Session 2004-124

ASEE ANNUAL MEETING
Salt Lake City, Utah
June, 2004

The Trebuchet Project: Launching a "Hands-On" Engineering Technology Approach To Conducting Hands-On Statics and Dynamics Laboratory Courses

Francis A. Di Bella, PE
Assistant Professor
Northeastern University, Boston, MA
Mechanical Engineering Technology

ABSTRACT

"…Hands-On, real word engineering experience" is the refrain that is justifiably used to identify the objectives of an Engineering Technology education. The pedagogy that is in place in engineering technology curriculums strives to satisfy this goal. Northeastern University's recent change to a semester system has also provided an opportunity to restructure most of its Engineering Technology programs. Specifically, every core engineering technology course now has an associated laboratory component. The lab session is scheduled within the classroom instruction period, with the full-time faculty conducting the experiments along with the students. In the case of the Statics and Dynamics courses an additional change has been implemented: the students will design and build their own statics and dynamics experiments using individual "loose" components. The experiments that can be replicated can be copied directly from the end-of-chapter problems found in the Statics and Dynamics textbooks. The intent is to employ and emphasize the "hands-on" criteria of the engineering technology program in a new and more relevant way. This paper describes the efforts and the various experiments that are being implemented.

Introduction

Northeastern University converted to a semester system in the fall of 2003. This conversion necessitated a review of the course content of all of the courses throughout the University and was found to be an ideal opportunity to update and improve those courses in many ways. One such decision was to have all core Engineering Technology courses have a laboratory constituent as part of the class-room work. Where previously the class room instruction in Thermodynamics, for example, was followed by another course identified as Thermo Lab now the Thermodynamics course contains a set of experiments and/or energy facility tours that require Lab Reports or mini-engineering energy studies of the energy facilities to be prepared.

The presence of a lab in most engineering technology courses is often looked upon by the student as a considerable investment in time in the lab as well as at home, doing the write-up Report for the lab. While the proportion of time spent in actual doing and writing is often not in proportion with the QPA points awarded, the lab experience is recognized as a vital part of the curriculum. The question inevitably becomes: How can the academic needs for the students be met while having the students content with what they are doing; particularly when the student wants to build something or perform legitimate "hands-on" activities?

This paper describes the methodology for one possible answer to this question. The paper concludes with an example of this methodology entitled: The Trebuchet Project: launching a new mechanical engineering technology lab curriculum.

Proposed Methodology for an active Lab Experience in Statics and Dynamics

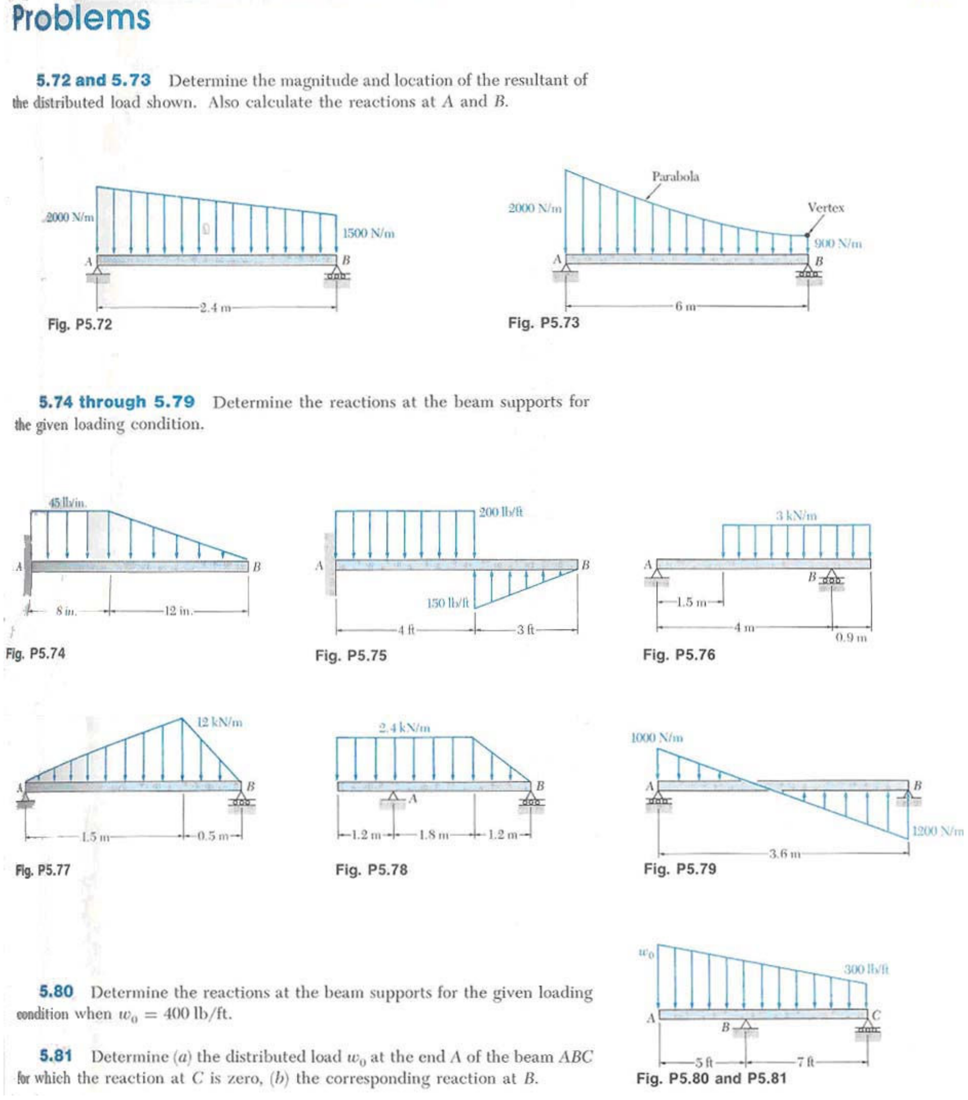
Every engineering technology textbook comes replete with many worked examples and even more problems at the end of the chapter. These later problems are used for homework assignments and/or solved by the Instructor during the classroom lecture. With this guidance the students see the solution methodology in action and eventually the student learns to solve similar problems and ultimately can solve problems by applying basic principles and good procedural habits. Certainly some students are quicker at the conceptual solution than others. The Instructor takes pains to point out that a student in either the fast or the slow category must always deploy one last step in the solution process: the Reality check. This final step is critical to the solution of an engineering problem because it asks the student to consider the reasonableness of the answer given the context of the problem. This paper proposes that the true engineering technology solution to a word problem should take a very relevant next step: to actually do the experiment that the textbook problem has identified. Certainly, the "hands-on" engineering technology student is more comfortable with this part of the solution for it gives him/her an opportunity to actually build something while also applying measurement techniques to the process and common sense to the study of the results.

A page from a textbook[1] illustrates this point. Figure 1a and b contains several worded problems from a statics and dynamics text. These are similar to any number of 'end-of-the-chapter' problems found in other textbooks on statics and dynamics. The student is certainly expected to be able to solve the problem after suitable time spent in the class room lecture and/or reading the textbook coverage of the relevant material. The suggestion made here is that the student should now take the problem and enter the laboratory where suitable equipment is available for the student to actually build the same problem with the proper instrumentation. The testing should then be performed the necessary number of times in order for the student to be able to statistically determine the average or nominal answer for the problem. With the instructor's help the differences in the experimental and theoretical answers can be explained and the student goes on to prepare a concise report of the testing, the theoretical solution, the experimental results and explaining the differences.

---

[1] Exerted from Beers and Johnston, Statics and Dynamics for Engineers

Figure 1a. Excerpt from Statics Chapter in Beer's and Johnstons' Textbook



185

Problems

5.72 and 5.73 Determine the magnitude and location of the resultant of the distributed load shown. Also calculate the reactions at *A* and *B*.

Fig. P5.72

Fig. P5.73

5.74 through 5.79 Determine the reactions at the beam supports for the given loading condition.

Fig. P5.74

Fig. P5.75

Fig. P5.76

Fig. P5.77

Fig. P5.78

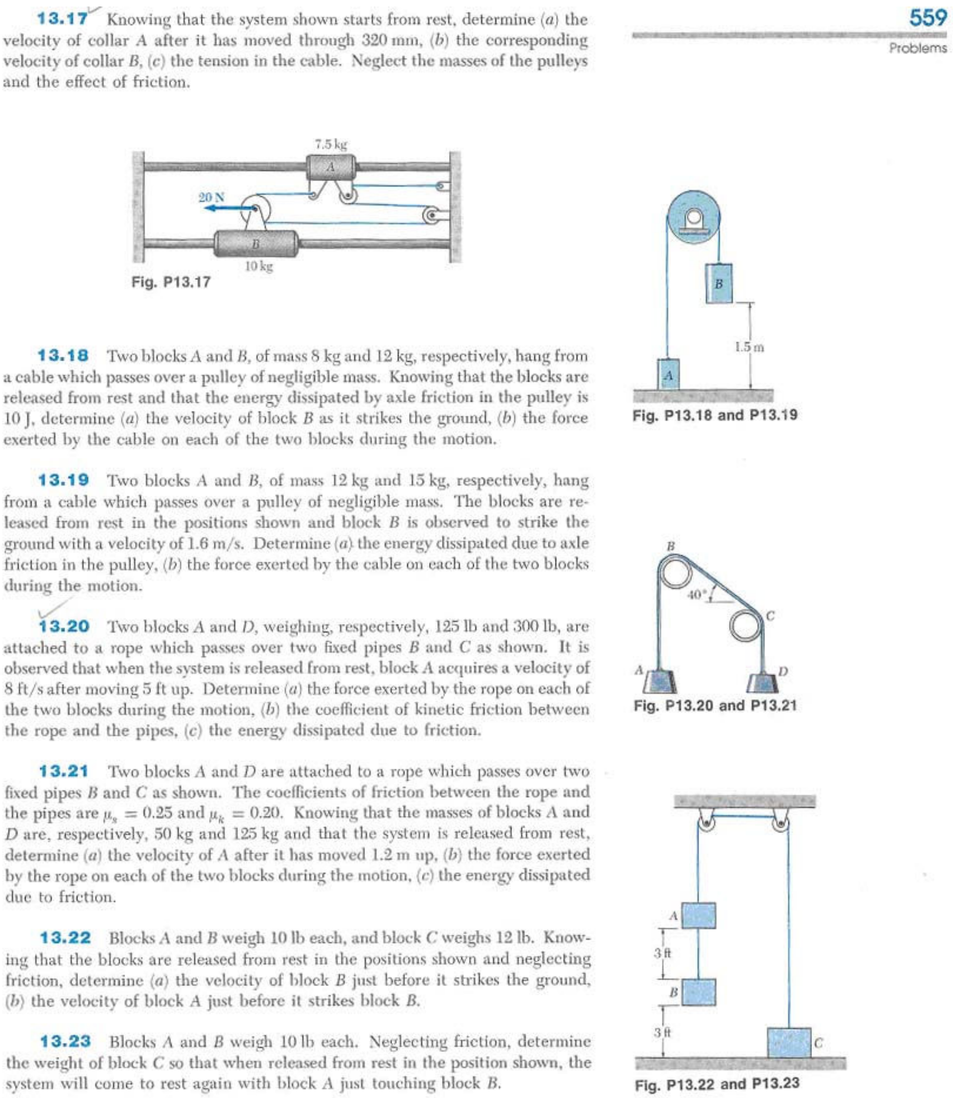
Fig. P5.79

5.80 Determine the reactions at the beam supports for the given loading condition when $w_0 = 400$ lb/ft.

5.81 Determine (*a*) the distributed load w_0 at the end *A* of the beam *ABC* for which the reaction at *C* is zero, (*b*) the corresponding reaction at *B*.

Fig. P5.80 and P5.81

Figure 1. Excerpt for Dynamics Chapter in Beers and Johnston Textbook



559

Problems

13.17 Knowing that the system shown starts from rest, determine (*a*) the velocity of collar *A* after it has moved through 320 mm, (*b*) the corresponding velocity of collar *B*, (*c*) the tension in the cable. Neglect the masses of the pulleys and the effect of friction.

Fig. P13.17

13.18 Two blocks *A* and *B*, of mass 8 kg and 12 kg, respectively, hang from a cable which passes over a pulley of negligible mass. Knowing that the blocks are released from rest and that the energy dissipated by axle friction in the pulley is 10 J, determine (*a*) the velocity of block *B* as it strikes the ground, (*b*) the force exerted by the cable on each of the two blocks during the motion.

Fig. P13.18 and P13.19

13.19 Two blocks *A* and *B*, of mass 12 kg and 15 kg, respectively, hang from a cable which passes over a pulley of negligible mass. The blocks are released from rest in the positions shown and block *B* is observed to strike the ground with a velocity of 1.6 m/s. Determine (*a*) the energy dissipated due to axle friction in the pulley, (*b*) the force exerted by the cable on each of the two blocks during the motion.

13.20 Two blocks *A* and *D*, weighing, respectively, 125 lb and 300 lb, are attached to a rope which passes over two fixed pipes *B* and *C* as shown. It is observed that when the system is released from rest, block *A* acquires a velocity of 8 ft/s after moving 5 ft up. Determine (*a*) the force exerted by the rope on each of the two blocks during the motion, (*b*) the coefficient of kinetic friction between the rope and the pipes, (*c*) the energy dissipated due to friction.

Fig. P13.20 and P13.21

13.21 Two blocks *A* and *D* are attached to a rope which passes over two fixed pipes *B* and *C* as shown. The coefficients of friction between the rope and the pipes are $\mu_s = 0.25$ and $\mu_k = 0.20$. Knowing that the masses of blocks *A* and *D* are, respectively, 50 kg and 125 kg and that the system is released from rest, determine (*a*) the velocity of *A* after it has moved 1.2 m up, (*b*) the force exerted by the rope on each of the two blocks during the motion, (*c*) the energy dissipated due to friction.

13.22 Blocks *A* and *B* weigh 10 lb each, and block *C* weighs 12 lb. Knowing that the blocks are released from rest in the positions shown and neglecting friction, determine (*a*) the velocity of block *B* just before it strikes the ground, (*b*) the velocity of block *A* just before it strikes block *B*.

13.23 Blocks *A* and *B* weigh 10 lb each. Neglecting friction, determine the weight of block *C* so that when released from rest in the position shown, the system will come to rest again with block *A* just touching block *B*.

Fig. P13.22 and P13.23

A major benefit to the experimental solution is that the student can physically see the 3-dimensional problem with which he/she is confronted. The actual effort of building the experiment starts the solution process for the student who may be having trouble seeing the 3-dimensional aspects of the problem when it is presented on a 2-dimensional textbook page. Relationships between component speeds and lengths of cable that are changing with time or forces and rates of change of momentum take on a new dimension; they are quickly and more physically apparent and certainly more convincingly demonstrated to the student.

Furthermore, changes can be made to the size, masses or speeds of the major components used in the problem to see how these changes effect the results. It is even possible to determine an optimum solution via the testing. In short, the student selects the experiment that is interesting to him/her, builds the experiment, performs the testing and reports on the results. Clearly the proposed pedagogy helps to expose students to “hands-on” statics and dynamics problems. But then there’s a second benefit borne from undertaking any engineering technology experiment: the need to instrument, measure and analyze the results. Certainly, any previous classroom instruction in Dimensional Analysis takes-on real, physical significance when the experiment is underway. The entire laboratory experience concludes with the need for written communication via a Lab Report that forces the student to hone his/her written and, if appropriate, oral communication skills.

Northeastern is in the process of outfitting a lab with enough “loose” and individual components to enable many of the statics and dynamics experiments taken from end-of-chapter problems to be fabricated by a group of students. A preliminary Bill of Materials (in progress) for this lab experiment is shown in Table 1.

TABLE 1. BILL of MATERIALS for Statics and Dynamics Components		The Lowell Institute School			Document Number	MET E924
		School of Engineering Technology				
	12/5/2003	120 Snell Engineering Technology			Revision	01
		Boston, MA 02115	Title:		Lab Equipment for	
					Exp. In Statics & Dynamics	
Vendor	Vendor Part Number	Description	Qty	UOM	Price	Total
Lab inventory	-	Fulcrum - load (3"equil.triangle)	8	EA.	$0	$0
Lab inventory	-	Fulcrum - wood of rollers casters	8	EA.	$0	$0
		(3"equil.?triangle)				
Lab inventory	-	Horizontal Beam - Wood 2"x1"x4'	2	EA.	$0	$0
Turner Steel 128 North Main St. West Bridgewater, MA	2"x2"x3/16" square tubing	Horizontal Box Beam - Steel	6	ft	$25	$25
Phone 508-583-7800						
McMaster-Carr http://www.mcmaster.com/	88875K67	Horizontal Box Beam - Aluminum Alloy 6063	6	ft	$42	$42
McMaster-Carr http://www.mcmaster.com/	9017K49	90° Angle - A36 Carbon Steel	6	ft	$15	$15
McMaster-Carr http://www.mcmaster.com/	88805K63	90° Angle - Aluminum Alloy 6063	6	ft	$29	$29
McMaster-Carr http://www.mcmaster.com/	7750K56	Pipe - Steel Schedule 40	5	ft	$34	$34
McMaster-Carr http://www.mcmaster.com/	5038K24	Pipe - Aluminum Schedule 40	6	ft	$74	$74
Lab Inventory	-	Distributed Load Weights Steel (triangle shape)	4	EA	$0	$0
Lab Inventory	-	Distributed Load Weights Aluminum (triangle shape)	4	EA	$0	$0
Lab Inventory	-	Distributed Load Weights Steel (retangular shape)	6	EA	$0	$0
Lab Inventory	-	Distributed Load Weights (semi-circular)	4	EA	$0	$0
McMaster-Carr http://www.mcmaster.com/	1728T16	Dial Utility Bench Scale 100lbs x 1lb	6	EA.	$81	$485
Student Procured	-	Imbedded wall section	1	EA.	$0	$0
McMaster-Carr http://www.mcmaster.com/	96485K154	Compression Spring 68 lbs/inch	2	EA	$22	$22
McMaster-Carr http://www.mcmaster.com/	96485K161	Compression Spring 134.4 lbs/inch	2	EA	$17	$17
McMaster-Carr http://www.mcmaster.com/	96485K178	Compression Spring 270 lbs/inch	2	EA	$24	$24
McMaster-Carr http://www.mcmaster.com/	96485K187	Compression Spring 617 lbs/inch	2	EA	$27	$27
					Ave.	**$794**

A Case-in-Point: The Trebuchet Project

The formal implementation of this pedagogy is delayed while the designs of all of the loose components are being completed and the equipment ordered. However, a recent group of sophomore students were already scheduled to take Dynamics. While waiting for the lab to be completed the Instructor offered the students in the Dynamics class an opportunity to initiate this pedagogy of classroom instruction plus lab experience using a very familiar exercise to engineering majors everywhere: building and testing a trebuchet catapult[2]. A dynamics class is a natural venue for this project because the trebuchet is a perfect example of the application of the Conservation of Energy and Newton's Laws of Motion.

During the regular classroom instruction and with the instructor's paced-assistance a spreadsheet program is programmed to model the performance of the trebuchet. The input page of this computer model is shown in Figure 2[3] with the results of the calculations shown in the rows and columns shown in Figure 3. The bordered and bold cells identify the input parameters required to be typed into the spreadsheet by the student. The non-bordered cells are outputs from the computer model. The spreadsheet is programmed to calculate the energy state of the catapult as a function of increments in the angle of the falling catapult arm. As the power arm falls, the power weight and arm lose potential energy; energy that is gained by the projectile's kinetic energy. Thus each row is an angular increment in the fall of the power arm and a new angular velocity for the next row's calculation is determined. The spreadsheet is programmed to enable various parameters to be changed in order to observe the effect on the projectile's performance. The output includes the angular acceleration of the catapult arm, the time of fall, the projectile's velocity and angle of release. This variability enables the student to optimize the predicted performance of the catapult which can then be easily checked with a prototype.

Thus the design and fabrication of a prototype trebuchet becomes essential. Here again is another benefit of the exercise: the design must be done by the student and may or should be timed to correspond to the student's classroom instruction of AutoCad or Solid Works. Thus the student uses all of what is being taught in the classroom to solve a "real world" problem and more! By more is meant that the sophomore students in this Dynamics class have not had formal instruction in experimental instrumentation, Measurements and Analysis or dimensional analysis techniques such as Buckingham-Pi theorem and dimensionless groups. However, the testing that follows and the Instructor's requests for measurements of accuracy, precision, average throwing distances for the catapult, parametric plots of the results using dimensionless groups and efficiency require the students to stop and listen to the Instructor's forewarning arguments of what they need

---

[2] Stated this way because the author understand that many engineering students have been exposed to the trebuchet (catapult) exercise in a number of classes.

[3] Artistic licensed is liberally utilized by the author in the use of the art work that is made available with excel!

(and should expect at the University) in the way of more engineering technology training in these areas to properly engineer the medieval machine.

As a case in point consider the Instructor's request to "…measure the efficiency of the trebuchet". This is puzzlement to all of the students. The students were well into the fabrication (based on their Solid Works designs) of their various sized catapults when the first mention of the 'efficiency' of the catapult is made by the Instructor. At this time some students gloated over the others that their catapult would throw a heavier projectile the farthest; as if the size of the projectile thrown the farthest is the critical issue. Particularly curiosity is given to one student who is building a catapult of "bread box" dimensions and with such pains taking care that the finished product (shown in Fig. 4) could be a very good coffee table-type conversation piece (at least while entertaining engineers and medieval historians). This trebuchet is seen to be no competition for the other catapults (shown in Fig. 5) that range in size from 2 ft. high to 4 ft (with sling arms as long as 7 ft.). After all, the small conversation-piece trebuchet tosses a 10 gram mass approximately 30 ft with a dead weight of 500 grams. Some of the other trebuchets have recorded average tosses of 50 ft with masses of 0.5 Lbm when using a dead weight of 50 Lbm[4].

The term efficiency is lost on these sophomores until it is explained that the efficiency of their machines can be defined a number of useful ways in engineering practice. Certainly any definition of the trebuchet efficiency must be able to distinguish which trebuchets use the power-mass to the greatest advantage. For example, one such efficiency is the measured distance divided by the predicted distance. Another definition (perhaps a Coef. of Performance) might be the ratio two products: the first is the distance thrown and projectile mass and the second product is the dead mass multiplied by the height of the Trebuchet. The student's quickly realize that there is a need for both testing and modeling combined with a true engineering understanding of the principals involved with even the seemingly simplest (and oldest) of machines. The more efficient machine is actually the smaller machine. Now the real engineering technology challenge: Can a large machine be built with the same, high efficiency? The answer: Of course, but you'll need the next classes in your curriculum to help answer this question. This last statement is less of a fore warning as it is an encouragement to the students to look forward to the next classes in the curriculum with a renewed sense of purpose for these courses.

---

[4] In fact the last toss destroyed the dead weight bucket and thus ended the testing for the day and the semester

Some Assessment Results

The course evaluation for the Dynamics course was completed by the students and the results indicate that the students enjoyed the "hands-on" experience and considered it a major part of their dynamics course. More specifically the following point score ratings (on a max. five point scale) were given by the 23 sophomore students who evaluated the class (it is interested to note that 48% of these students have Grade Point Averages from 2.3 to 2.75 and 30 % between 2.76 and 3.25):

a. Usefulness of Outside Assignments: 4.4 out of 5
b. Overall rating of the Course: 4.0 out of 5.
c. Overall Rating of the Instructor's Effectiveness: 4.5 out of 5.

Conclusion

A suggestion has been made in this paper of a new way of teaching, learning and doing statics and dynamics that encompass more engineering technology and more of what the students believe engineering technology is: building something for a purpose and testing what has been built. The pedagogy outlined in this paper has been launched at Northeastern University with success. The success has been measured by the enthusiasm of the very busy students who spent considerable time building their catapults and then tested them, undaunted by the New England whether. In other words the students have enjoyed the experience and learned to apply what they were studying and they have been given a reason for the next classes they will study, having seen where this education is effectively used in engineering technology.

The next step is to fully implement the pedagogy with the Bill of Materials shown in Table 1 and gauge the acceptance of this "hands-on" solution to statics and dynamics problems with formal course evaluations.

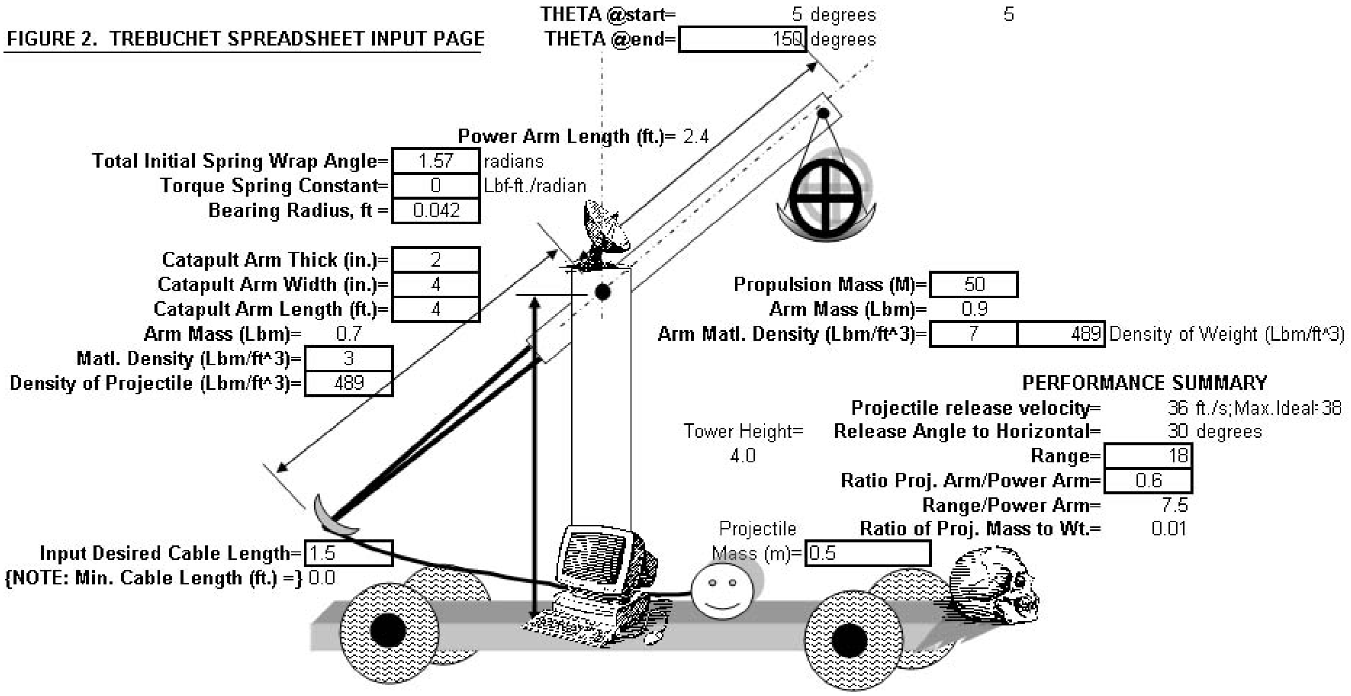


FIGURE 2. TREBUCHET SPREADSHEET INPUT PAGE

THETA @start= 5 degrees 5
THETA @end= 150 degrees

Power Arm Length (ft.)= 2.4
Total Initial Spring Wrap Angle= 1.57 radians
Torque Spring Constant= 0 Lbf-ft./radian
Bearing Radius, ft = 0.042

Catapult Arm Thick (in.)= 2
Catapult Arm Width (in.)= 4
Catapult Arm Length (ft.)= 4
Arm Mass (Lbm)= 0.7
Matl. Density (Lbm/ft^3)= 3
Density of Projectile (Lbm/ft^3)= 489

Propulsion Mass (M)= 50
Arm Mass (Lbm)= 0.9
Arm Matl. Density (Lbm/ft^3)= 7 489 Density of Weight (Lbm/ft^3)

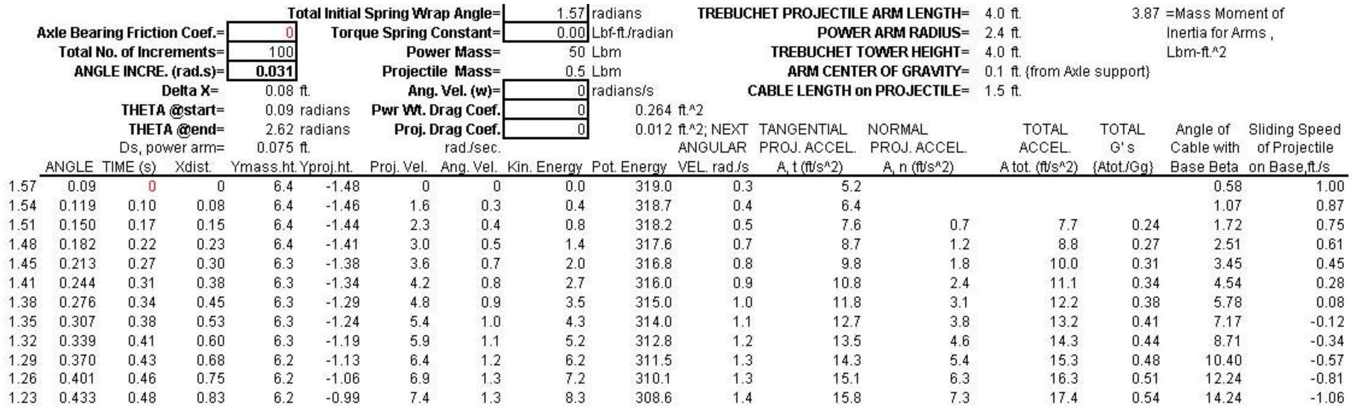
PERFORMANCE SUMMARY

Projectile release velocity= 36 ft./s; Max.Ideal= 38
Release Angle to Horizontal= 30 degrees
Range= 18
Ratio Proj. Arm/Power Arm= 0.6
Range/Power Arm= 7.5
Ratio of Proj. Mass to Wt.= 0.01

Tower Height= 4.0

Projectile Mass (m)= 0.5

Input Desired Cable Length= 1.5
{NOTE: Min. Cable Length (ft.) =} 0.0



Total Initial Spring Wrap Angle= 1.57 radians
Axle Bearing Friction Coef.= 0
Torque Spring Constant= 0.00 Lbf-ft./radian
Total No. of Increments= 100
Power Mass= 50 Lbm
ANGLE INCRE. (rad.s)= 0.031
Projectile Mass= 0.5 Lbm
Delta X= 0.08 ft.
Ang. Vel. (w)= 0 radians/s
THETA @start= 0.09 radians
Pwr Wt. Drag Coef. 0 0.264 ft.^2
THETA @end= 2.62 radians
Proj. Drag Coef. 0 0.012 ft.^2;
Ds, power arm= 0.075 ft.

TREBUCHET PROJECTILE ARM LENGTH= 4.0 ft.
POWER ARM RADIUS= 2.4 ft.
TREBUCHET TOWER HEIGHT= 4.0 ft.
ARM CENTER OF GRAVITY= 0.1 ft. {from Axle support}
CABLE LENGTH on PROJECTILE= 1.5 ft.
3.87 =Mass Moment of Inertia for Arms , Lbm-ft.^2

	ANGLE	TIME (s)	Xdist.	Ymass.ht.	Yproj.ht.	Proj. Vel.	rad./sec. Ang. Vel.	Kin. Energy	Pot. Energy	NEXT ANGULAR VEL. rad./s	TANGENTIAL PROJ. ACCEL. A, t (ft/s^2)	NORMAL PROJ. ACCEL. A, n (ft/s^2)	TOTAL ACCEL. A tot. (ft/s^2)	TOTAL G's {Atot./Gg}	Angle of Cable with Base Beta	Sliding Speed of Projectile on Base,ft./s
1.57	0.09	0	0	6.4	-1.48	0	0	0.0	319.0	0.3	5.2				0.58	1.00
1.54	0.119	0.10	0.08	6.4	-1.46	1.6	0.3	0.4	318.7	0.4	6.4				1.07	0.87
1.51	0.150	0.17	0.15	6.4	-1.44	2.3	0.4	0.8	318.2	0.5	7.6	0.7	7.7	0.24	1.72	0.75
1.48	0.182	0.22	0.23	6.4	-1.41	3.0	0.5	1.4	317.6	0.7	8.7	1.2	8.8	0.27	2.51	0.61
1.45	0.213	0.27	0.30	6.3	-1.38	3.6	0.7	2.0	316.8	0.8	9.8	1.8	10.0	0.31	3.45	0.45
1.41	0.244	0.31	0.38	6.3	-1.34	4.2	0.8	2.7	316.0	0.9	10.8	2.4	11.1	0.34	4.54	0.28
1.38	0.276	0.34	0.45	6.3	-1.29	4.8	0.9	3.5	315.0	1.0	11.8	3.1	12.2	0.38	5.78	0.08
1.35	0.307	0.38	0.53	6.3	-1.24	5.4	1.0	4.3	314.0	1.1	12.7	3.8	13.2	0.41	7.17	-0.12
1.32	0.339	0.41	0.60	6.3	-1.19	5.9	1.1	5.2	312.8	1.2	13.5	4.6	14.3	0.44	8.71	-0.34
1.29	0.370	0.43	0.68	6.2	-1.13	6.4	1.2	6.2	311.5	1.3	14.3	5.4	15.3	0.48	10.40	-0.57
1.26	0.401	0.46	0.75	6.2	-1.06	6.9	1.3	7.2	310.1	1.3	15.1	6.3	16.3	0.51	12.24	-0.81
1.23	0.433	0.48	0.83	6.2	-0.99	7.4	1.3	8.3	308.6	1.4	15.8	7.3	17.4	0.54	14.24	-1.06

Figure 3. Spreadsheet Rows and Columns for Modeling Trebuchet

Figure 4. The Man and the Machine…forever an efficient conversation-piece

Figure 5. The Trebuchets from Dynamics Class (Fall, 2003) …getting the job done