Session 1793

Power, Energy, and Work: A Study Module for First Year Students In Engineering Technology

John W. Blake
Austin Peay State University

Abstract

Any instructor preparing a course for first year students seeks to include material that is appropriate for students with a wide range of backgrounds and will be useful to them in the future. Also, one hopes that the material will build on their interests and encourage them to continue in the field. One subject that meets all of these criteria is the subject of work, energy, and power. This paper will explore the use of and describe the author's experience with using these topics in introductory classes.

Introduction

Many programs in both engineering technology and engineering find it worthwhile to require introductory courses for first year students. If one looks at textbooks available for these courses,[1, 2, 3, 4] one finds a mix of descriptive information on engineering and technology and material on engineering calculations and analysis. The math required for calculations must be at a level appropriate for incoming students.

The analytical material commonly starts with a review of math topics and a treatment of units of measure. The topic of measures and units is common to all areas of engineering and science; one also finds these topics in the introductory sections of texts covering a wide range of engineering subjects. For the introductory courses, the subjects of weight and mass and of radian measure are commonly included. Along with these topics, one may find more topics from math, introductory topics from engineering science, design, and student projects. Ideally, the topics covered build upon the earlier material and will be useful to majors in any area of engineering and technology.

A study of work, energy, and power fits well in this package. The topic meets the criteria of building on earlier material in the course and of being useful in different engineering disciplines. It is found in courses on mechanics and has practical application in design.

Calculations involving work, energy, and power can be treated at the basic algebra level. These calculations may (or may be written to) require unit conversions. If one starts with the weight as part of the given information in a problem, problems can require that students find the mass. Thus, this topic makes direct use of topics covered earlier in the course. The topic has another advantage; it relates directly to the design and operation of a wide range of machines and devices. This ability to relate course material to real devices and design problems makes this a subject that can excite the student's interest.

The current trend in both engineering technology and engineering education is to move away from the traditional lecture course format and to a modular course structure where students work in teams and directly apply the materials studied in group problems and projects throughout the course. To restructure a course taught by traditional methods, one looks to either restructure existing material into modular form or to replace current material with material that matches the new instructional format. The topics of work, energy, and power are amenable to this new format. Given their application in sizing and design, this is an ideal candidate for group design problems and projects.

Work, Energy, and Power as Topics for Introductory Classes

This subject is included as a component of the introductory course – ENGT 1000 Introduction to Engineering and Engineering Technology – required for majors in engineering technology at Austin Peay State University. The course serves both students pursuing our Bachelor of Science degree in Engineering Technology and students who will transfer later to an engineering school.

This component of the course is introduced following discussion of measures and systems of units. This preceding component includes the topics of weight and mass and of radian measure. Both of these topics are needed in the discussion of work, energy, and power. Also, torque is introduced through problems in unit conversion.

These topics are covered in physics courses and in basic courses in mechanics and other engineering subject areas. The topics are introduced here as an example of analytical tools as used in engineering that can be presented at the appropriate math level and that students can relate to their experiences outside of the classroom.

Work, energy, and power are presented first in conceptual form. Following this, concepts are translated into mathematical formulas. Starting with concepts should guard against producing students who are merely able to make calculations without understanding the physical significance of the results.

One can take this opportunity to look ahead to advanced topics in mathematics. For example, the formula for work at both the conceptual and the math level appropriate for the class has limitations. The simplest formula for work is

$$\text{Work} = \text{Force} \cdot \text{Distance}.$$

For this simple form to be valid, the force must 1) be constant and 2) must act in the direction of motion. Students attempting to use this may miss the restrictions and misapply this formula. The most general form gives the equation in integral form with the summation of external forces and position as vector quantities:

$$\text{Work} = \int \Sigma \underline{F}_{ext} \cdot d\underline{r}.$$

This level is well beyond the math background expected of students in introductory level classes. Starting the discussion with this form and then simplifying, however, does drive home the point that one must be careful to meet the criteria for the simplified form, i.e., the force component in the direction of motion. Even if they do not understand the math at this point, it breaks the image that this is as simple as the formula implies. Students must be reassured here that they are not expected to work at this level of math in the introductory course.

Showing this form also gives the instructor the opportunity to describe integrals, vectors, and the vector dot product in words. This gives students a preview of topics from higher math courses. Students should recall this when they see these topics in later courses and appreciate the need for this material. In addition, this discussion gives the opportunity to introduce the notion of using – and finding – the average force over the interval.

The concept of system energy follows well after the discussion of physical work. This is used as it relates to work; the work required can be determined from the change in system energy. While one could introduce a large number of energy terms, it is best here to work primarily with kinetic energy in translation and gravitational potential energy. As with the higher level math topics, one can look ahead to discussing other energy terms in future courses.

Finally, the concept of power is introduced as the rate of doing work or of change in the system energy. This line of development leads to formulae for power in mechanical systems. These fit a wide range of common machines familiar to the students. In the most basic form for mechanical problems, power can be written as either

$$\text{Power} = \text{Force} \cdot \text{Speed}$$

or

$$\text{Power} = \text{Torque} \cdot \text{Shaft Speed},$$

where shaft speed is in radians per second. A discussion of torque is necessary to introduce the second form.

Using the second form of the equation requires students to make unit conversions. Shaft speed is commonly measured and should be given in revolutions per minute (RPM). To use these basic equations, students must make the unit conversion from RPM to radians per second, building on what was covered in the preceding component of the course.

On completion, further work is necessary on the units. With SI units, the equation gives results in N·m/sec; students must then recognize that this is defined as a Watt. Often, this can give students experience with metric prefixes in conversion from Watts to kilowatts. With US customary units, the results are in ft·lb/sec. Here, students must make the conversion to horsepower. This gives further exposure to the nature of these units. The number of 550 ft·lb/sec for one horsepower was defined by James Watt based on observations of working draft horses.[5] As another example of engineering practice, it is worthwhile to discuss here why Watt needed this and how he arrived at this number. Watt wanted to sell steam engines as replacements for horses. To put power output in the language of his customers, he needed to relate the output of his engines to the work done by the draft horses currently in use. This number is a high estimate. Using a high estimate was useful to Watt, as he wanted to assure potential buyers that the engines would do at least as much, if not more, than advertised.

Once students have some experience with this, it is appropriate to introduce the common textbook or handbook equations for shaft power of the general form:

$P = T \cdot N / 9{,}550{,}000$ SI Units; results in Watts

$P = T \cdot N / 63{,}025$ US Customary Units; results in Horsepower

where torque (T) is in either N·mm or in·lb (lb·in) and shaft speed (N) is in RPM.[6]

In future applications of the material, students are likely to use these equations. Specific units must be used and unit conversions are included based on these units. Having built to this from the general conceptual form, one can clearly demonstrate why there is a constant and why the constant changes for different systems of units. This discussion should help students understand how the handbook formulas were developed, the link between the formulas and the basic principles, and to recognize the critical importance of using the units as specified in the handbook equation.

Torque must be included in a discussion of power and rotating machines. This brings up an interesting point regarding units; while the units of work and energy and of torque are dimensionally the same, these are very different pieces of information. This gives an opportunity to encourage students not only to check for consistent units but also to check that the number used is the correct piece of information for the application; the units alone may not tell you this.

If time permits, one can look at a system where energy and power are changed between mechanical, fluid, and electrical forms. In general, power may be expressed as a rate (or flow) term multiplied by a potential term.[7] Discussion of this general nature can be used to link discussion of electrical power, fluid power, and mechanical power.

This component of the course has important practical applications. These tools are used to determine power demand and to size the power source and the drive train for machines used in all fields of engineering.[8] For machines driven by electric motors, this information is necessary to size the motor and the electrical supply system necessary for the motor.

A good example of all three topics – and of their use – is to look at the problem of sizing the motor for a hoist. The work done can be determined from the change in system energy from the instant that the hoist starts to lift a load until the instant that the load is deposited at a higher level. The average power requirement can be then determined by dividing this number by the time allowed for the task.

This example can be used to introduce elements of engineering design. There is no single number set for the time allowed for the hoist to lift the object. The need for the designer to make a choice within agreed-upon limits of acceptable practice is common to engineering problems. One can point to design standards as a source of acceptable values based on collected wisdom and design experience. Even with guidelines, different designers may reach different decisions about acceptable performance. If one considers elevators as similar systems, the students are likely to have experienced differences in elevator speeds, and this can be pointed out as evidence of different design decisions.

The value found for the power requirement is an average power; this method does not give a number for the peak demand that occurs when the load is initially accelerated from rest. Here, one can introduce the common engineering practice of using applications or service factors to estimate peak demand for a given application from average demand based on relatively simple calculations.

A different and useful example of design decisions may be introduced here by following this example with a discussion of automobile drive trains. One can discuss a specific example of two cars that are identical in all aspects except the drive train. One is the economy version with the smaller power plant, and the other has the optional large engine. Both cars perform the same basic function, serving as a means to travel from point A to point B. Both drive trains can do the same physical work of bringing the vehicle up to legal speeds. However, the engine that produces more power can do so more quickly. The car with the smaller power plant does not do well in acceleration tests, but is more economical in operation. The different options reflect different needs, wants, and, in turn, design decisions. With these differences, both vehicles are successful designs and find buyers.

Current Use in Traditional Instruction

Currently, this topic is covered in one component of a three credit hour course – ENGT 1000 Introduction to Engineering and Engineering Technology – required of majors at Austin Peay State University. While the course has not been transformed from the traditional lecture format, the subjects covered in the course break down into informal modules. This topic serves as one of the informal modules or components, and follows a component on measures and units.

Components of an introductory course should help the students to understand technology and engineering, relate to other material covered in the course, and relate to the student's real world experiences. This course includes both descriptive and analytical material on engineering and technology. As part of the analytical content, this component demonstrates the link between concepts in words and in mathematical form, gives students a demonstration of how and why concepts of this type are applied in engineering and technology, and illustrates aspects of engineering calculations and design practice.

The material is currently presented in the traditional lecture format. Students are assigned homework individually and tested on this material as part of regular examinations. Three sample problems drawn from current homework and exam questions are given below.

Sample Problem No. 1: A mixer is to be driven at 300 RPM. If the torque required at 300 RPM is 5.6 Newton·meters, how much power is required in Watts and kW?

Sample Problem No. 2: The output shaft of an electric motor is turning at 1750 RPM. If the motor is producing 2.7 horsepower, what is the torque in foot·pounds?

Sample Problem No. 3: A hybrid vehicle is driven by an electric motor. At a steady speed of 50 km/hr, the drive motor is drawing an electric current of 15.6 Amperes.

a) Given that the electric system operates at a voltage of 300 Volts and that, for electrical devices, determine the power in watts and kW.
b) If the electric motor is turning at a speed of 673 RPM, determine the torque (in N·m) on the motor shaft.
c) Use the power to determine the force (in N) required for the car to move along the road at this speed (50 km/hr).

Sample problems 1 and 2 require students to make direct use of the relationship between power, torque, and shaft speed in a rotating machine. Both require students to take information in one form and to convert it into the specific form required in the calculation. Students must convert to radian measure of angular speed. They must pay attention to the required units and make the necessary unit conversions. As these topics are covered earlier in the course, these problems require students to make use of these concepts in solving practical problems.

In solving a problem of this type in practice, one would use a handbook formula that would include the unit conversions. While these problems are less realistic in that students must deal with shaft speed in radians per second, they do illustrate the nature of the handbook equations with their built-in unit conversions.

The third problem goes beyond the basic relationship for a rotating machine, and demonstrates the link between electrical and mechanical forms of power. The first part focuses on electrical power, and the electrical power input to the motor is linked to the shaft power output in part b). This is linked to the power required for the machine's function in part c). One can construct problems of this type that would include fluid power as well. One could also include energy storage devices, and could do more with electrical power topics.

Experience with the topic has shown it to fit well with earlier topics and with the course. It has proven to be one of the more challenging parts of the course's analytical content. Problems on this topic tend to be the "hard" problems on the exam. However, students have shown reasonable success in meeting this challenge. Since it can be clearly related to automobiles and other machines of interest, this topic can be very attractive to students. The broad range of applications for this topic should ensure that this component is useful to students later, both in the classroom and in their careers.

Plans for Future Developments

As the primary instructor for this course, my plans are to reduce the lecture aspect and to do more with team-based instruction and student projects. This topic is adaptable to changes in instructional format. Some formal explanation of the material will still be required, but one can redesign problems to be solved by groups of students. Also promising as group activities are simple and inexpensive experiments.

Demonstration and student experiments would be designed to help students visualize concepts and to see the connection between calculations and real devices and systems. This material is well adapted to physical demonstrations; these can be as simple as moving a table across the floor to demonstrate physical work. If one applies a force with both horizontal and downward vertical components to the table, students can see clearly that only the horizontal component of the force results in motion. This should reinforce the concept that work is done only by the component of force acting in the direction of motion.

Of more interest are experiments to be done by the students. These should not require expensive equipment. Some simple experiments can be set up using Hot Wheels cars and track. Track can be set up with similar slopes at each end. A car released from one end would travel down the track and climb up to a lower level on the other side, and the students would be able to mark that point. With this information, students could work backward to determine losses. A more sophisticated system could be set up with a track setup where the car goes along a level path after the initial run down the slope. With optical or magnetic sensors, one could determine the actual speed of the car and compare this to theoretical calculations based on conservation of energy. Again, one can use this information to determine losses.

In doing either of these simple experiments, students can use the analytical tools to predict results in a direct application. The results of the experiment will give them a clear indication of the difference between ideal models and real results. This should help them to recognize that calculations are idealized approximations to reality and that they must use judgment in relating calculation results to real physical systems.

As discussed earlier, a hoist can be used as a good example of work, energy, and power topics. An Erector set or other construction toy components can be used to build a simple hoist or elevator. A known load can be lifted, and the time required to lift can be measured. This actual test data can be used to calculate the average power output of the drive. With reasonable estimates of motor and drive train efficiency, one can use this to calculate the electrical power demand. If a power meter is available, one can compare this to the actual value. Distance of travel and time can be measured; students can use this information to determine average speed and average force. If a tachometer is available and can be connected to the shaft, one can use the calculated power and the measured shaft speed to determine output torque. If the motor has or can be set up with a visible gear drive train, speed reduction and torque multiplication concepts and calculations can be included as well.

This form of experiment should give students hands-on experience with the topics discussed in this component. Information from the tests can be used to characterize the drive and then be applied in the design of other simple machines.

Experiments such as these need to be added to the course. Currently, the course lacks a direct link between these concepts and an actual machine or systems. These experiments would add that link, and in turn would reinforce the link between the class material and other machines familiar to the students. These experiments would require students to become actively involved, and would be easily adaptable to student teams.

Conclusions

A component on the topics of work, energy, and power can be a useful addition to an introductory course in engineering technology or engineering. These topics fit well with other components commonly found in these courses, and can be used to demonstrate aspects of engineering design calculations and practice. Students can relate these topics to their experiences with machines outside of the classroom. This component can be adapted to modular and team-based instruction. Experiments done by students should be used to help students visualize the concepts and to understand their real world applications.

References

1. Pond, R.E., Introduction to Engineering Technology, 5th ed., Prentice-Hall, Upper Saddle River, NJ, 2002.
2. Eide, A.R., R.D. Jenison, L.H. Mashaw, and L.L. Northup, Engineering Fundamentals and Problem Solving, 4th ed., McGraw-Hill, NY, 2002.
3. Holtzapple, M.T., and W.D. Reece, Foundations of Engineering, 2nd ed., McGraw-Hill, NY, 2003.
4. Burghardt, M. D., Introduction to Engineering Design and Problem Solving, WCB/McGraw-Hill, NY, 1999.
5. Cardwell, Donald, The Norton History of Technology, New York, W.W. Norton & Co., 1995.
6. Spotts, M.E., Design of Machine Elements, 5th ed., Prentice-Hall, Englewood Cliffs, NJ, 1978.
7. Holmes, R., The Characteristics of Mechanical Engineering Systems, New York, Pergamon Press, 1977.
8. Anon, The Speed Reducer Book, Winsmith Industries, Springville, NY, 1980.

Biographical Information

JOHN W. BLAKE is Associate Professor and Chair of the Department of Engineering Technology at Austin Peay State University, Clarksville, TN. He received his B.S., M.S., and Ph.D. in Mechanical Engineering from Northwestern University, and is a registered Professional Engineer in the State of Tennessee. He has taught first year introductory courses for engineering technology students at Austin Peay and for engineering students at Vanderbilt University.