Impulse Calculation of Model Rocket Engines

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Dr. Landman is a Professor of Aerospace Engineering at Old Dominion University where he teaches graduate level classes in aerodynamics and statistical based experiment design, and supervises doctoral and masters students. His current research areas include use of Design of Experiments(DOE) in wind tunnel force measurement system design, and development of in-flight test methods for use with unmanned aerial vehicles. Landman was jointly appointed as Chief Engineer at the Langley Full-Scale Tunnel (LFST) at NASA Langley until its closing in September 2009. During his 13 year tenure at the LFST, Dr. Landman was responsible for designing force measurement systems and supervising wind tunnel tests on a variety of test articles including aerospace and ground vehicles. Dr. Landman has served as an international consultant for training engineers in DOE as applied to aerospace ground testing.

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Ben Stuart currently holds the position of Senior Associate Dean and Professor of Civil and Environmental Engineering at Old Dominion University. His current research interests include biofuels production from waste and renewable feedstocks (specifically algal biomass), CO2 capture using a novel membrane photobioreactor, and thermochemical processing of biomass. Dr. Stuart received his Ph.D. from the Department of Chemical and Biochemical Engineering at Rutgers, the State University of New Jersey and he is a registered professional environmental engineer in the State of Ohio.

Mr. Joseph Tyler Zongolowicz, NAVAIR

I attended Old Dominion University for Mechanical Engineering where I focused my studies on Thermal Sciences. Towards to end of my undergraduate career I began taking graduate classes to earn my master's degree one year after my bachelor's degree. Upon completion of my degrees I moved to Maryland to work for the NAVAIR as a civilian. My current areas of interest include air breathing propulsion technologies, rocket propulsion, test methods, and heat/energy transfer.

Dr. Linda Vahala, Old Dominion University

Dr. Linda Vahala received her B.S..degree from the University of Illinois in 1969, an M.S. degree from the University of Iowa in 1971, and a Ph.D from Old Dominion University in 1983. Her publications include

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IMPULSE CALCULATION OF MODEL ROCKET ENGINES FROM EXPERIMENTAL DATA

Abstract

In order to provide the engineering freshmen with a hands-on rocketry experience and teach them important physical and calculus concepts, a model rocket thrust test stand was designed and integrated with a data acquisition system. The purpose of the experiment was to show how impulse can be calculated experimentally. The thrust test stand features a precise load cell and a flexure load frame that ensures that only the thrust from the engine is measured. The test stand was designed and built by a graduate student so that the students in the introduction to engineering course can conduct their own experiments using model rocket engines of various sizes. From obtained time-thrust curves, the students were successful in using three different techniques (adding trapezoid areas using Excel, manually counting the number of squares under the thrust curve and using a MATLAB program) to calculate the impulse. A students' attitude survey showed that the students were highly satisfied with this hands-on experience in rocket science and integration.

Introduction

Experiential learning is a well-documented [1-3] and a well recognized part of Kolb's experiential learning cycle/spiral [4-6] that is used as a powerfull pedagogical strategy in many engineering programs. Project-based learning (PBL) pedagogy is well accepted in education. It is also emphasized as one of the high priority education methods/pedagogies required in early engineering education. This paper describes a successfull implementation of PBL in an introduction to engineering course. The practical experience described in this paper is realization centered.

For several years, building of model rockets and analyzing various aspects of their operation was used as a powerful motivational tool for students [7-16]. A model-rocket test stand is used in a calculus course [17]. A description of a test stand with a data acquisition hardware and software for impulse determination is presented by Zongolowicz [18]. Namely, impulse (I), in units of N-sec, is a fundamental characteristic of both actual and model rocket engines. It can be calculated by using the following equation: $I = M_b V max - M_0 V_0$; where V_0 is the velocity at lift-off which is zero; M_b and M_0 are the burn-out and lift-off mass values, and V_{max} is the maximum or the burn-out velocity. Impulse is also equal to the acting net force multiplied by the burn time. Calculation or confirmation of the impulse is one of the important outputs of engine testing activities performed by engine and launch vehicle manufacturers. This paper describes how freshmen engineering students were exposed to impulse calculation using various methods. In Figure 1, propellant provides impulse that generates thrust to propel the rocket.

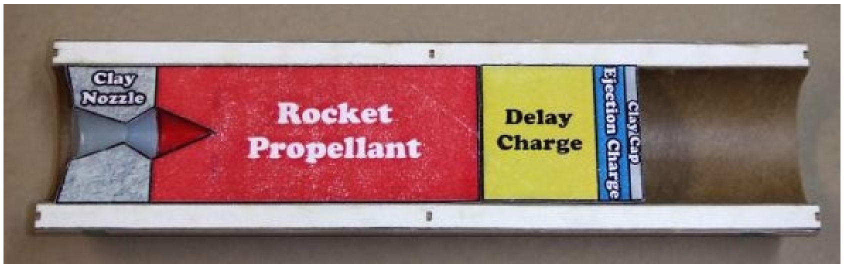


Figure 1. Components of a Solid Model Rocket Engine [19]

Initially, engines of different sizes are fired as shown in Figures 2 and 3 to demonstrate thrusting and ejection concepts.

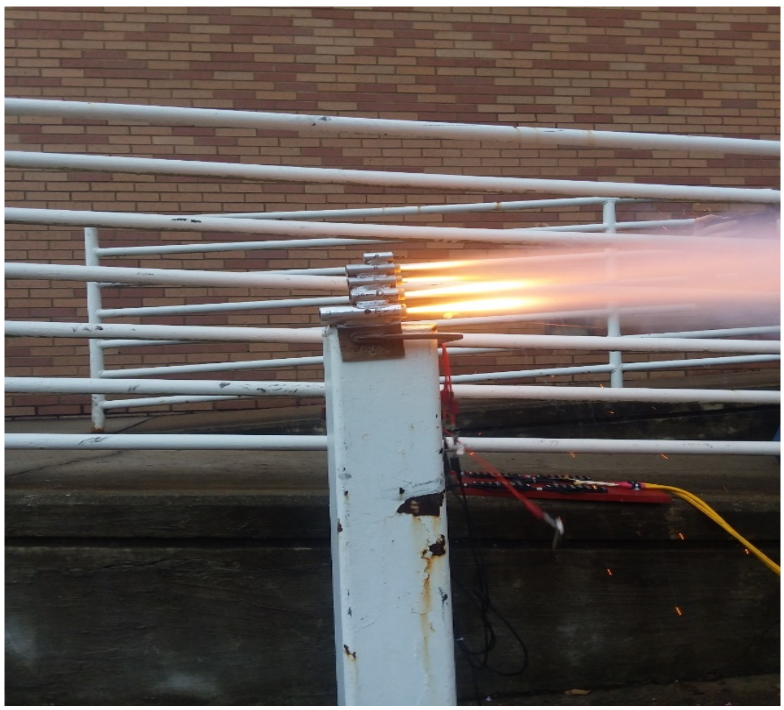


Figure 2. Static Engine Thrusting Demonstration

Students really enjoy the static engine firing demonstrations as a prelude to the main project.

Figure 3. Static Engine Parachute Ejection Demonstration

Figure 4 shows engines with pre and post firing masses.   The difference is the sum of the masses of the four chemicals shown in Figure 1.

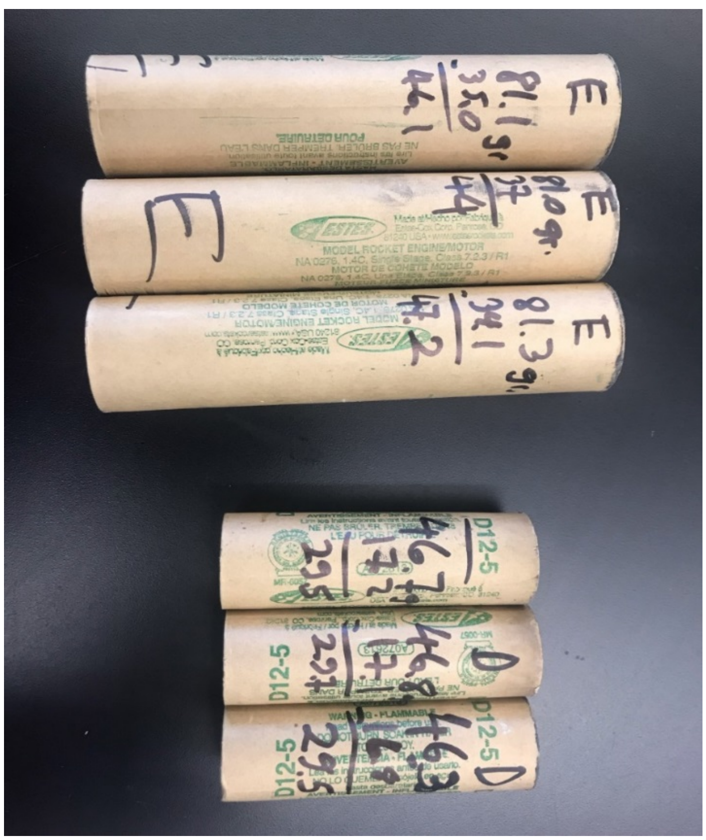


Figure 4. Used D12-5 and E16-6 Engines

Curricular Context

ENGN 110 is an introduction to engineering and technology course designed to "introduce a variety of engineering and technology disciplines" through a series of engineering projects. The course emphasizes team work, design, testing, communication and presentation skills, as well as discovery, creativity, and innovation. The course is a one-semester, 2 credit course required for all engineering and engineering technology programs. The described practical calculus and physics related engineering experience presents one of the major learning modules in this course.

Educational Goals, Activities, and Outcomes

Educational goals of this project include increased excitement for engineering resulting in increased retention, motivational preparation for further studies in engineering, and gaining an insight into what engineers do. The practical experience consists of several activities. There are several project learning outcomes that stem from project educational goals that are reinforced/implemented through project activities. The project learning outcomes include 1) development of teamwork skills, 2) increased appreciation for future coursework in physics, statics, dynamics, and thermodynamics, 3) an early understanding of the role of experimental and analytical approaches to engineering problem solving, 4) development of written communication skills through writing technical team reports, and 5) increased appreciation for engineering by experiencing a "real life" like hands-on engineering project from start to finish. These outcomes are closely related to ABET-EAC Criterion 3, 1-7 student learning outcomes, specifically outcome 1 - an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics, outcome 3 - an ability to communicate effectively with a range of audiences, and outcome 6 – an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.

Practical Experience

Students used a previously constructed model rocket engine thrust stand and obtained time thrust curves for Estes D12-5 solid model rocket engines. The data was plotted with excel and the area under the curve was calculated using three methods: 1) simple excel coding based on trapezoid area calculations, 2) manually counting the number of blocks under the curve, and 3) using a MATLAB program provided by the instructor. All three methods yielded the same impulse value. Larger E16-6 engines were not tested, but the published data [20] was used in the same manner.

The ENGN 110 Rocket Test Stand Design

The ENGN 110 rocket thrust measurement stand consists of an engine mount supported by four flexured struts. Under the influence of engine thrust, struts are deflected, and the applied force is directly transferred to a load cell. The four-strut design is machined from two plates as seen in Figure 5. The signal from the load cell is digitized through a stand-alone analog to digital data acquisition unit. Analysis of the data is accomplished with a personal computer and National Instruments LabVIEW software. The user obtains a record of impulse, burn time, and thrust with respect to time.

The data from the load cell is collected and analyzed using a stand-alone data acquisition unit and LabVIEW software. The user obtains burn-time (x) and thrust (y) data. Integrating the resulting curve y(x) yields the impulse (N-sec) using an embedded MATLAB program invoked by the GUI used to run the entire experiment. The design of the stand is horizontal to avoid error caused by changes in engine mass during combustion. Deflection of the flexures at the load cell level is on the order of 0.003 inches and any small effects on thrust due to the flexures are calibrated out using dead weight loading.

The engine mount features a rectangular vent which allows the ejection charge to escape. The thrust measurement range is between 0 and 25 lbs. at a sampling rate of up to 1 kHz. Common hobby-grade solid rocket motors (up to 24 mm in diameter) will fit in the cylindrical engine mount using various adapter sleeves. The entire test assembly is suspended on a mobile cart allowing the unit to be moved between laboratory sites. The finished cart with a rocket engine at thrusting and ejection stages are shown in Figures 6 and 7. The details of the test stand design can be found in Zongolowicz [18].

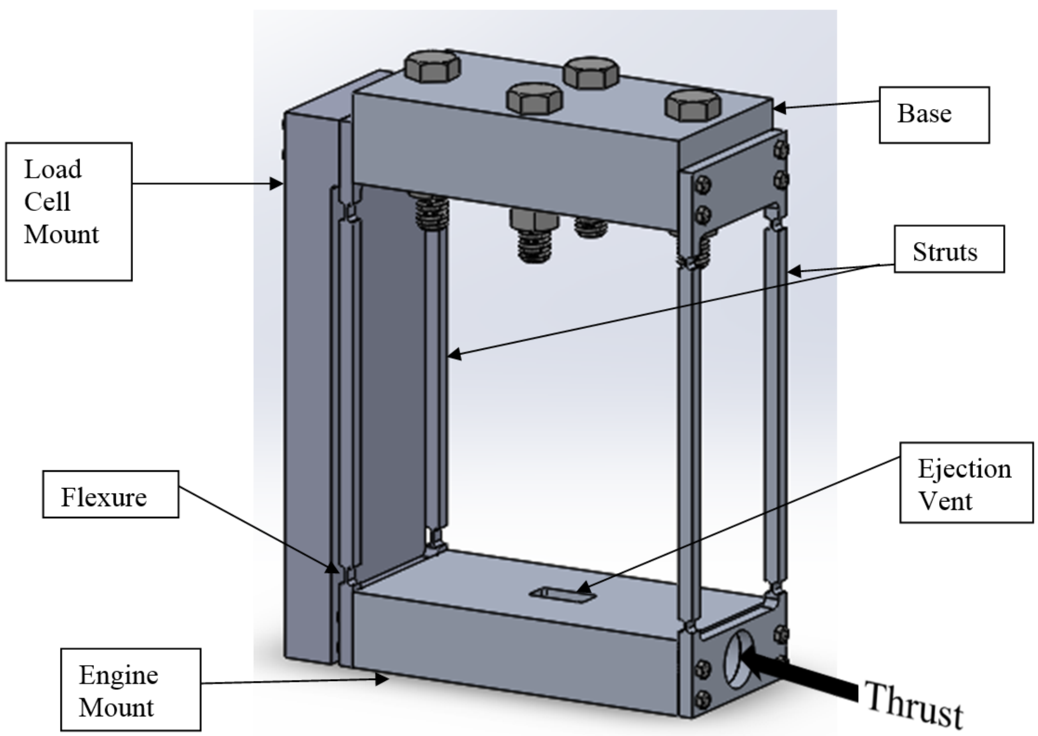


Figure 5. Model Rocket Engine Thrust Stand

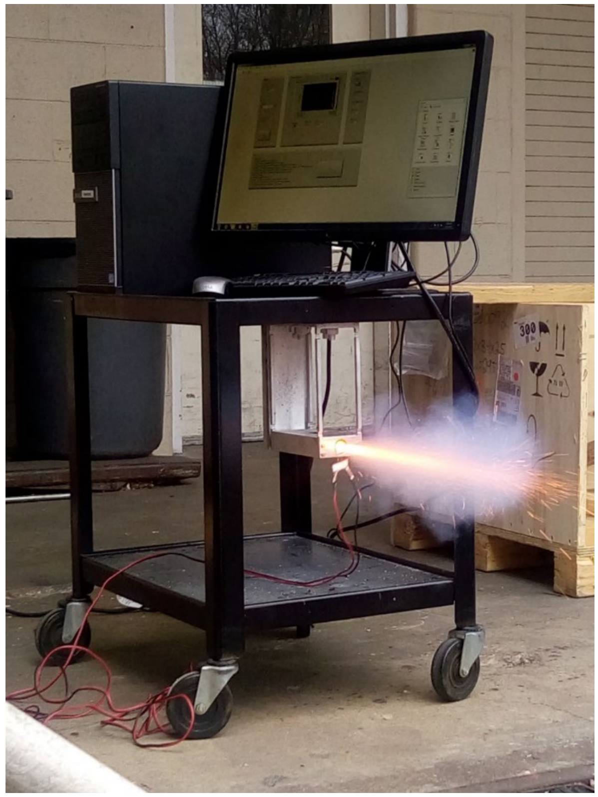


Figure 6. Rocket Test Stand at D12-5 Engine Thrusting

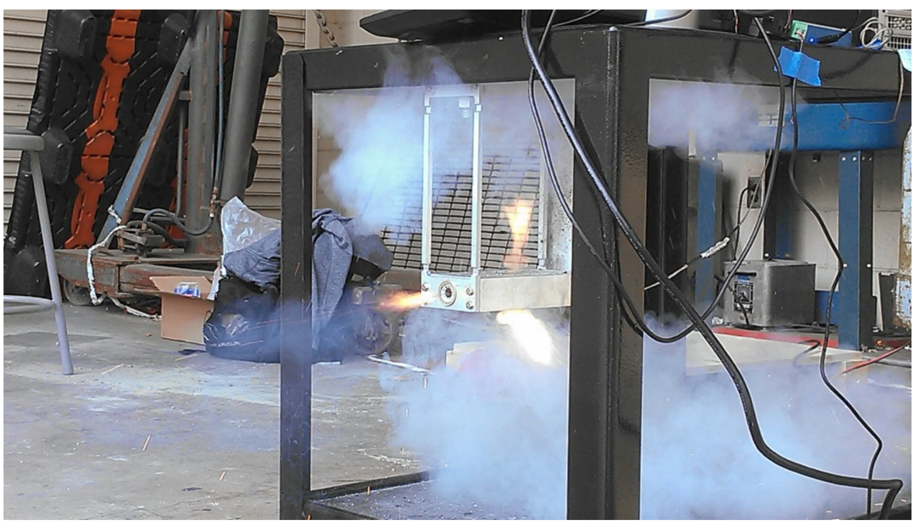


Figure 7. Rocket Test Stand at D12-5 Engine Parachute Ejection

Figure 8 shows time thrust data for an engine D12-5 which is almost identical to the published reference data [21]. Many tests were conducted, but not all tests yielded an ideal curve as in Figure 8. Tables 1 and 2 show the application and the results of the method 1 for the D12-5 engine data in Figure 8.

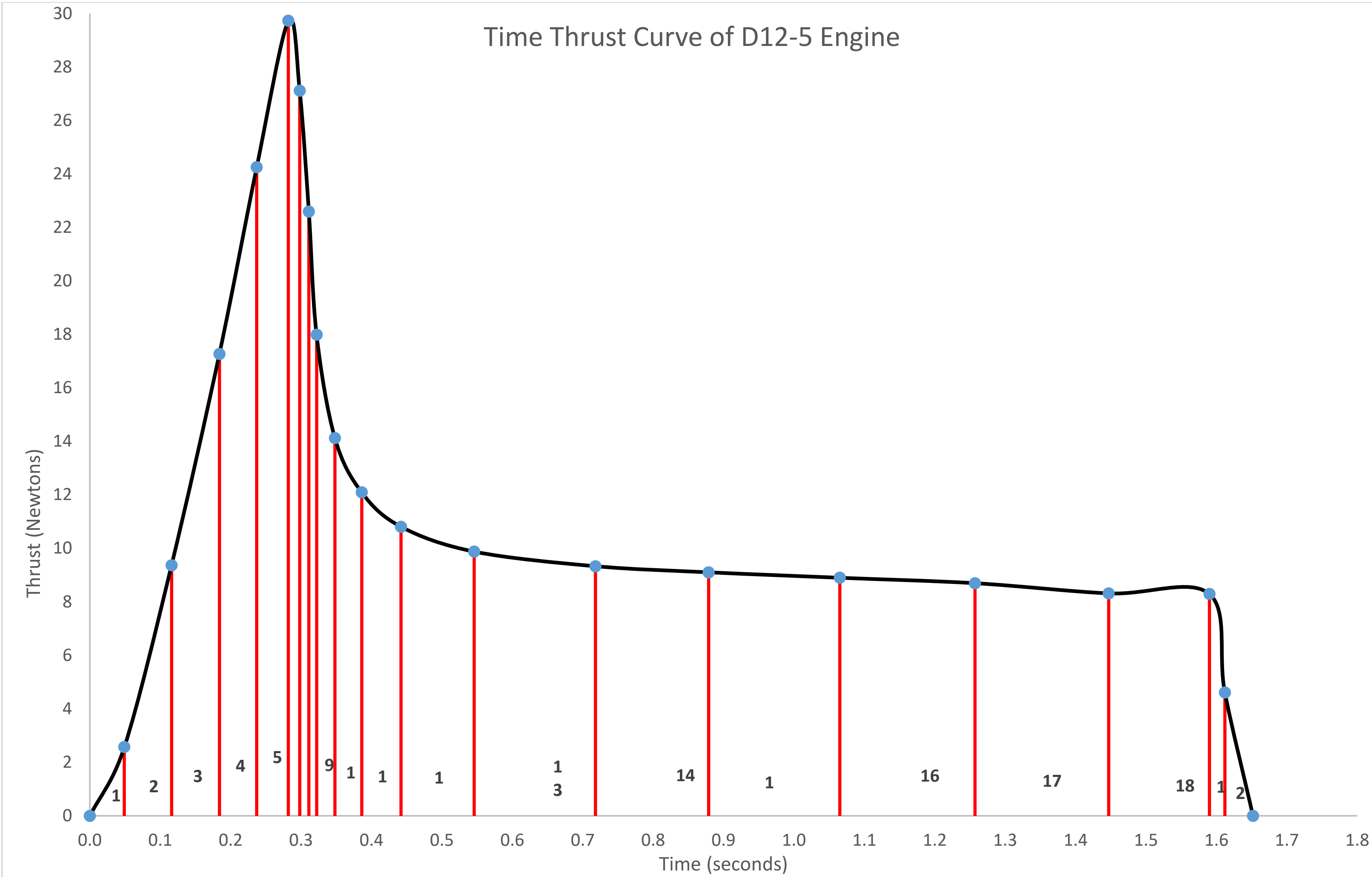


Figure 8. Time Thrust Data for Engine D12-5

Table 1. Excel Code for D12-5 Engine Impulse Calculation Using the Trapezoid Areas

Row Number	Time (X) Column F	Thrust (Y) Column G	Trapezoid No. Column H	Width Column I	left Height Column J	Right Height Column K	Area or Impulse Column L
4	0.000	0.00					
5	0.049	2.57	1	=F5-F4	=G4	=G5	=(I5)*((J5+K5)/2)
6	0.116	9.37	2	=F6-F5	=G5	=G6	=(I6)*((J6+K6)/2)
7	0.184	17.28	3	=F7-F6	=G6	=G7	=(I7)*((J7+K7)/2)
8	0.237	24.27	4	=F8-F7	=G7	=G8	=(I8)*((J8+K8)/2)
9	0.282	29.73	5	=F9-F8	=G8	=G9	=(I9)*((J9+K9)/2)
10	0.297	27.01	6	=F10-F9	=G9	=G10	=(I10)*((J10+K10)/2)
11	0.311	22.59	7	=F11-F10	=G10	=G11	=(I11)*((J11+K11)/2)
12	0.322	18.00	8	=F12-F11	=G11	=G12	=(I12)*((J12+K12)/2)
13	0.348	14.13	9	=F13-F12	=G12	=G13	=(I13)*((J13+K13)/2)
14	0.386	12.10	10	=F14-F13	=G13	=G14	=(I14)*((J14+K14)/2)
15	0.442	10.81	11	=F15-F14	=G14	=G15	=(I15)*((J15+K15)/2)
16	0.546	9.88	12	=F16-F15	=G15	=G16	=(I16)*((J16+K16)/2)
17	0.718	9.31	13	=F17-F16	=G16	=G17	=(I17)*((J17+K17)/2)
18	0.879	9.11	14	=F18-F17	=G17	=G18	=(I18)*((J18+K18)/2)
19	1.066	8.90	15	=F19-F18	=G18	=G19	=(I19)*((J19+K19)/2)
20	1.257	8.70	16	=F20-F19	=G19	=G20	=(I20)*((J20+K20)/2)
21	1.436	8.31	17	=F21-F20	=G20	=G21	=(I21)*((J21+K21)/2)
22	1.590	8.29	18	=F22-F21	=G21	=G22	=(I22)*((J22+K22)/2)
23	1.610	4.61	19	=F23-F22	=G22	=G23	=(I23)*((J23+K23)/2)
24	1.650	0.00	20	=F24-F23	=G23	=G24	=(I24)*((J24+K24)/2)
						Total Impulse:	=SUM(L5:L24)

Using the trapezoid No.3 in Figure 8, the right and left sides are 9.37 N and 17.28 N on the thrust axis while the width on the time axis is 0.184-0.116 = 0.068 seconds. The average height is 13.325 N and the area is 13.325 x 0.68 = 0.906 N-sec as shown in Table 2. As smaller widths are used, this approximation becomes very accurate.

Figure 9 and Table 3 show the same analysis for the larger E16-6 engine. The results (16.84 N and 33.37 N) match the published means [20, 21], but no two firings are alike, and the results vary.

Table 2. D12-5 Time Thrust Data and Impulse Calculation Using the Trapezoid Areas (integration)

Time	Thrust	width	left Height	Right Height	Area
0.000	0.000				
0.049	2.569	0.049	0.000	2.569	0.06294
0.116	9.369	0.067	2.569	9.369	0.39992
0.184	17.275	0.068	9.369	17.275	0.90590
0.237	24.258	0.053	17.275	24.258	1.10062
0.282	29.730	0.045	24.258	29.730	1.21473
0.297	27.010	0.015	29.730	27.010	0.42555
0.311	22.589	0.014	27.010	22.589	0.34719
0.322	17.990	0.011	22.589	17.990	0.22318
0.348	14.126	0.026	17.990	14.126	0.41751
0.386	12.099	0.038	14.126	12.099	0.49828
0.442	10.808	0.056	12.099	10.808	0.64140
0.546	9.878	0.104	10.808	9.878	1.07567
0.718	9.306	0.172	9.878	9.306	1.64982
0.879	9.105	0.161	9.306	9.105	1.48209
1.066	8.901	0.187	9.105	8.901	1.68356
1.257	8.698	0.191	8.901	8.698	1.68070
1.436	8.310	0.179	8.698	8.310	1.52222
1.590	8.294	0.154	8.310	8.294	1.27851
1.612	4.613	0.022	8.294	4.613	0.14198
1.650	0.000	0.038	4.613	0.000	0.08765
				Sum	16.84

Figure 9 shows the time-thrust curve of engine E16-6 provided by Estes [20]. Figures 10 and 11 show the application of the method 2. Students simply estimate the area under each curve by counting. The results are the same as in the method 1. Students are in fact integrating and performing numerical analysis albeit without realizing it. Figure 12 shows the MATLAB code (method 3) provided to the students to calculate impulse via curve fitting to data and trapezoid geometry.

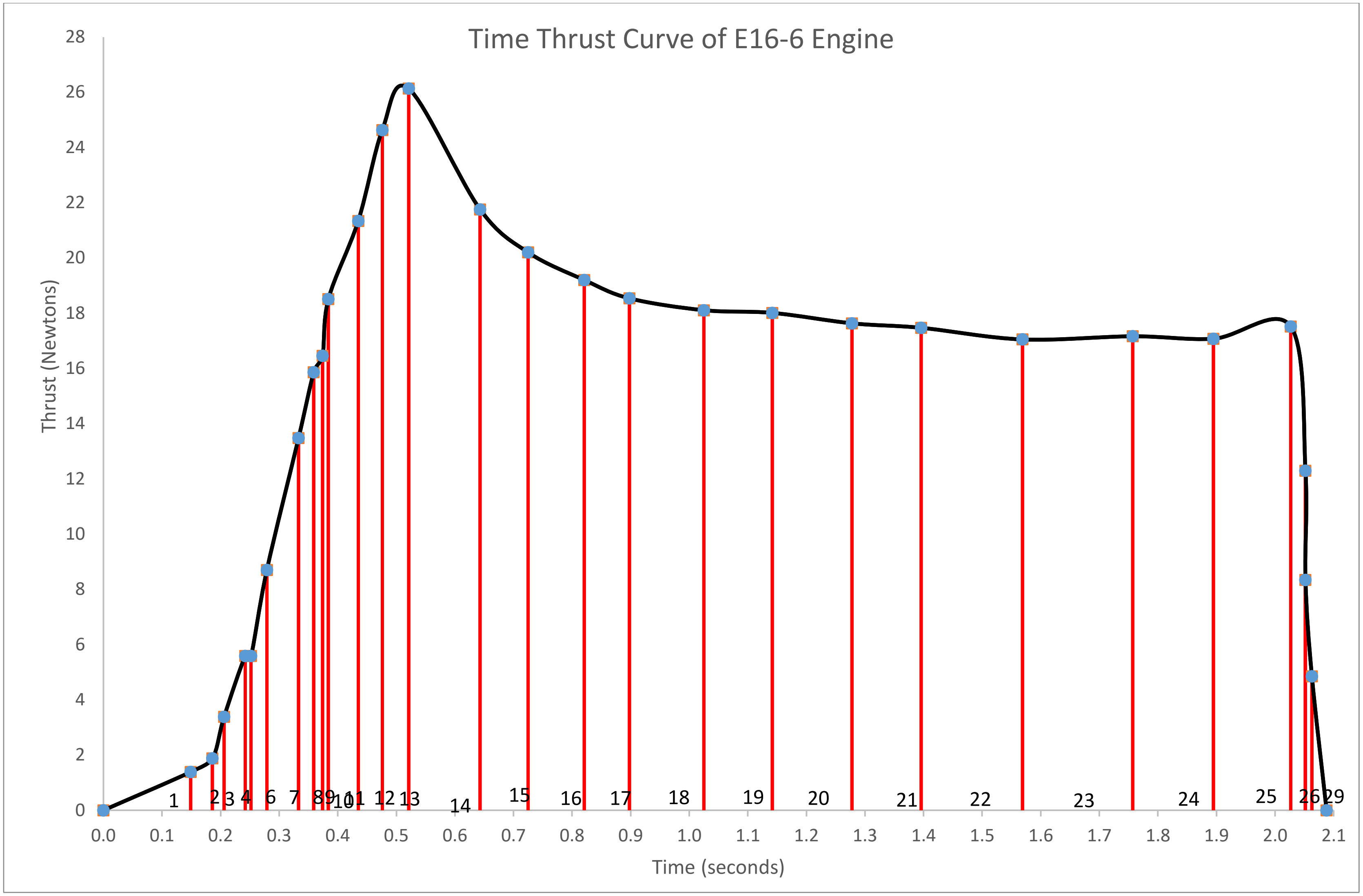


Figure 9. Time Thrust Data of Engine E16-6

Table 3. E16-6 Time Thrust Data and Impulse Calculation Using the Trapezoid Areas

Trapezoid	Time	Thrust	width	left Height	Right Height	Area
0	0.000	0.000				
1	0.15	1.371	0.150	0.000	1.371	0.10283
2	0.186	1.92	0.036	1.371	1.920	0.05924
3	0.206	3.387	0.020	1.920	3.387	0.05307
4	0.242	5.587	0.036	3.387	5.587	0.16153
5	0.252	5.587	0.010	5.587	5.587	0.05587
6	0.277	8.705	0.025	5.587	8.705	0.17865
7	0.333	13.474	0.056	8.705	13.474	0.62101
8	0.359	15.858	0.026	13.474	15.858	0.38132
9	0.374	16.592	0.015	15.858	16.592	0.24338
10	0.394	18.509	0.020	16.592	18.509	0.35101
11	0.435	21.344	0.041	18.509	21.344	0.81699
12	0.476	24.631	0.041	21.344	24.631	0.94249
13	0.521	26.44	0.045	24.631	26.440	1.14910
14	0.643	21.61	0.122	26.440	21.610	2.93105
15	0.725	20.202	0.082	21.610	20.202	1.71429
16	0.821	19.201	0.096	20.202	19.201	1.89134
17	0.898	18.538	0.077	19.201	18.538	1.45295
18	1.025	18.109	0.127	18.538	18.109	2.32708
19	1.142	18.012	0.117	18.109	18.012	2.11308
20	1.259	17.634	0.117	18.012	17.634	2.08529
21	1.396	17.472	0.137	17.634	17.472	2.40476
22	1.569	17.172	0.173	17.472	17.172	2.99671
23	1.757	17.165	0.188	17.172	17.165	3.22768
24	1.895	17.076	0.138	17.165	17.076	2.36263
25	2.027	17.516	0.132	17.076	17.516	2.28307
26	2.042	12.294	0.015	17.516	12.294	0.22357
27	2.052	8.337	0.010	12.294	8.337	0.10316
28	2.063	4.85	0.011	8.337	4.850	0.07253
29	2.09	0	0.027	4.850	0.000	0.06547
					Sum	33.37114

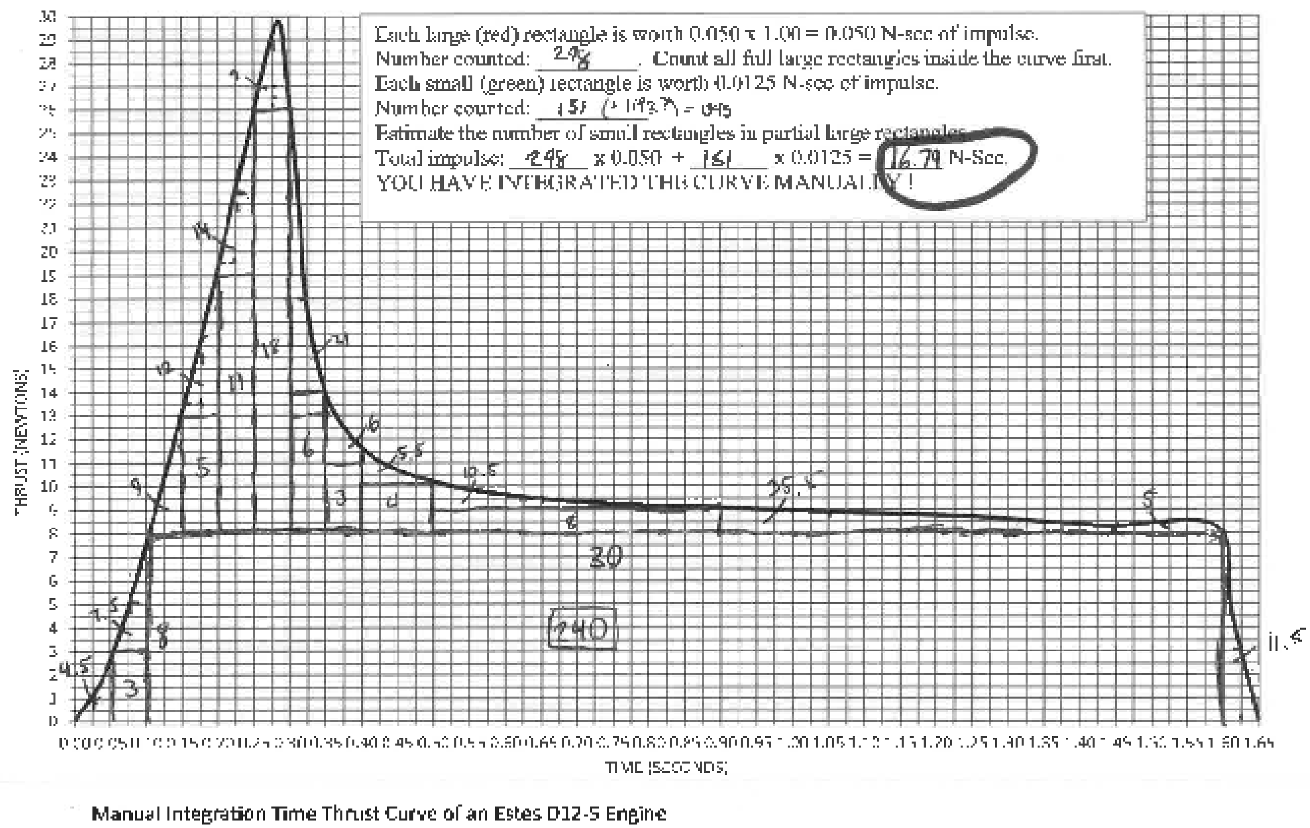
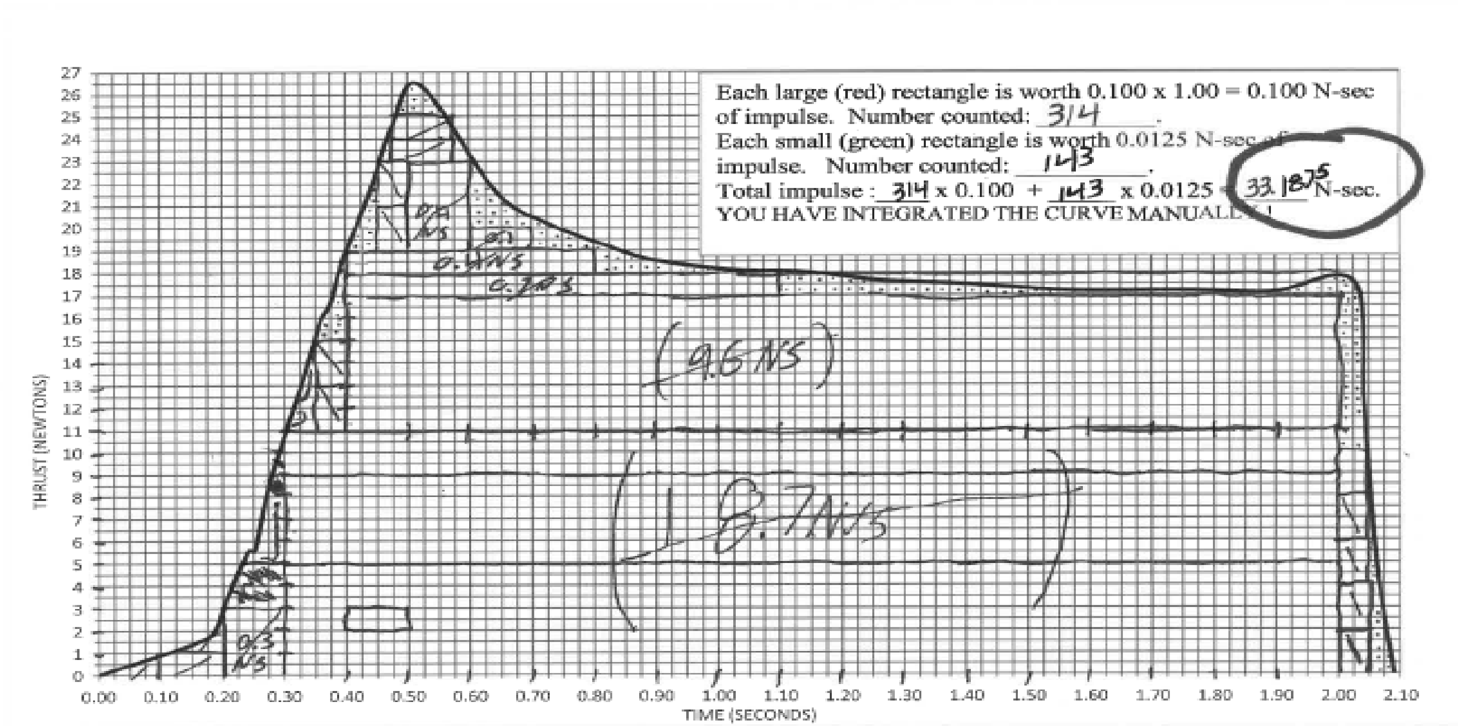


Figure 10. Manual Integration of Time Thrust Curve for an Estes D12-5 Engine

0.4.2+0.1+0.7+9.6+18.7+0.1+0.1+.1+0.1+0.4+0.1+0.1+0.1+0.2+0.2



. Manual Integration Time Thrust Curve of an Estes E16-6 Engine

Figure 11. Manual Integration of Time Thrust Curve for an Estes E16-6 Engine

```
clc, clear, close all
% start to read xls data
filename = 'D engine impulse calc.xlsx';
xlRange = 'C4:D24';
n=60; % refineness of curve fitting change it to see diff.
%readxls
TTDat=xlsread(filename,xlRange);
x=TTDat(:,1); y=TTDat(:,2);
ind=zeros(size(x));
Wdth=zeros(size(x)-1);
areabygeo=zeros(size(x)-1);
areabyintegral=zeros(size(x)-1);
xx = linspace(0,x(end,1),length(x)*n); % create linear spacing for curve coordinates
for i= 1:length(x)  % replacing our orijinal x values to the linearly generated
intervals
[ d, ix ] = min( abs( xx-x(i) ) );
xx(ix)=x(i);
ind(i)=ix;
end
yy = pchip(x,y,xx); % Best fitting =Piecewise Cubic Hermite Interpolating Polynomial
(PCHIP)
%plot
figure
plot(x,y,'o')
line(x,y)
grid minor
hold on
plot(xx,yy)
title('Time Thrust Curve of D12-5 Engine')
ylabel('Thrust (Newtons)')
xlabel('Time (Seconds)')
for i=1:length(x)
     xl = [xx(ind(i)) xx(ind(i))];
     yl = [0 yy(ind(i))];
    line(xl,yl)
end
hold off
%area by trapezoidal geo.
fprintf('Area by Trapezoidal Geometry:\n')
for i=1:length(ind)-1
Wdth(i)=x(i+1)-x(i); %width
areabygeo(i)=Wdth(i)/2*(y(i)+y(i+1));
fprintf('Trapezoidal Area #%d=%g\n',i,areabygeo(i));
end
%area by integral trapz
fprintf('Area using Integral of  polynomial curve:\n')
areabyintegral(1)=trapz(xx(1:ind(2)),yy(1:ind(2)));
 fprintf('Trapezoidal Area #%d=%g\n',1,areabyintegral(1));
for i=2:length(ind)-1
 areabyintegral(i)= trapz(xx(1:ind(i+1)),yy(1:ind(i+1)))-
trapz(xx(1:ind(i)),yy(1:ind(i)));
   fprintf('Trapezoidal Area #%d=%g\n',i,areabyintegral(i));
end
Areasumgeo=sum(areabygeo);
 fprintf('\nTotal Area by Geometry =%g\n',Areasumgeo);
 Areasumint=sum(areabyintegral);
 fprintf('Total Area by Integral Under Curve =%g\n',Areasumint);
```

Figure 12. MATLAB code used for method 3.

Figure 13 shows the results of the method 3.

Area by Trapezoidal Geometry:	**Area by Trapezoidal Geometry:**
Trapezoidal Area #1=0.0629405	Trapezoidal Area #1=0.102825
Trapezoidal Area #2=0.399923	....
Trapezoidal Area #3=0.905896	Trapezoidal Area #14=2.93105
....	....
Trapezoidal Area #16=1.6807	Trapezoidal Area #16=1.89134
....	....
Trapezoidal Area #20=0.087647	Trapezoidal Area #29=0.065475
Area using Integral of polynomial curve:	**Area using Integral of polynomial curve:**
Trapezoidal Area #1=0.0556796	Trapezoidal Area #1=0.0881378
Trapezoidal Area #2=0.384838	....
....	Trapezoidal Area #14=2.96001
Trapezoidal Area #13=1.64186	....
....	Trapezoidal Area #28=0.0713905
Trapezoidal Area #20=0.081588	Trapezoidal Area #29=0.0559821
Total Area by Geometry =16.8394	Total Area by Geometry =33.3711
Total Area by Integral Under Curve =16.7979	Total Area by Integral Under Curve =33.379

Figure 13. The results of the Method 3 for D12-5 (left) and E16-6 (right) Engines

Lessons Learned and Educational Impact

The learning outcomes of this project include an understanding of how the physical experiments and analytical calculations can yield almost the same values in impulse calculations. Other learning outcomes include gaining a firm belief that engineering data is often resource intensive, facility dependent, and it must be carefully recorded and saved for future use. Students received a practical introduction to many engineering concepts they will encounter later. For ¾ of the students, this was their first encounter with Excel and certainly MATLAB. They began learning Excel earlier in the course.

As mentioned earlier, there were several educational goals expected of this project: 1) gain appreciation for future coursework in physics, statics, dynamics, and thermodynamics, 2) obtain an early understanding of the role of experimental and analytical approaches to solve engineering problems, 3) gain practice in writing lab reports, 4) experience a “real life” like hands-on engineering project from start to finish, 5) learn more rocket science in general, 6) get excited about engineering. These educational goals above were either accomplished or it is too soon to tell as in the case of goal 6 that also seeks to improve retention. Anonymous exit survey (shown in Figure 14) taken on the last day of classes indicate that a majority (74 %) of the students felt this project was a good or a very good learning experience for all the goals above.

In addition, substantial qualitative evidence suggests that this project had a positive impact on student learning and retention. Positive student comments about the project were not just limited to student exit survey and course evaluations. The instructor kept receiving positive feedback from those who somehow heard about this project.

Students’ Model Rocket Engine Impulse Calculation Project Attitude Survey

Please rate the following four questions.

1. Working with model rocket engines was ____________.
   1 = really boring, 2 = somewhat boring, 3 = neither boring nor exciting, 4 = somewhat exciting, 5 = very exciting
2. From this experiment I learned ___________ about impulse and integration.
   1 = nothing, 2 = very little, 3 = something, 4 = much, 5 = very much
3. By performing calculations using Excel I became ___________ with coding in Excel.
   1 = less proficient, 2 = somewhat less proficient, 3 = neither less nor more proficient, 4 = somewhat proficient, 5 = very proficient
4. By performing calculations using MATLAB I became ___________ with MATLAB software.
   1 = less proficient, 2 = somewhat less proficient, 3 = neither less nor more proficient, 4 = somewhat proficient, 5 = very proficient
5. Physical model rocket engine tests with calculations were __________ in my understanding of the integration concept.
   1 = unhelpful, 2 = somewhat unhelpful, 3 = neither unhelpful nor helpful, 4 = helpful, 5 = very helpful

Please comment on your experience with obtaining the experimental data and calculations of impulse:

1. What is it that you liked the most about the model rocket engine tests and subsequent calculations?
2. Which part of the experience (preparation for the test, running the test, gathering data, analyzing data, etc.) was the easiest/hardest for you?
3. How would you improve this educational experience?

Figure 14. Students’ Attitude Survey

Conclusions

Students enjoyed conducting experiments using the new apparatus. They observed different impulse values for successive tests using ostensibly identical engines. This, in turn, partially accounted for different maximum altitudes reached by the same model rocket. The primary educational benefit of the experiment comes from using the downloaded test data and processing the data manually as a team project. Students learned how to directly calculate the impulse by writing code in Excel and using a MATLAB code to calculate the area under the thrust vs. burn-time curve. Hence, students were able to understand and apply the concept of integration as they were analyzing data obtained from a real event. The concept of "area under the curve" and its importance in engineering became clear early on, even before many of them have taken calculus. For the above set of activities, a students' attitude assessment survey was designed, implemented, and analyzed. Overall, students felt this was a very exciting and a worthwhile learning experience that taught them the concept of integration and variability in experimentally acquired quantities. Students also claimed that this learning experience enhanced their Excel skills while introducing them briefly to MATLAB software and its capabilities. However, no test was conducted to check if the students' grasp the concepts has improved with this experiment vs. without this experiment.

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