAE) form of Lagrange's equation to obtain a DAE model in one of several standard forms
- numerically solve the resulting DAE initial-value problem using the DYMOLA software package
- assess the reliability of the numerical solution.

The numerical solution of initial-value problems in DAEs is a current research topic. DAE theory is both much more recent than ODE theory and is more in a state of flux [5]. Software for the solution of initial-value problems in DAEs includes the code DASSL by Petzold [6], RADAU5 by Hairer and Wanner [7], LDAE by Fabien [8], and several codes specialized for constrained mechanical systems such as MEXX by Lubich et al. [9]. The commercial package selected for this course is DYMOLA [10], which incorporates a version of DASSL for integrating initial-value problems in DAEs as well as several algorithms for integrating ODEs. DYMOLA was selected for the course for its ease of use as an ODE/DAE solver (the software's hierarchical models and component libraries and connectors are not used in this course).

The class is a conventional 4-credit-hour lecture course, meeting four times per week for ten weeks. Fourteen of the 50-minute class periods are set aside for lab/project work. Three of these lab/project periods are used for software tutorials; eleven are used for project work. Course grading reflects this emphasis on the projects: homework is 18% of the final course grade, two exams are each 18%, the first project is 18%, and the second project is 28%. The projects account for nearly half (46%) of the course grade.

This was the first offering of the course at Rose-Hulman (Fall 2002) and enrollment was small—only five students. The class included three graduate and two undergraduate students, one female and two international students, and two of the students were double-majors—one in mechanical engineering and electrical engineering and the other in mechanical engineering and computer science.

3. Projects overview

Modeling and simulation projects give students opportunities to apply the theory and methods of the course to nontrivial problems. Two projects are assigned. In the first project, working individually, students reproduce the results of a published modeling and simulation problem, gaining familiarity with the course software and writing standards. In the second project, working in teams, students select an open-ended problem in modeling and simulation.

A writing assignment is due each week, according to the schedule shown in Table 1. The only items in Table 1 that are graded are the two final reports, emphasizing: 1) that the purpose of the interim deliverables is to encourage consistent progress and to give regular feedback with the explicit goal of improving the final report; and 2) that in this profession, the document on which one's performance is usually assessed is the final submission.

Table 1: Schedule of project assignments

Week	Due	Week	Due
1	Proj. 1 preliminary proposal	6	Proj. 1 final report (graded)
2	Proj. 1 proposal	7	Proj. 2 proposal
3	Proj. 1 draft	8	Proj. 2 draft
4	Proj. 1 draft results	9	Proj. 2 draft results
5	Proj. 2 preliminary proposal	10	Proj. 2 final report and oral presentation (graded)

The author worked with students individually and in teams to help them reach a level of reporting approaching professional standards. The report format is adapted from the guidelines for conference papers established by the American Society of Mechanical Engineers (ASME Intl) [11]. The course webpage provides templates for reports and memoranda, guidelines for graphic elements (tables, figures, and equations), and a link to the ASME author guidelines. These guidelines introduce (or possibly reintroduce) students to the form and content of professional technical writing. The ASME guidelines are used in this case because these students are ME majors. Similar guidelines are published by other professional societies, and instructors wishing to apply this method in their own courses could use guidelines published in their disciplines, making the case to students that such standards are indeed relevant to education in their discipline.

To further emphasize the importance of communication in engineering education, the students are encouraged to present their projects at a regional or student conference of an engineering society such as ASME, ASEE, or IEEE. As an additional incentive, an increase in their course grade is offered (retroactively, if necessary) if the students make the presentation anytime during the following two quarters. The format (oral, written, poster) depends on the conference. As of this writing, one student has submitted the final report of his team's project to a conference on symbolic computation and a second student is planning to present her team's project at a student conference.

4. Dymola tutorials

Computer simulation, in this case, the numerical solution of initial-value problems in ODEs and DAEs using DYMOLA, is one of the main course topics. The author wrote elementary tutorials for the first two lab/project periods to help students gain basic proficiency in using DYMOLA. The objective of Lab 1 is to use DYMOLA to create a model, solve the ODE, and plot the results. The objective of Lab 2 is to use MATLAB to import and plot results from DYMOLA simulations. Both tutorials are available on the course webpage.

Near mid-term, two of the students successfully used the DYMOLA/SIMULINK interface in the course of their project work. As a service to the class, one of these students prepared and delivered a 20-minute lesson on this topic, forming the basis for a third software tutorial the author plans to develop for the next offering of the course. This event illustrates another way in which the projects support the course learning objectives. All of us learned something new about the software package and the student who gave the lesson gained the experience of acquiring new technical expertise and then teaching it to others.

5. Descriptions and results of projects

5.1 Overview of Project 1: Individually reproducing published simulation results

In the first project, working individually, students reproduce the results of a modeling and simulation problem of their choosing from a conference proceeding, journal article, or other published source. The primary learning objectives of this project are:

- to gain familiarity with modeling and simulation literature
- to gain familiarity with the Dymola software package
- to gain familiarity with the course writing standards.

Learning objectives also include:

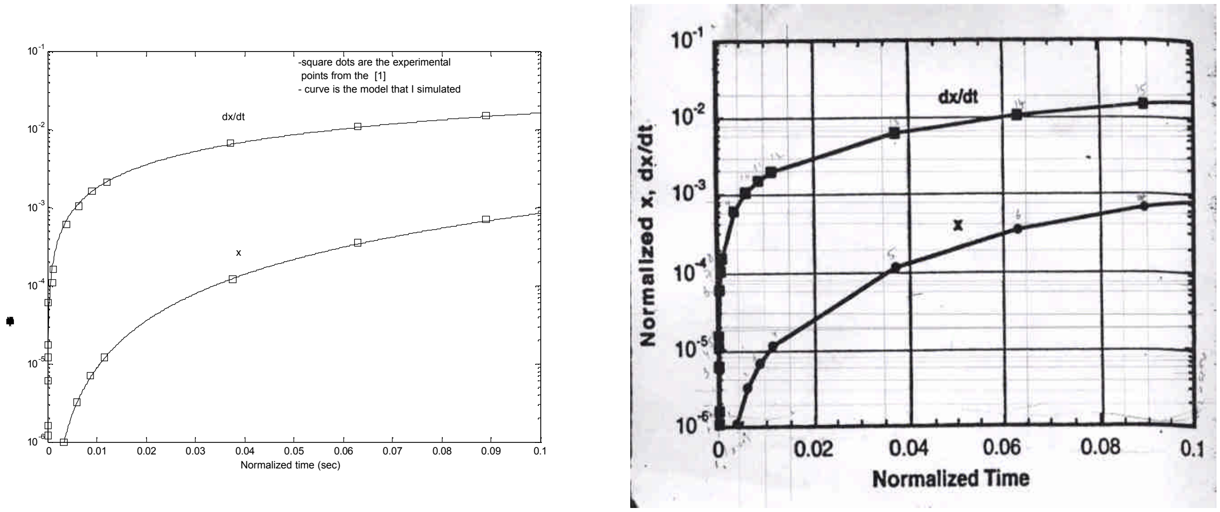
- close reading for understanding (necessary if one is to reproduce another's work)
- critically reading published work to identify elements of the modeling and simulation problem that are omitted or incompletely developed and then correcting the deficiency
- developing methods to compare one's simulation results to previously published results.

Project 1 is an individual effort, and no two projects are the same. The instructor provided examples of modeling and simulation problems from the literature and students selected one of these or found their own source in an area of interest to them. The projects and their sources are:

- reproducing a simulation of an electrostatic actuator [12]
- reproducing a simulation of a printer belt drive [13]
- reproducing a simulation of a linear compressor [14]
- reproducing a simulation of a stiff elastic tape wrapped onto a drum [15]
- reproducing a simulation of a high-speed pantograph [16].

5.2 Results of Project 1

Electrostatic actuator. In the actuator project based on [12], the model is a third-order nonlinear ODE. One of the plots developed by the student to compare his simulation results to the published results is shown in Fig. 1. In Fig. 1(a), the two curves shown are DYMOLA numerical solutions. The discrete data symbols in Fig. 1(a) represent the student's best estimate of data from the source paper, shown in Fig. 1(b). Difficulties the student overcame in obtaining this comparison include: the initial conditions of the initial-value problem were not clearly identified in the source paper, requiring the student to read closely for understanding; initial simulation results were unstable, requiring the student to deal with numerical integration issues such as solver order and tolerance; subsequent simulation results were still unstable due to a model error—the student omitted a constant coefficient—illustrating the importance of care in writing computer code and that simulation reliability depends on details such as assigning numerical parameters correctly.



(a) Results from the student's simulation. (b) Results from the source paper [12].

Fig. 1: Example of comparing student simulation results to published simulation results.

Printer belt drive. In the belt drive project based on [13], the model is a third-order linear ODE. In this case, the source authors provided an analytical expression for their results which the student used to generate a data set in MATLAB that could be subtracted point-by-point from her DYMOLA results, creating a "simulation error" comparison. The error, shown in Fig. 2, is two orders of magnitude smaller than the simulation results, indicating satisfactory agreement with the published results. Difficulties the student overcame in obtaining this comparison include: matching the time interval between output points in the MATLAB–generated results and the DYMOLA–generated results; and importing DYMOLA results into the MATLAB environment.

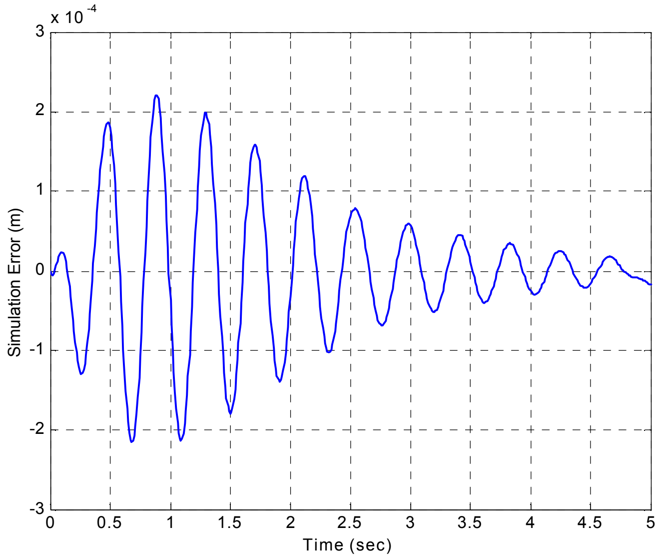
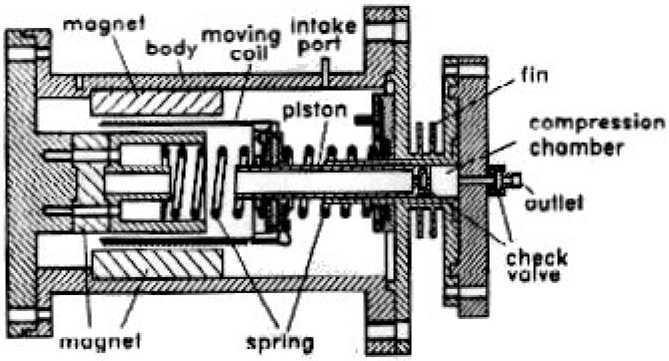
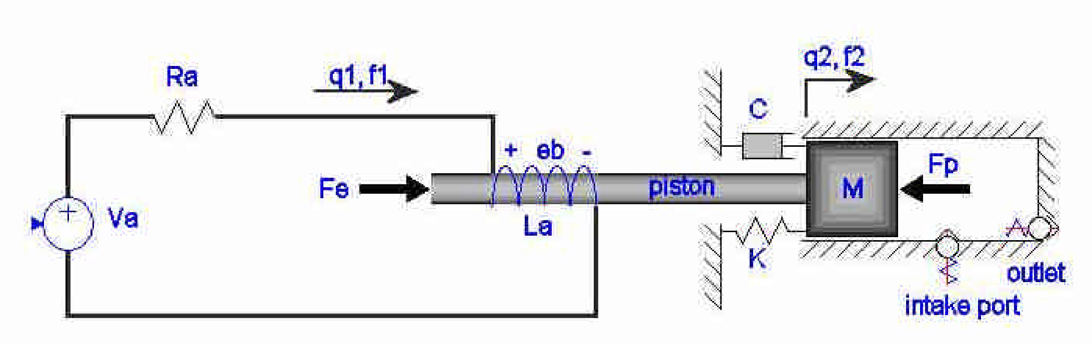


Fig. 2: Point-by-point comparison of a student simulation to published simulation.

Linear compressor. In the linear compressor project based on [14], the model is a third-order linear ODE. In this case, the authors of the source paper included a cross-sectional view of the linear compressor (see Fig. 3a), but did not include an engineering schematic of the system to illustrate the interactions of the components. The student used the information given in the paper, including the equations of motion, to develop the schematic shown in Fig. 3(b), correcting a minor deficiency in the source paper.



(a) Cross-sectional view of a linear compressor, from [14].

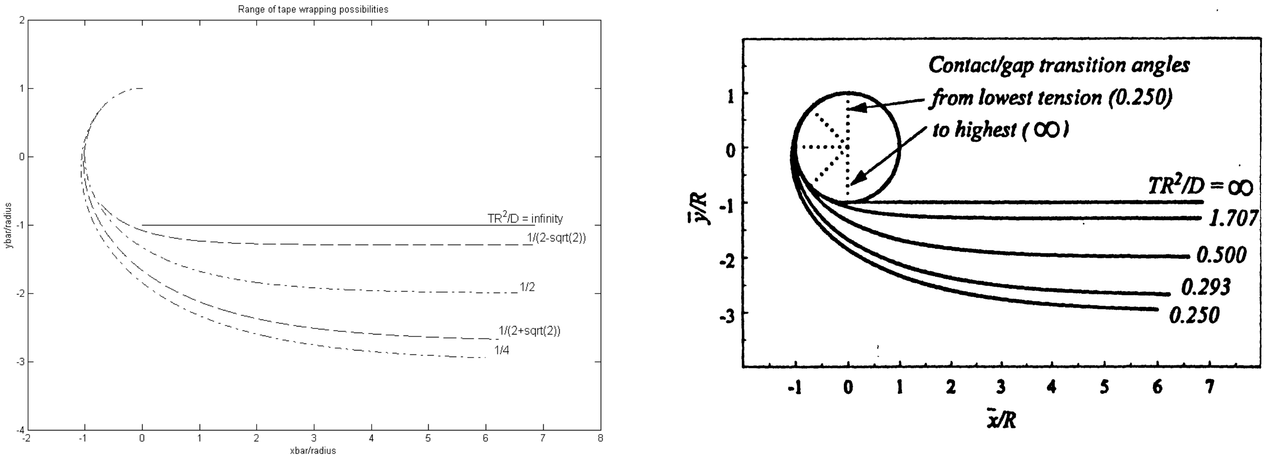


(b) Student-developed schematic of the linear compressor showing parameters and state variables.

Fig. 3: Example of a student-developed schematic to illustrate the operation of the physical system.

The comparison of simulation results to published results is similar in kind to that shown in Fig. 1 and so is not reproduced here. Difficulties the student overcame in obtaining this comparison include: the system input is a pseudo-random binary signal (PRBS) and a model of this signal is not included in the source paper—the student did the necessary research to define the signal and wrote the SIMULINK code to model it; the student worked out the details of embedding the DYMOLA model of the system in a SIMULINK block, a case for which the DYMOLA documentation was somewhat limited; because the input is random, the student's simulation results and the published results are not identical—the student had to develop a quantitative comparison based on characteristics of the two results such as maximum and minimum amplitude and average response frequency rather than a direct, point-by-point comparison.

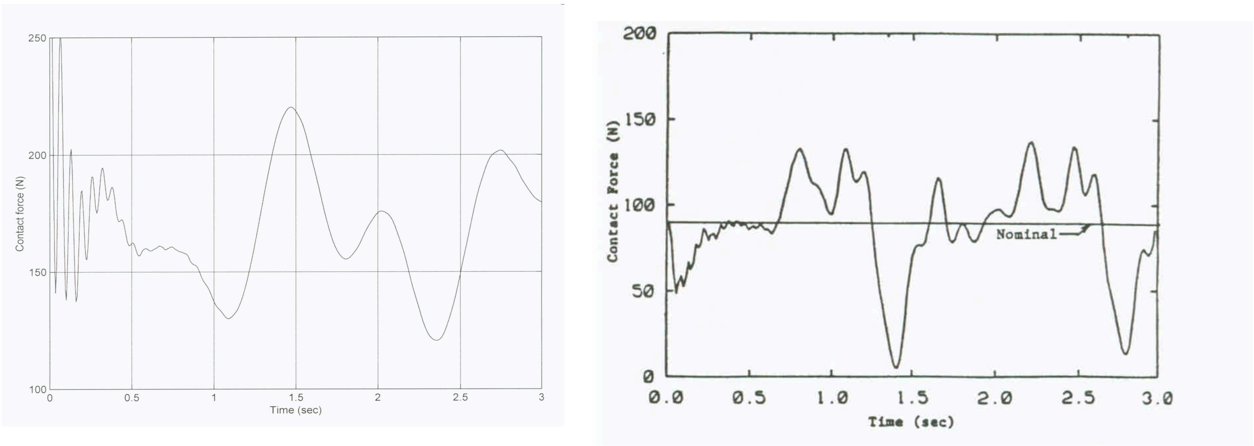
Stiff elastic tape wrapped onto a drum. In the tape-and-drum project based on [15], the model is a third-order nonlinear ODE. The plot developed by the student to compare his simulation results to the published results is shown in Fig. 4. The curves in Fig. 4(a) are the numerical solutions obtained using DYMOLA; Fig. 4(b) is from the source paper. The primary difficulty the student overcame in obtaining this comparison was close reading for understanding. The source paper is unclear on 1) which of the many equations provided constitute the final system model, and 2) on the method of normalizing the results. The theory developed in the paper suggested a numerical integration was required to produce the results shown, but on closer reading, only a simple coordinate transformation was required. An additional minor difficulty is that the independent variable in this problem is a displacement variable *s* instead of the usual time variable *t*. Care was required in setting up the simulation because DYMOLA assumes time is the independent variable.



(a) Results from the student's simulation. (b) Results from the source paper [15].

Fig. 4: Example of comparing student simulation results to published simulation results.

High-speed pantograph. In the pantograph project based on [16], the model is a fourth-order linear ODE. Difficulties the student overcame in reproducing the published results relate primarily to information missing from the source paper. For example, the source paper contained a schematic of the system but neither a model nor a statement of initial conditions; the student had to develop his own model from the schematic and to infer initial conditions from simulation results in the paper. The system input (the catenary shape) is experimental and a model of the input is not provided; the student had to develop a discrete Fourier-series model of the input based on a graph given in the source paper. A precise definition and model of the contact force (one of the variables for which a comparison of results is sought) was not provided by the authors. The student's best effort (with faculty assistance) to model this force produced results that do not duplicate the published results. A comparison of these results is shown in Fig. 5. The student results have a much greater degree of oscillation at the beginning of the simulation than the published results, probably indicating an difference in initial conditions. (Note that the two figures have different scales on the vertical axes.) The average value of the student's result is nearly twice that of the source's, probably due to a difference in the model of the contact force. And the shapes of the two plots, which should be identical, are quite different, probably due to differences in the input model.



(a) Results from the student's simulation. (b) Results from the source paper [16].

Fig. 5: Example of a failed duplication of published simulation results.

5.3 Overview of Project 2: Open-ended team-project in modeling and simulation

In the second project, working in teams, students select an open-ended problem involving a physical system of their choosing. Possible topics include parameter identification, model validation, and automated model formulation. The primary learning objectives of this project are:

- model a system using Lagrangian DAEs
- simulate the system using DYMOLA
- validate the results

Learning objectives also include:

- developing a project topic, scope of work, and final report suitable for presentation at a student conference or a student-paper competition
- applying modeling and simulation techniques at higher cognitive levels (levels 4, 5, or 6 of Bloom's taxonomy)

The instructor assigned students to teams of 2 or 3 based on student interests. The projects have a scope of work that is large enough to warrant the team effort. The students develop project proposals based on suggestions from the instructor. The two projects that emerged are:

- Creating a MAPLE worksheet to automatically generate elements of a Lagrangian DAE.
- Parameter identification, modeling, and simulation of a cart and pendulum.

5.4 Results of Project 2

Team 1: Creating a MAPLE worksheet to automatically generate elements of a Lagrangian DAE. This project is primarily a programming effort aimed at creating a software tool to eliminate some of the mathematical manipulations involved in modeling with Lagrangian DAEs. The primary customers for the project are the instructor and future students in this course. The software tool eliminates the error-prone and time-consuming process of pencil-and-paper differentiation associated with Lagrangian DAEs. This should help students in future offerings of this course model complicated systems with less drudgery and less likelihood of symbolicmanipulation error than when doing these differentiations by hand. (The LDAE computer package also incorporates an automatic differentiation feature [8].)

As part of their programming effort, the students developed flowcharts to represent the process of creating the equations of the Lagrangian DAEs from the expressions for energy, work, and constraints that are the basis for the modeling approach taught in this course. One of these flow charts is shown in Fig. 6, which illustrates the differentiations involved in creating the inertia matrix M and the generalized effort vector Y of the Lagrangian DAE. The top row of the chart represents the variables and functions declared by the user before running the program. Displacement q and flow f are n-dimensional vectors; energy, content, and virtual work are scalar functions of q and f. The differentiations indicated produce n-dimensional vectors and n×n-dimensional matrices.

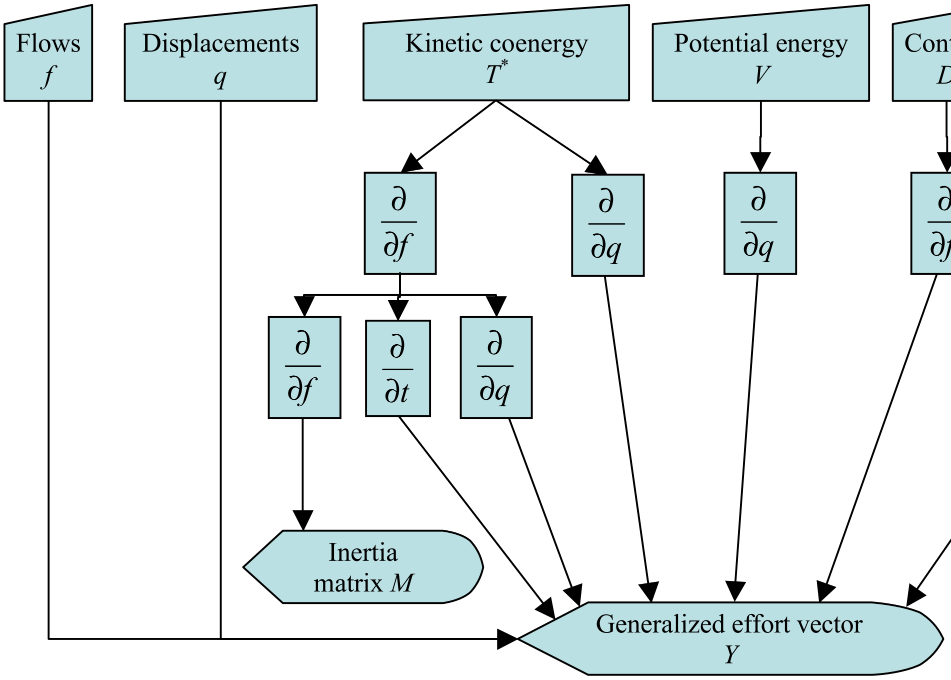


Fig. 6: Flowchart of the differentiations involved in generating the M matrix and the Y vector.

Modular sections of code were developed and tested, using example problems from the course, before incorporating them into the program. The test cases exercised all features, including limiting cases in which some or all of the variable declarations were empty. The DAEs produced by the worksheet were compared to the models for the same systems derived by hand. The final version of the program produced correct mathematical models for all test cases.

The primary difficulty the student team overcame in this project was related to project management. One student was the main programmer; initially the other two students were not sure how to proceed. The only guidance they needed was a working meeting or two facilitated by the instructor to define specific tasks and roles and suggest ways to improve their productivity. Once these project-management issues were addressed, the team made good progress.

Team 2: Parameter identification, modeling, and simulation of a cart and pendulum. This project is primarily an experimental determination of friction-related parameters in an existing cart-and-pendulum apparatus used in the Controls Lab. The customers for this project are the teachers and students using the apparatus. To develop useful control algorithms for this apparatus, the system parameters such as mass, moments of inertia, damping coefficients, motor constants, and armature resistance and inductance must be known. The friction-related parameters change over time and so have to be determined experimentally.

The cart-and-pendulum apparatus is a conventional experiment in automatic control, consisting of a pendulum suspended from a cart that moves along a linear track. The position of the cart is controlled via a DC motor, gear and sprocket, and plastic chain as indicated in Fig. 7. The friction terms of interest in this project are the unknown rotational damping coefficient b_R at the bearing that pins the pendulum to the cart and the unknown linear damping coefficient b_L at the linear bearing between the cart and the rails.

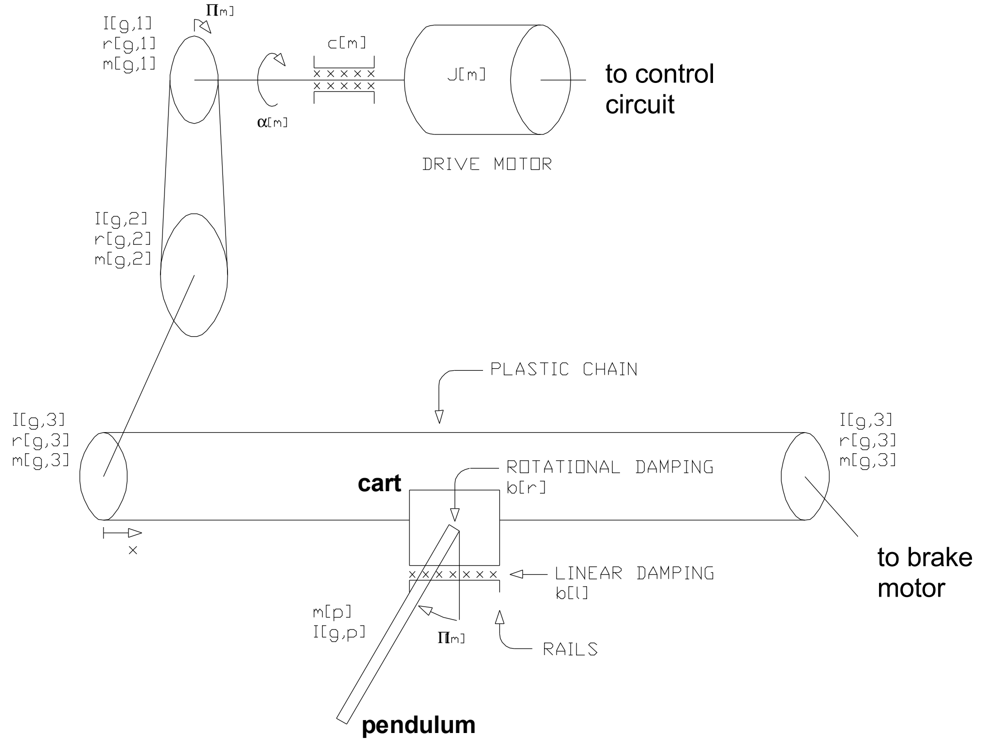


Fig. 7: Partial schematic of the cart-and-pendulum apparatus.

The student team designed and built separate experiments to determine each of the two unknown coefficients. The experiments are based on well-known, elementary parameter-identification procedures found, for example, in [17]. In the first experiment, with the cart stationary, the pendulum is given an initial displacement and its free-response is measured. In the second experiment, with the pendulum removed, springs are attached to either side of the cart and secured to stationary brackets. The cart is given an initial displacement and its free response is measured. In both cases, a mathematical model of the system is used to predict the free response. The difference between the prediction and the experimental measurement is minimized by varying the unknown friction coefficients. The students examined both viscous friction, which is proportional to velocity, and coulomb friction, which is constant. Stiction is neglected. Simulations were run using SIMULINK with DYMOLA blocks.

An example of their results for the pendulum free response is shown in Fig. 8. The difference between the model prediction and the experimental measurement has been minimized by varying the unknown friction coefficient b_R. The two plots do not match exactly, indicating that the physical system contains unmodeled dynamics, a common problem in quantifying friction.

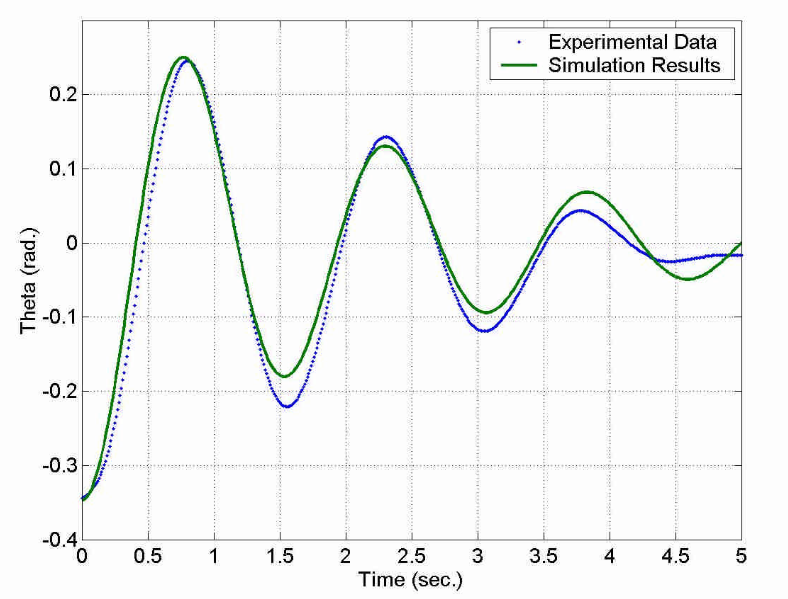


Fig. 8: Parameter-identification results, comparing experimental data to simulation results.

The difficulties the student team overcame in this project include: the operating principles of the apparatus are not clearly described in the existing documentation, requiring the students to develop their own expertise; designing, assembling, and testing two separate experiments; developing friction models based on supplementary reading; the mass moments of inertia of the rotors were not equal to published values, requiring the students to do an iterative optimization on both damping and mass moment of inertia parameters. These are typical difficulties associated with experimental model validation and the students responded to them successfully.

6. Discussion and conclusions

As illustrated by the excerpts from the student final reports, the projects were generally successful in meeting their technical goals and provided the means of meeting course learning objectives. In summary, learning objectives are supported as follows:

- the objective of reproducing published work was met successfully in Project 1
- modeling using Lagrange’s equation is supported by Project 2
- the use of DYMOLA is supported by both projects
- validating simulation results is a component of both projects
- close reading for understanding was required in several, though not all, of the projects

- several of the students had to read critically to overcome some of the project difficulties and successful completion required a response to their findings of errors or omissions in their sources
- as shown in the discussion of Project 2, students successfully developed their project topics, scope of work, and deliverables in a manner consistent with the requirement that the work be suitable for conference presentation.

In addition, in the author's opinion, the students' final reports would be suitable for conference presentation with one more round of editing.

One of the drawbacks of using projects as described in this paper is that to achieve a satisfactory conclusion for each project, the instructor became essentially an ad-hoc member of each team. This is possible in a small class, but would be increasingly difficult as class size grows. Another problem arises due to the project grading scheme. With only the final reports being graded, a student might unwisely decide to discount the importance of the interim deliverables, leaving the "real" writing to the last minute and thereby producing a first draft just before the deadline for the final report. To mitigate this problem, the author allowed some flexibility in meeting the deadlines scheduled in Table 1 without reducing the high expectations for technical thoroughness and coherence.

Student response to the projects was uniformly positive (not uncommon in such a small class, of course). On a 5.0 scale, the student course evaluation results are 4.4 overall rating of the course, 4.7 for the lab reinforcing the course material, and 5.0 for the overall learning experience. Sample student comments from the course evaluations are:

- "The multiple drafts of the papers were good."
- "I thoroughly enjoyed the class. The material is difficult but it was well worth the work."
- "The course was very challenging but very rewarding. It really sharpens one's skills in multiple disciplines."

Student response to the DYMOLA software package was also generally positive. In response to a brief survey regarding the use of DYMOLA in the course, students replied:

- "DYMOLA is easy to use for solving differential equations."
- "For solving differential equations, DYMOLA is easier to use than MAPLE and MATLAB."
- "Plotting in DYMOLA isn't difficult, but the plotting features are limited compared to those in MATLAB. Plotting is much easier in MATLAB."
- "I liked how easy it was to integrate DYMOLA and MATLAB."
- "I like that in DYMOLA you can input DAEs, it's easier and more convenient than substituting the constraints back in" (to create a set of independent ODEs).
- "Helping us through the initial learning stages of using DYMOLA was especially helpful."

In my opinion, these positive results are the consequence of my close involvement with each student on each project, the requirement that projects have sufficient technical depth to require more than a superficial student effort, the expectation of good writing, and the ongoing guidance I provided in writing and project management, helping the students produce project results and reports that are technically thorough and coherent.

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