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Interconnecting the Mechanical Engineering Curriculum Through An Integrated Multicourse Model Rocketry Project

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Abstract

Conventional undergraduate mechanical engineering curricula are split into topical tracks where, from the students' perspective, each track has limited interconnectivity or overlap with the others. To provide students a more coherent and cohesive view, we created and are delivering a multicourse curriculum-integrated engineering project that permeates and unifies five required classes within our undergraduate curriculum: 1) Freshman Design, 2) Dynamics, 3) Numerical Methods, 4) Fluid Mechanics, and 5) Thermodynamics. Students enrolled in these Rocket Project (RP) classes design, build, flight test, and analyze model rockets through hands-on exercises designed to enhance their awareness of topical connectivity across the mechanical engineering curriculum. These activities challenge students to work on different aspects of the same rocket project across all four years of their degree program.

Our method is to redesign discrete laboratory exercises in five required mechanical engineering courses to integrate the rocket project within our existing curriculum without need for administrative changes (i.e., no course catalog changes). At the end of each RP class, students evaluate the rockets or flight simulations they created, analyze their design decisions and assumptions, and reflect on the impacts their choices had on rocket performance using distinct tools from the discipline of each course.

Among the novel aspects of our approach is to expand beyond a two-course project sequence spanning just one academic year, a technique already used in many engineering curricula. Instead, our project is integrated into a multi-year five-required-course sequence with at least one course appearing in each year of the four-year mechanical engineering curriculum. We expect this approach to engender significant benefits to student learning. First, it promotes "spaced repetition", wherein learners encounter the same material in briefer sessions spread over longer time periods rather than the study of information in single blocks, as many engineering curricula do. Second, our approach allows students to realize the interdisciplinary nature of engineering problems, which discrete course subjects artificially isolate. Our approach enables students to apply what they have learned in previous classes to solve new aspects of the same project. Third, this project demonstrates the true iterative nature of engineering design and development wherein students reassess their modeling assumptions and perform necessarily more detailed experiments to validate their conceptual design changes.

Both direct and indirect assessments are planned to evaluate our program. We will track the number of students enrolled in RP courses who join aerospace student organizations like AIAA and who take aerospace industry internships or jobs. We will also track the performance of student-built rockets in courses where rocket launches are part of the exercise. With respect to indirect assessment, we plan to use a survey taken at the end of each RP class in which the students evaluate several metrics including their own 1) interest, 2) understanding, 3) perceived workload, 4) appreciation of course interconnectivity, and 5) level of project enjoyment.

INTRODUCTION

We are delivering to undergraduate mechanical engineering (ME) students at the Milwaukee School of Engineering (MSOE) multicourse curriculum-integrated aerospace engineering projects. Students design, build, flight test, and analyze model rockets through hands-on projects that unify different ME classes by permeating five unique areas within our undergraduate curriculum: 1) Freshman Design, 2) Dynamics, 3) Numerical Methods, 4) Fluid Mechanics, and 5) Thermodynamics. These classes will hereafter be referred to as Rocket Project (RP) classes. Students' awareness of topical connectivity across ME divisions is being enhanced by challenging them to work on different aspects of the same rocket project in these five courses across all four years of their degree program.

In alignment with the purpose of the NASA Exploration Systems Mission Directorate (ESMD), the course projects develop highly-skilled engineers needed to implement NASA's Vision for Space Exploration by addressing areas deemed critical by ESMD [1] to future space exploration: 1) Spacecraft [guidance, structures, modeling, power systems]; 2) Propulsion [motors, testing, fuels]; and 3) Ground Operations [pre-launch, launch, mission operations, landing and recovery]. The integrated projects also uniquely expose MSOE ME undergraduates to aerospace engineering, facilitating future recruitment of this highly trained technical cohort into aerospace careers. Without this exposure, our ME program graduates might not consider aerospace engineering careers due to lack of early aerospace experiences within conventional ME curricula. Moreover, recruitment into AIAA of MSOE students enrolled in courses with aerospace projects will be another important outcome and benefit and a conduit for NASA employment.

The educational benefits of these projects include better engagement of students using material common to different courses throughout the ME curriculum. The interconnected projects build a foundation preparing students to apply system engineering concepts by allowing them to see the inter-related nature of engineering problems that discrete course subjects have artificially isolated to focus on one problem at a time.

BACKGROUND

Conventional undergraduate ME curricula are split into topical tracks (e.g., Freshman Design, Dynamics, Numerical Methods, Fluids, and Thermodynamics) where, from the students' perspective, each track has little connectivity or overlap with the others. To provide students with a more coherent and cohesive view, Newcomer [2] recommended a two-quarter project sequence and described how it reinforced technical concepts and promoted continuity of skill development. Hussmann and Jensen [3] showed how two-course project sequences significantly enhance design instruction, help develop professional behaviors, and enrich students' experience. For example, 63% of students enrolled in their two-course sequence agreed that they "learned a lot from the design project" (only 11% disagreed). Prince et al [4] have repeatedly and convincingly shown how learning of content and concepts overlapping syllabi of courses taught by different faculty in different disciplines can be enhanced by cooperative learning techniques and project-based learning developed by a team of faculty members.

Among the novel aspects of our approach is to expand beyond the two-course project sequence spanning just one academic year (already demonstrated in [2] and [3]) to create a multi-year five-course project sequence with at least one course appearing in each year of the four-year ME curriculum. We expect this approach to engender significant benefits to student learning for several reasons. First, our approach promotes “spaced repetition”, wherein learners encounter the same material in briefer sessions spread over longer time periods rather than the study of information in single blocks, as many engineering curricula do. With this approach, students are re-exposed to aerospace applications and modeling throughout the ME curriculum. Spaced repetition produces impressive results. In 2007, researchers from the University of California-San Diego showed that students who relied on a spaced approach to learning had nearly double the retention rate of students who studied the same material in a consolidated unit [5,6]. Integrated programs have additional benefits. Everett, et al. [7] report statistically significant improvement in student performance in integrated versus traditional programs as well as higher levels of student motivation, performance, and satisfaction. According to Feynman, integrated curricula make meaningful learning easier to achieve because students can attach new material to existing related knowledge rather than merely adopting arbitrary frameworks for memorizing the material [8].

Another of our innovations is providing earlier access to aerospace material than is typical within conventional ME programs. Aerospace topics are generally only taught as senior-level technical electives disjointed from the core ME curriculum. However, the co-investigators’ common passion for aerospace engineering and the existing project-based MSOE ME curriculum offer a unifying thread and a natural opportunity to enable aerospace material to be seamlessly presented in required ME courses within different ME tracks across all four program years.

METHODS/DESCRIPTION

To disseminate to the engineering education community the discipline-specific sub-projects that encompass the overall multi-course rocket project, we describe key activities and learning outcomes related to each RP class. Courses are listed in the progression order they appear in the ME curriculum, which also corresponds to the most likely order in which students would encounter each sub-project: 1) Freshman Design, 2) Dynamics, 3) Numerical Methods, 4) Fluid Mechanics, and 5) Thermodynamics.

FRESHMAN DESIGN

The first course in the sequence is the freshman design course, “Introduction to Engineering Design”. This course develops students’ basic solid modeling skills and teaches stages of the formal engineering design process through a design project. To adapt this general course design-and-build experience as a component in the multi-course rocket project, students were asked to satisfy the following identified need:

“A model rocket company needs a payload module that can carry a specific altimeter with embedded accelerometer on a model rocket in a way that will allow the altimeter to record the rocket’s altitude as it flies skyward.”

Constraints placed on the problem solution were that the design:

- Must not alter the altimeter in any way;
- Must be capable of sensing the altitude;
- Must allow the altimeter to be easily removed and reinstalled;
- Must allow the altimeter battery to be easily removed and replaced;
- Must allow for the activation of the altimeter, reset of the mode button. and confirmation of mode by viewing the mode LED;
- Must allow the flight data to be downloaded without having to remove the altimeter from the payload module;
- Must be sized so that all parts of the payload module fit within a 3.5 x 3.5 x 7 inch volume (total rapid prototype volume available for each team); and
- Must be safe for a typical college student to operate.

After being assigned to project teams, students were supplied with a project kit that included the model rocket parts, the altimeter, and the basic tools needed to measure and assemble the rocket and payload. As part of their preparation for solving this design problem, teams had to reverse engineer the model rocket parts, digitize each part into a virtual solid model, and then assemble the parts into a virtual solid model of the entire rocket. The only additional instructor-supplied information, beyond the engineering design process, was a basic understanding of center of gravity, center of pressure, and how they relate to rocket stability.

As the teams worked through the design process, they developed solid models of their payloads using Solid Works (Figure 1). A design review in the form class presentations allowed the teams to explain how all the project constraints were being met as well as to receive feedback on their designs. The completed payload designs were fabricated using a solid laser sintering process in MSOE's Rapid Prototype Center (Figure 1). On the last weekend of the quarter in which the course is taught, each team flew their designs.

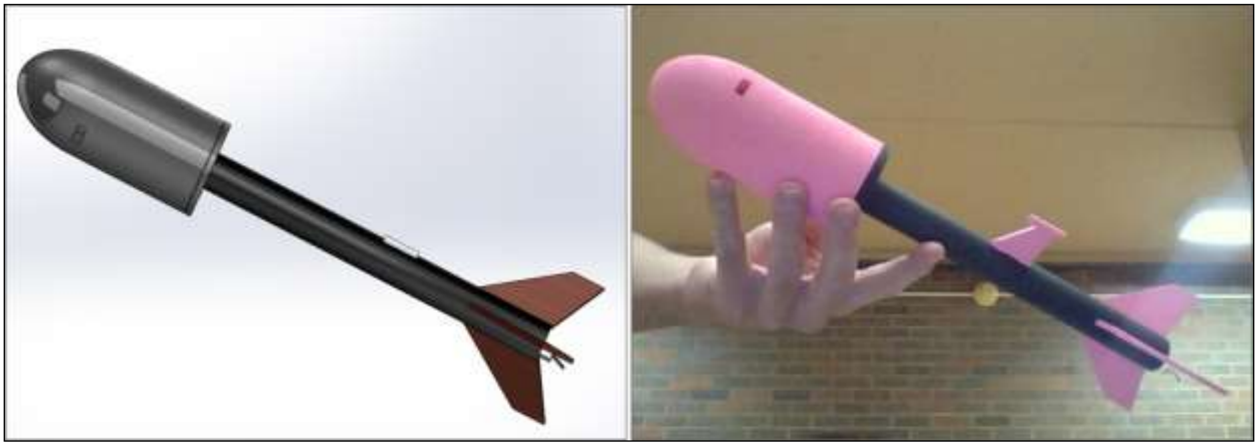

Figure 1: A mid-range sample of rocket payload module design to accommodate an altimeter. Design in both virtual solid model (left) and physical model (right) forms are presented.

Rockets created in the freshman design course form the baseline group of designs against which rockets from later courses in the multi-course RP sequence are compared. Students in this first class are not given any exposure to aerodynamics concepts such as drag or to thermodynamic concepts like conversion of rocket fuel (chemical energy) to altitude (potential energy). Thus, performance of the resulting designs is mixed. Aerodynamically, payload modules ranged from “tear drop” to “block” in shape; the example given in Figure 1 represents a mid-altitude design. Moreover, little thought was given to weight reduction.

All the student-built rockets in Freshman Design flew, but due to high drag and high weight, a good number of them did not achieve enough altitude to allow the parachute recovery systems to deploy before hitting the ground. As a result of inadequate braking distance, a number of the altimeters did not survive impact with the ground, but an example of data retrieved from a successful flight can be seen in Figure 2. The other major common problem suffered by the payload designs was inadequate venting for the barometric altimeter resulting in inaccurate altitude measurement.

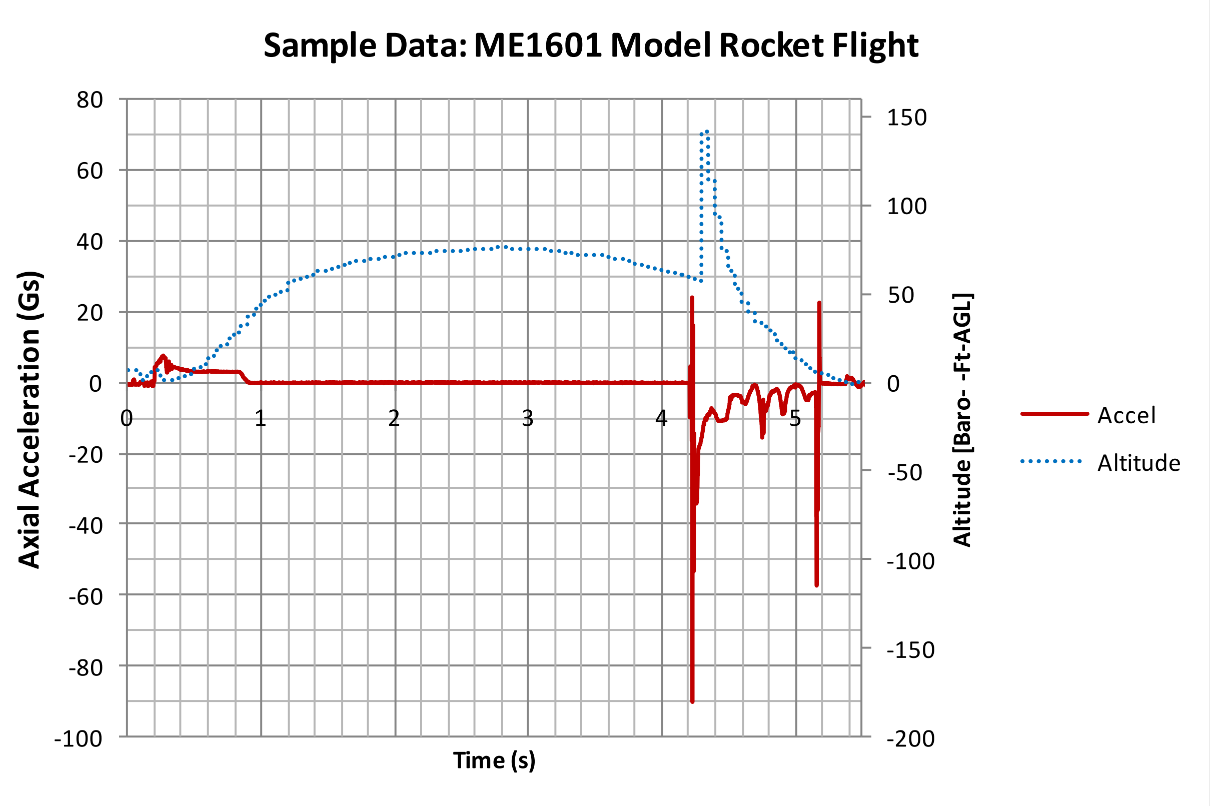

Figure 2: Sample flight data from a successful Freshman Design rocket launch with superimposed rocket altitude and acceleration.

An important lesson learned from these launches was need for test flights with low-value proxy payloads to ensure adequate rocket performance and recovery before using them to launch high-value altimeters. In the future, student rockets will first be tested with mocked-up payloads that stand in for the altimeters by presenting the same outside dimensions and weight. Without active components, no expensive sensors will be destroyed if these low-value test payloads hit the ground at high velocity. Once a rocket’s performance has been vetted with a proxy payload, it will be re-flown with an altimeter for active data collection. Another goal of the multi-course project sequence is to better equip future groups of freshman with a knowledge base for rocket design. This goal will be achieved by inviting to class upperclassmen who have experienced other later phases of the multi-course rocket project sequence to help guide the freshmen by imparting additional understanding of aerodynamics, thermodynamics, and rocket concepts.

DYNAMICS

The second class in the multi-course rocket project sequence is sophomore-level dynamics. This course incorporates computer laboratory sessions that apply use of numerical simulation and approximation in dealing with particle kinematics and kinetics concepts. With respect to the rocket project, students revisit their long-held modeling assumption from lower-division physics that air resistance can be neglected in particle trajectory calculations. Numerical model simulation assignments are introduced that require calculation of work due to non-conservative forces, primarily friction, and inclusion of velocity-dependent acceleration relations in curvilinear coordinate systems inherent in rocket flights from oblique launches (Figure 3).

Figure 3: Typical oblique rocket launches result in classical parabolic flight trajectories.

The actual rocket drag coefficient, i.e. *the truth*, is still too complex for students at this level. So, the idealized nature of the drag model is emphasized, but now a frictional component is added to the rocket acceleration wherein:

$$a_{DRAG} = \frac{1}{2}\rho A C_D v^2(-\hat{e}_t) \tag{1}$$

where ρ is air density, A is maximum rocket cross sectional area, C_D is the drag coefficient, and v is rocket velocity. In this equation, the direction of frictional acceleration, $\hat{e}_t$, always directly opposes the velocity of the rocket. In revisiting the model of projectile motion that includes air resistance, students must account for both this frictional acceleration as well as the gravitational acceleration, which they are told to assume remains constant and directed toward the Earth at all times.

To tie the rocket performance modeling work in this course to the actual rockets built in Freshman Design, the cross-sectional area of student-designed nose cones, A, and the measured mass of student-designed rockets (complete with altimeter and battery payload) are used by the sophomore dynamics students in their calculations. Rocket drag coefficient, C_D, which is measured in a wind tunnel by juniors in the fluid mechanics course later in the multi-course sequence (described below) is also given to the dynamics students for their calculations.

To learn if relaxing physical modeling assumptions, i.e. ignoring drag, is warranted, students evaluate the classic parabolic model results, which neglect air resistance, as a benchmark. Students then complete the following, more advanced, analysis:

1. Add the frictional component of acceleration and recalculate the projectile path;
2. Plot the rocket path with this refined model including air resistance along with the parabolic trajectory that neglected air resistance;
3. Compare and contrast the two flight paths and comment critically whether the classic parabolic model was “good enough”; i.e. quote percent differences in such critical output predictions as maximum range, maximum altitude, and flight time; and
4. Generalize the new advanced model to simulate launch angles and determine that at which the projectile range is maximum.

While students used real measured rocket geometry, weight, and drag coefficients to build their performance models, they only compared simulated results that first ignored drag and then accounted for it. The initial course offering of this project module did not include comparison of simulated rocket trajectories to actual trajectories. In the future, this comparison will be made by using the freshman design course altimeter data. Students in the junior-level numerical analysis course will analyze in-flight acceleration data (as described below) from freshman design course rockets to obtain experimental velocity and altitude time histories subsequently feeding that analysis to the dynamics course. From these experimentally-measured flight data can be gleaned the critical output predictions now used to compare the students’ two rocket path simulations: maximum range, maximum altitude, and flight time. Thus, in future course offerings, students will compare their two models against actual rocket flight paths as they critically evaluate whether these models are “good enough” to predict actual performance.

MODELING & NUMERICAL ANALYSIS

The third class in the multi-course rocket project sequence is a junior-level dynamics modeling and numerical analysis class. At MSOE, this course devotes substantial time to model construction: simplifying physical assumptions, validation of numerical simulation results, and model iteration via revisiting physical assumptions inherent in the earlier models. To incorporate elements from the multi-course rocket project, about 40% of the quarter is now devoted to computer laboratory time in which the rocket launch is modeled with techniques much more sophisticated than those introduced in the sophomore-level dynamics course. These laboratories involve the following activities:

1. Double numerical integration of in-flight acceleration data [obtained in the freshman design course] to obtain experimental velocity and altitude time histories (and potential flight trajectories for oblique launches);
2. Calculation of work performed by aerodynamic drag forces;
3. Direct comparison of model/flight simulation velocity, altitude, and trajectory with three velocity-dependent drag model assumptions;
4. Determination of model prediction sensitivity to:
    a. Impulse delivered assuming a square pulse thrust profile, or

    b. Impulse delivered using experimental test data from a typical A8-3 Estes rocket motor [obtained in the senior thermodynamics course – described below]; and
5. Determination of model prediction sensitivity to assumptions regarding rocket payload weight including:
    a. Assuming constant rocket weight, or
    b. Accounting for mass fuel burn

For their baseline model, students assume constant rocket mass and constant step input (square pulse) thrust for the rocket. Using Newton's second law, the governing differential equation is

$$m\frac{dv}{dt} = T - W - F_D(v) \tag{2}$$

where m is the constant mass of the rocket, v is the velocity of the rocket, T is a constant thrust delivered over a specified amount of time, W is the weight of the rocket, and $F_D(v)$ is the drag force on the rocket given as a function of velocity. Three drag models are evaluated: 1) No drag $F_D(v) = 0$, 2) Linear drag $F_D(v) = bv$ where b is a linear coefficient of drag [which is instructor-provided, but based on limited theory and no experimental data], and 3) Aerodynamic drag $F_D(v) = \frac{1}{2}\rho C_D A v^2$ where ρ is the density of air, C_D is the drag coefficient estimated by wind tunnel test data taken by juniors in the fluid mechanics course [described below] and corroboration with literature-published values [9], and A is the cross-sectional area of the rocket. The velocity of the rocket is updated employing the simplest explicit time integration of Eqn. 2

$$v_{i+1} = v_i + \frac{1}{m}\left(T - W - F_D(v_i)\right) \tag{3}$$

using Euler's forward method (here i indicates the time step). In a subsequent modeling laboratory, the students are given experimental thrust data, from which the mass of the rocket can be determined as a function of time assuming there is a constant burn of the fuel [10]. The governing equation now becomes

$$m(t)\frac{dv}{dt} = T(t) - W(t) - F_D(v). \tag{4}$$

Again, Euler's forward method is used to update the velocity

$$v_{i+1} = v_i + \frac{1}{m_i}\left(T_i - W_i - F_D(v_i)\right). \tag{5}$$

The height of the rocket is determined numerically, using Euler's forward method. As before, the in-flight acceleration data is integrated, using the trapezoidal rule, once to obtain the velocity and twice to obtain the height. The experimental rocket velocity is plotted in Figure 4, along with the velocities found using the linear drag model and the aerodynamic drag model with constant mass and with variable mass. Figure 5 shows the rocket height from the experimental flight compared to predicted model heights using constant and variable mass along with the linear drag and aerodynamic drag models.

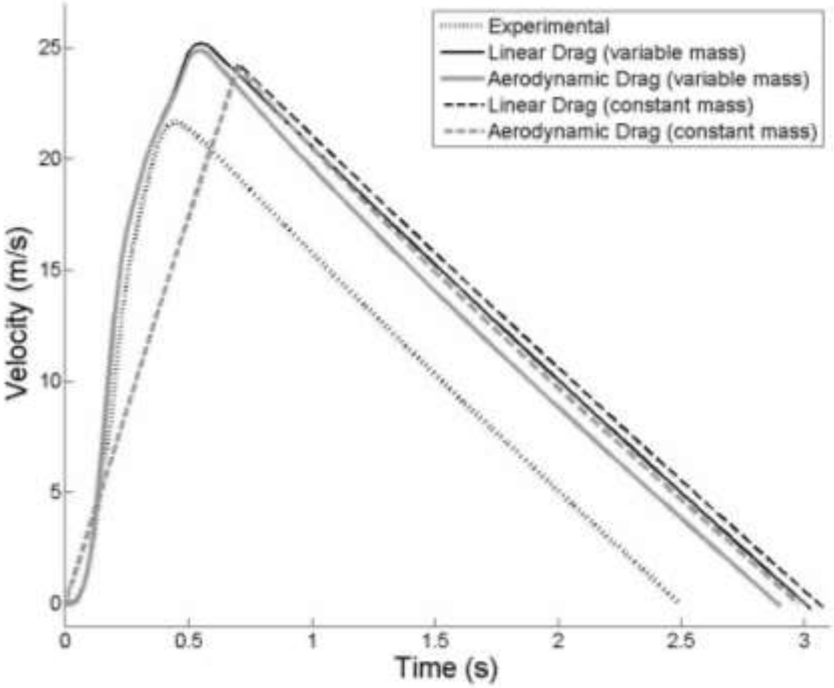

Figure 4: Rocket velocity as a function of time from the experimental flight compared against velocity history predicted by the model using constant and variable mass. The linear drag and aerodynamic drag models are shown.

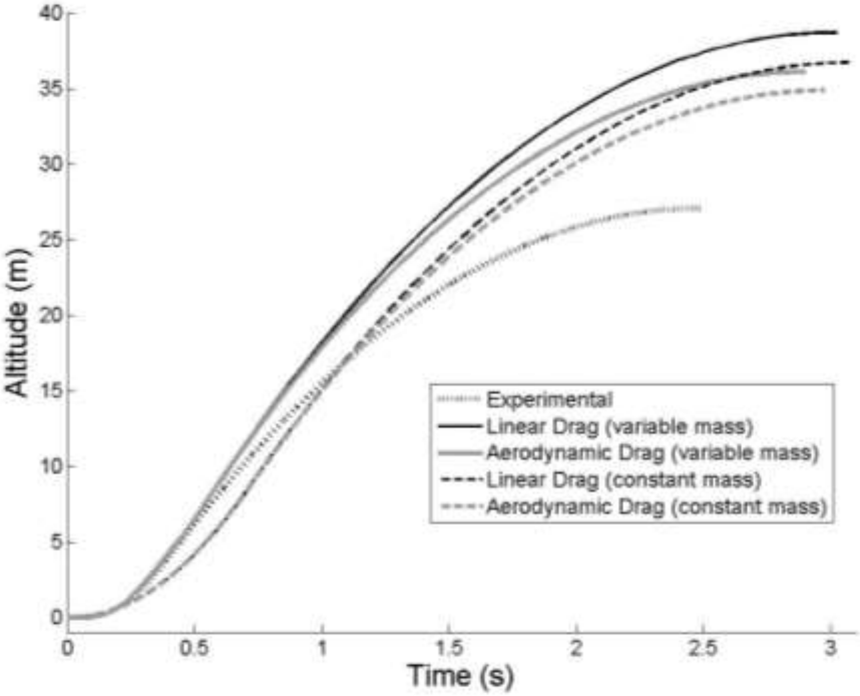

Figure 5: Rocket altitude from experimental flight data compared against altitude predicted from simulation using constant and variable mass. The linear drag and aerodynamic drag models are shown.

FLUID MECHANICS

The fourth class in the multi-course rocket project sequence is a junior-level fluid mechanics course. At MSOE fluid mechanics is a hybrid lecture/laboratory course that emphasizes use of experimental techniques to validate theoretical predictions. To complement the external flow module embedded in this course, a rocket based wind tunnel experiment was devised to give the students a simple but highly visual means to estimate rocket drag as a function of tunnel velocity.

As shown in Figure 6, a model rocket is initially hung in the tunnel working section with the turbine off using two very thin threads positioned around the center of gravity. The mass of the rocket model is measured in advance of the experiment. A tripod-mounted digital camera captures the location of the rocket relative to a T-square, which indicates the vertical direction. A laser beam is directed at 45° from horizontal to calibrate the image against unintended angle offsets between the camera and the working section.

The wind tunnel is then turned on, and its velocity is measured using a pitot-static probe. Drag induced in the horizontal direction causes the model to swing backward and assume a new equilibrium orientation. The new angle between the suspending rocket threads and horizontal is photographed for later measurement using digital image analysis software. The resulting drag coefficient determined using Eqn. 6,

$$D = \frac{mg}{\cos\Theta} \tag{6}$$

where m is the rocket mass, g is the gravitational acceleration, and θ is the angle between the suspension threads and horizontal. Initially, the instructor was concerned that maximum tunnel velocity would be too slow to capture data within the flight velocity range of the rocket. However, reliable data were taken at tunnel speeds as high as 32.9 m/s, which is faster than ~25 m/s achieved by the rocket, as determined from experimental flight data (see Figure 4).

A plot of drag force versus tunnel velocity was produced from these measurements. The data where then non-dimensionalized using rocket geometric and air fluid

Figure 6: Model rocket drag coefficient as a function of velocity is experimentally measured in a wind tunnel. By suspending models about their center of mass by two threads. Wind tunnel velocity is increased and the resulting angle between the horizontal and the thread (black lines) is photographed for measurement. A laser beam projected 45° from horizontal (red lines) corrects for any systematic error in angle between the tunnel working section and tripod-mounted camera.

dynamic parameters to create a plot of drag coefficient versus Reynolds number, as shown in Figure 7.

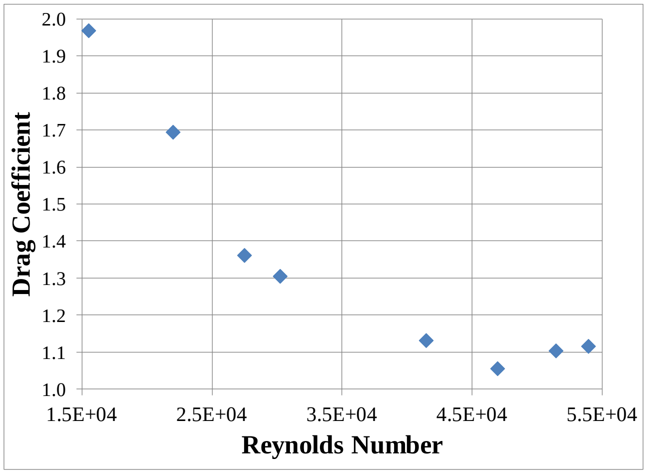

Figure 7: Rocket model drag coefficient as a function of Reynolds number measured in the Fluid Mechanics component of the rocket project. As with drag coefficient over a simple shape, like a sphere, drag coefficient is a strong function of Reynolds number for laminar flow, but this dependence disappears as flow transitions to turbulent.

Challenges with technique revolve around use of thread to suspend the rocket. The thread, which presents its own drag coefficient when subjected to external airflow, assumes a hyperbolic shape. Therefore, it is difficult to accurately measure the thread's angle of attachment to the rocket. To estimate the angle between the threads and horizontal, students draw a straight line between attachment points (as shown in Figure 6). In an attempt to eliminate this difficulty hollow rigid aluminum tubes were initially tried to suspend the rocket as an alternative to thread. However, these tubes, which presented a cylindrical profile to the oncoming flow, were in the vortex shedding Reynolds number regime across most of the tunnel's velocity range. Vortex shedding caused the model rocket to swing violently, which prevented it from settling to a state-state equilibrium position for accurate angle measurement.

To validate the experimentally-measured rocket drag coefficients, students used OpenRocket, an open source model rocket simulation code available free-of-charge on-line. [11] Students measured outside rocket dimensions and digitized results into the OpenRocket interface. Based on input geometries, the software estimated rocket drag coefficient as a function of velocity (entered as fractional Mach numbers). OpenRocket estimated drag coefficients for Estes Alpha III model rocket bodies with enlarged nose cones from the freshman design course in a range from 0.70 to 2.0, which is consistent with the measured range. Apparent in Figure 7 is the drop in drag coefficient with increasing Reynolds number (i.e. tunnel velocity). Above Reynolds number of about 40,000 the drag coefficient seems to lose its functional dependence on Reynolds number. Qualitatively, this behavior is consistent with external flow over three-dimensional objects in that increasing Reynolds number generally decreases drag coefficient until the flow transitions to the fully turbulent regime where Reynolds number no longer has an effect on drag coefficient. For a circular disk with its face aligned to the flow, fully turbulent flow occurs at $Re_d > 10^3$, but for more complex shapes (i.e. model rockets with custom-fabricated nose cones) flow visualization is needed to determine the nature of flow around an immersed object.

In the future, the rocket-suspended-by-thread experiment will be complemented by a direct drag force measurement capability enabled using a more conventional tail-mounted sting with built-in load cell. The two experiments will then be run in serial laboratory sessions to allow the students to evaluate the merits and limits of measurement uncertainty arising from both experiments.

Moreover, the tail-mounted sting will enable experiments to be run the in the MSOE flow visualization wind tunnel to determine whether transition to wholly turbulent flow occurs at $Re_d \approx 40{,}000$, as suggested by preliminary data.

THERMODYNAMICS

The fifth class in the multi-course rocket project sequence is a senior-level applied thermodynamics course. In the MSOE ME Department, students take a sequence of three thermodynamics classes. The final course in this sequence, Thermodynamics Applications, is a hybrid lecture/laboratory course that emphasizes experimental validation of theory taught in previous courses using full-scale equipment. For example, a commercial-building-scale 200-ton chiller is run to demonstrate refrigeration cycles while automotive spark ignition and compression ignition engines demonstrate Otto and Diesel cycles, respectively. Combustion chemistry is introduced in this course and typically applied to burning natural gas with air in an industrial water heater or burning gasoline with air in MSOE's Cooperative Fuels Research (CFR) engine.

Figure 8: An Estes A8-3 model rocket engine is tested on the motor thrust apparatus.

Thermodynamics Applications includes a two-week elective topic period during which the instructor has flexibility to introduce any thermodynamic subject of his choice, which draws on the taught content but is typically beyond the coverage range of a conventional undergraduate thermodynamics course. For example, previous elective topic periods have covered such topics as combined-heat-and-power (CHP) cycles, aquaponics, and renewable biomass energy. The Thermodynamics Applications curriculum also includes a required 10-week design-and-build project in which students apply the formal engineering design process (first learned in the freshman design course) to build a functioning system, which typically is connected to the instructor's elected topic.

To incorporate elements of the multi-course rocket design project into this thermodynamics course, an experimental thrust measurement apparatus was constructed that can accommodate model rocket motors in the 13.0 mm, 18.0 mm, and 24.0 mm diameter size classes. Thus, any hobby-scale solid rocket motor from the 1/4A up to E total impulse classes can be tested. The motor is securely mounted in a vertical orientation atop a compression load cell and ignited so exhaust is vented through a hood out of the test cell (Figure 8). A data acquisition system collects thrust data at 0.002-second intervals and a low-pass-filter, implemented in the data collection software, eliminates high frequency vibration artifacts to produce a smooth thrust-versus-time curve. The resulting curve is used by juniors in the Numerical Analysis course to predict rocket performance.

To validate the thrust measurement apparatus, thrust curves were compared against curves published by the manufacturer based on data acquired through testing by the National

Association of Rocketry (NAR), as shown in Figure 9. A useful repository of hobby rocket motor thrust curve data is archived on-line at www.thrustcurve.org. [12]

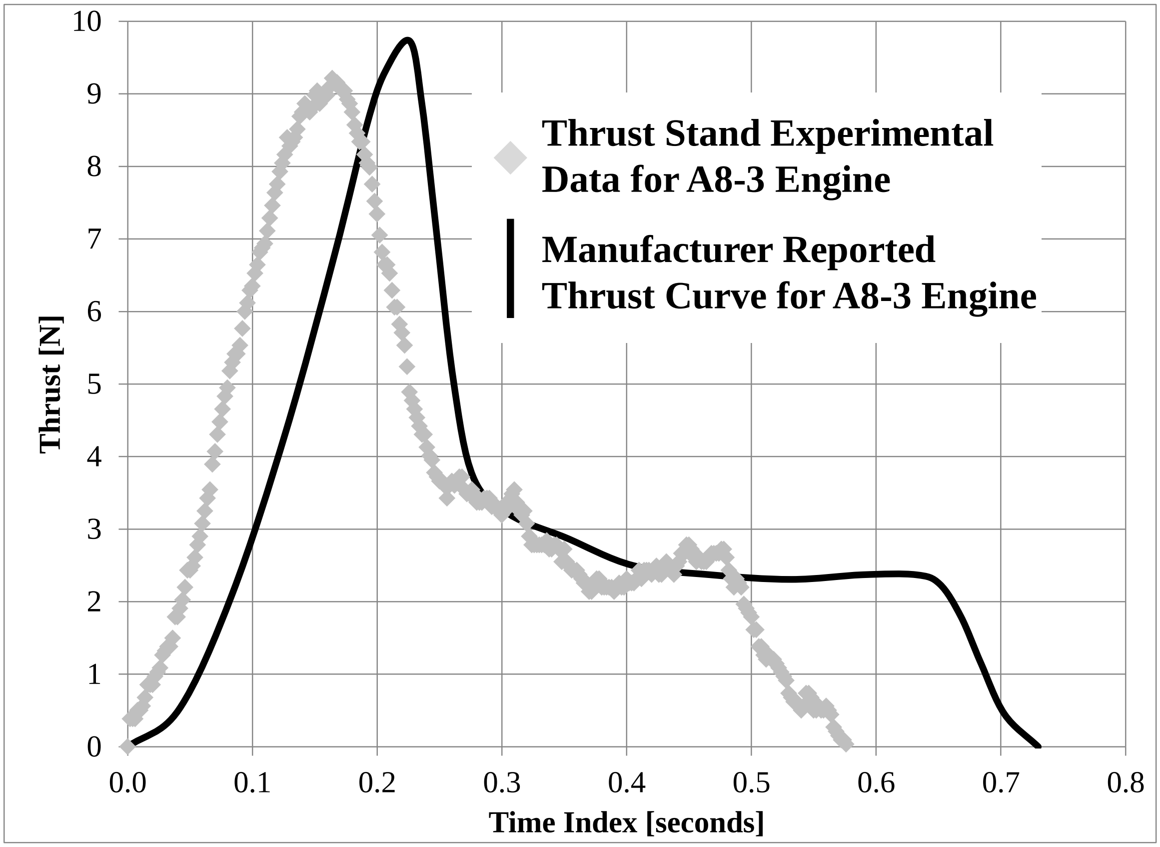

Figure 9: Comparison of manufacturer reported thrust curve for an Estes A8-3 model rocket engine versus experimental data collected using the motor thrust apparatus.

For the specific Estes A8-3 motor tested in Figure 8, the experimental thrust apparatus under-measures manufacturer-stated maximum thrust by 5.3%, under-measures total impulse by 8.2%, under-measures burn time by 0.152 seconds, and under-measurers average thrust by 2.7%. However, these data represent a single engine test, and, as pointed out by Haw [13], repeated tests generating enough data to enable statistical analysis would provide the most accurate global representation of motor performance.

The first time the rocket thrust apparatus was incorporated into Thermodynamics Applications, it was used as a demonstration to illustrate one application of combustion processes beyond water heating and internal combustion engines typically analyzed in the course, and no data analysis beyond looking at the thrust curve was performed by students in this course. However, in the future, the instructor plans on shifting the two-week elective topic period toward the thermodynamics of rocket propulsion and motor design. For example, the combustion analysis techniques already taught in Thermodynamics Applications can be applied to black powder solid rocket motors (charcoal and sulfur fuel combined with potassium nitrate oxidizer) to determine the specific energy released during the combustion process given formation enthalpies of the reactants and products:

$$8C + 3S + 10KNO_3 \rightarrow 2K_2CO_3 + 3K_2SO_4 + 6CO_2 + 5N_2 \tag{7}$$

Specific energy, e, obtained from the combustion analysis can then be compared against that released during experimental tests as represented by the thrust curve.

$$e = \frac{{}^1\!/_2(m_{f,i} - m_{f,f})}{m_{f,i}} v_e^2 \tag{8}$$

where $m_{f,i}$ and $m_{f,f}$ are respectively initial and final fuel mass and v_e is nozzle exit velocity. This velocity can be determined exactly via the following equation [14]:

$$v_e = \frac{\int_o^t F(t)dt}{\int_0^t \dot{m}(t)dt} \tag{9}$$

The numerator is calculated numerically as the area under the experimentally-measured thrust-versus-time curve. However, the function for instantaneous expulsion of mass, which appears in the denominator, cannot be determined from available experimental data as the rocket motor mass change cannot be separately measured from thrust data. Thus, the mass expulsion rate will be assumed to be linear, $\dot{m}(t) \approx (m_{f,i} - m_{f,f})/\Delta t$, which is a reasonable engineering assumption for solid rocket motor grain that presents a constant area combustion front.

In the future, the Thermodynamics Applications course design-and-build project will also be modified to become the capstone element of the multi-course rocket project. Given the same design constraints as the freshman design course, seniors in this class will design a rocket with a rapid prototyped nosecone to carry aloft the same altimeter payload as in the freshman course. Armed with knowledge and experience from previous elements of the multi-course project; design, performance simulation, aerodynamic drag, and rocket motor combustion analysis; the seniors are expected to create rockets that in general achieve better performance than the freshmen.

Moreover, as part of the course project, students will also design, build, and test their own solid rocket motors using a variety of sugars as fuel and potassium nitrate as oxidizer. Sugars with melting temperatures below their chemical disassociation temperature (i.e., sorbitol, xylitol, and dextrose) will be melted on a hot plate and oxidizer will be mixed in. The slurry will then be molded into a rocket motor housing and cured. Sugar-based rocket motor design will allow students to validate stoichiometric chemical balance equations (i.e., Eqn. 7) by varying the fuel to oxidizer ratio of their motors. They will also be able to evaluate how the enthalpy of formation provided by different fuels impacts the specific energy of the resulting motor as well as its thrust-versus-time curve. Preparations are currently ongoing in collaboration with the MSOE Health and Safety Office to ensure this proposed rocket motor design module can be safely carried out.

RESULTS – DATA COLLECTION

An indirect assessment instrument has been developed that will be administered to the students in all RP classes. This survey will be delivered on-line, and it is meant to assess students' perception of the benefits and drawbacks of the multi-course project. Direct assessment of the program's impact will occur by quantifying the career directions of participating students and the scholarly (pedagogical and research) productivity that arises directly from faculty involvement in the project.

Indirect Assessment Tools: Student Self Evaluation

Indirect program assessment will be performed through computerized student exit surveys (similar to [3]) at the end of each quarter. Surveys will include quantitative Likert scale questions as well as qualitative short answer questions concerning how well student expectations were met. The assessment instrument will address (1) students' perceived development of technical skills and knowledge and (2) students' perceived interest in aerospace engineering careers. The instrument will also assess issues with the multi-course project, which were identified as drawbacks by previous researchers; for example, student perceptions that RP classes are too time consuming and that students enrolled in previous RP classes have an advantage over students that have not with respect to grades.

The assessment questions we are using for indirect program assessment are given here.

General Questions
1. What is your last name?

2. What is your first name?

3. In which of the following ME courses have you seen Rocket Design Project material?
ME 1601: Introduction to Engineering Design [Yes] [No]
ME 206: Engineering Dynamics [Yes] [No]
ME 300: Modeling and Numerical Analysis [Yes] [No]
ME 317: Fluid Mechanics [Yes] [No]
ME 416: Thermodynamics Applications [Yes] [No]

4. In the future, which of the following ME courses do you plan to take with the Rocket Design Project material?
ME 1601: Introduction to Engineering Design (Dr. Farrow) [Yes] [No] [N/A]
ME 206: Engineering Dynamics with (Dr. Prantil) [Yes] [No] [N/A]
ME 300: Modeling and Numerical Analysis (Dr. Prantil or Dr. Weiss) [Yes] [No] [N/A]
ME 317: Fluid Mechanics (Dr. Traum) [Yes] [No] [N/A]
ME 416: Thermodynamics Applications (Dr. Traum) [Yes] [No] [N/A]

5. The Rocket Design Project demonstrated how various ME courses are interconnected.
[N/A] [Strongly Disagree] [Disagree] [Agree] [Strongly Agree]

6. The Rocket Design Project demonstrated how various mechanical engineering concepts are interrelated.
[N/A] [Strongly Disagree] [Disagree] [Agree] [Strongly Agree]

7. The Rocket Design Project reinforced technical concepts developed in previous courses.

[N/A] [Strongly Disagree] [Disagree] [Agree] [Strongly Agree]

8. The Rocket Design Project strengthened the skills I developed in previous courses.
[N/A] [Strongly Disagree] [Disagree] [Agree] [Strongly Agree]

9. Students who were previously enrolled in courses that used Rocket Design Project material were at an advantage for success in my current class.
[N/A] [Strongly Disagree] [Disagree] [Agree] [Strongly Agree]

10. My cumulative Rocket Design Project experience has enhanced my practical knowledge in the following fields:
Chemistry [Yes] [No]
Mathematics [Yes] [No]
Physics [Yes] [No]
Engineering Design [Yes] [No]
Computer Simulation [Yes] [No]
Technical Communication [Yes] [No]
Statics [Yes] [No]
Dynamics [Yes] [No]
Control [Yes] [No]
Mechanics of Materials [Yes] [No]
Numerical Analysis [Yes] [No]
Thermodynamics [Yes] [No]
Materials Science [Yes] [No]
Fluid Mechanics [Yes] [No]
Machine Design [Yes] [No]
Heat Transfer [Yes] [No]
Manufacturing [Yes] [No]
Engineering Economics [Yes] [No]

11. Please describe your favorite aspect of the Rocket Design Project experience.
[Open-ended Response]

12. Please describe your least favorite aspect of the Rocket Design Project experience.
[Open-ended Response]

13. Please provide any general comments about the Rocket Design Project experience.
[Open-ended Response]

14. Please suggest ways the instructors can improve the Rocket Design Project experience.
[Open-ended Response]

15. What questions do you wish had appeared on this survey but were not asked?
[Open-ended Response]

Course Specific Questions

16. The Rocket Design Project increased my interest in *Course Number*.
[N/A] [Strongly Disagree] [Disagree] [Agree] [Strongly Agree]

17. The Rocket Design Project increased my understanding in *Course Number*.
[N/A] [Strongly Disagree] [Disagree] [Agree] [Strongly Agree]

18. I feel the workload in *Course Number* sections with the Rocket Design Project was __________ the workload in *Course Number* sections without the Rocket Design Project.
[Much Less Than] [Less Than] [Equal To] [Greater Than] [Much Greater Than] [I don’t know]

19. I feel the Rocket Design Project had the following impact on my *Course Number* grade:
[Negative Impact] [No Impact] [Positive Impact]

Direct Assessment Tools

The following measurable direct evaluation metrics will be cataloged for analysis and assessment as evidence of project success:

1. Number of papers reporting new research findings, educational best-practices, and novel pedagogical outcomes submitted for publication in the peer-reviewed engineering research and education literature or presented at refereed research and pedagogical conferences.

2. Performance comparison of student-built rockets from the freshman design course versus the senior thermodynamics course. In both course projects, achieving the highest altitude will be posited as the students’ project goal. Therefore, rocket altitudes are expected to increase systematically with class year to reflect the students becoming more skilled and experienced through exposure to multi-course project components.

3. Number of students enrolled in project courses who join AIAA and/or take aerospace industry jobs after graduation. It is noteworthy that tangential to the organization of the multi-course rocket project, students and faculty in the MSOE ME Department organized a student chapter of AIAA to enhance professional service and networking opportunities for students seeking careers in the aerospace industry.

DISCUSSION

Sensitivity Analysis: How Experimental Data Maps to Model Performance

Arguably, two of the more powerful aspects of engineering models are their utility for predicting system response and for parameter studies to guide and supplant extensive and costly experiments. Undergraduate students often tend to seek a single solution for any posed problem versus providing ranges of acceptable parameters within which the system response is acceptable. As such, they often exhibit some rigidity in their assessment of the accuracy of simplifying assumptions of the physical character of laws (such as the velocity-drag relation used in the dynamics and numerical methods RP classes). By revisiting their original models for rocket flight in the numerical analysis course and then comparing predicted outcomes to experimental data, students experience firsthand that some simplifications are insensitive. For instance, for rocket geometries with low coefficients of drag and relatively low thrust, it may appear from model predictions that a linear drag law predicts altitude histories in better agreement with data than those employing an aerodynamic drag model. This outcome may be exacerbated by not accounting for the variable mass in a rocket whose weight includes a substantial payload of fuel. In the process of revisiting modeling assumptions for drag-velocity relation, thrust profile history and variable rocket mass, students are exposed to several characteristics of model development:

- Sensitivity of pertinent results to model parameter variation is valuable to determining the relative importance of these parameters;
- Modeling errors introduced by neglecting a parameter or physical mechanism may be compensated for by other model inconsistencies so as to render predictions that mistakenly appear to be in better agreement with experimental results; and
- Sensitivity to different model parameters can vary widely

In the numerical analysis rocket project laboratories, students were required to account for variable thrust, variable rocket mass, and drag models somewhat independently in order to construct a proper picture of the sensitivity of rocket performance to each. For instance, model predictions that do not account for variable rocket mass have led students to draw incorrect conclusions regarding the appropriate choice of drag law when the linear drag law coefficient is chosen arbitrarily large so as to seem to best match flight altitude data.

Further, students' interpretation of inadequacies of data vs. model pedigree may not be made with the requisite confidence that comes with repeated exposure to the same problem. By experiencing the same rocket project multiple times through exposure to different elements of the multi-course rocket project, students learned to question both apparent inconsistencies in experimental data and the need for additional data to be obtained.

Data Inconsistencies

Many students discussed an apparent inconsistency between the thrust data in Figure 9 and the in-flight accelerometer data in Figure 2. The rocket acceleration should become negative very close to the time at which the thrust phase is completed. Figure 9 indicates end of fuel burn to be about 0.58 seconds while Figure 2 appears to show that the rocket begins to decelerate in the vicinity of 0.45 seconds where the thrust should still too high to be overcome by drag and gravitational forces. For rockets' whose maximum flight velocities are higher, this may not be a discrepancy at all, but that determination led students to question what might be an inconsistency. This questioning is an integral part of good model development and physical understanding. It also heightens students' awareness of the relationship of otherwise seemingly unrelated coursework in their curriculum.

CONCLUSIONS

The authors collaborated across conventional ME Department division boundaries to create and deliver a multicourse curriculum-integrated rocket project that permeates and unifies five different classes within the ME undergraduate curriculum: 1) Freshman Design, 2) Dynamics, 3) Numerical Methods, 4) Fluid Mechanics, and 5) Thermodynamics. This paper reports the techniques used in the first year the rocket project modules were taught, and it highlights key initial observations, outcomes, and learned lessons. This paper also highlights future aspirations and directions for the project, describing what the future program will be rather than what it currently is.

Students enrolled in RP classes design, build, flight test, and analyze model rockets through hands-on exercises designed to enhance their awareness of topical connectivity across the mechanical engineering curriculum. These activities challenge students to work on different aspects of the same rocket project across all four years of their degree program using distinct tools from the discipline of each unique course.

Both direct and indirect assessments are described, which we will use to evaluate the program. We will track the career path choices of students enrolled in RP classes as well as their interest to join aerospace student organizations like AIAA. We will also track the performance of student-built rockets in courses where rocket launches are part of the exercise, and we expect performance to improve as students acquire more skill and experience through exposure to rocket project components. With respect to indirect assessment, we plan to use a survey taken at the end of each RP class in which the students evaluate several metrics including their own 1) interest, 2) understanding, 3) perceived workload, 4) appreciation of course interconnectivity, and 5) level of project enjoyment.

The expected educational benefit of an interconnected multi-course project is better student engagement with the variety of material common to different courses throughout the ME curriculum. Moreover, the interconnected project is expected to build a foundation preparing students to apply system engineering concepts by allowing them to see the inter-related nature of problems. Initial evidence of these benefits is already apparent from anecdotal observations of students' synthesis of data obtained from different sources. For example, by comparing rocket flight simulation models to experimental data, students realize that some aspects of their simulations are insensitive to the nature of simplifying assumptions used. For rocket geometries with low coefficients of drag and relatively low thrust, a linear drag law predicts altitude histories in better agreement with experimental data than those employing the accepted correct aerodynamic drag model. Further, students were observed to compare, critique, and question experimental data arising from two different sources that suggested inconsistencies. Rocket thrust data obtained in a thermodynamics class from direct experimental measurement suggests a longer period of acceleration than was observed from altimeter data in flight tests in a freshman design course. While this apparent discrepancy may not be a technical inconsistency, it nonetheless induced students to question the data's validity. This questioning is an integral part of good model development and physical understanding. It also heightens students' awareness of the relationship of otherwise seemingly unrelated coursework in their curriculum.

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