A Multipurpose Windmill Design Project

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ABSTRACT

There is growing recognition of the value of having engineering design projects in the freshman curriculum[1]. The Windmill Project described here not only provides a design challenge, but incorporates elements of team-building, laboratory data collection, engineering design calculations and optimized testing procedures. If desired, the project can be expanded to include significant research and writing on the history of windmills or on ecological issues.

A key element of this project is a windmill test stand that enables simultaneous measurement of torque and speed. This test stand can be built from readily-available materials, at reasonable cost, with simple tools. It can be collapsed quickly into a small bundle convenient to transport or store.

With different levels of expectation, this project can be appropriate for class levels from high school to at least the sophomore year of engineering.

BACKGROUND

It has become widely recognized in both Engineering and Engineering Technology that the old approach of developing basic skills in math and physics before beginning any design courses can turn off some students and scare away others. For example, the University of Florida experienced a dramatic increase in retention associated with a lab-based rather than a lecture-based Introduction to Engineering[2]. It is important to introduce students to the challenge and excitement of engineering design early in the college experience for many reasons, some of which are:

(1) It shows the relevance and importance of having a good command of basic math and physics. (ET students in particular tend to be impatient with theory and abstract reasoning if they cannot see practical applications.)

(2) It provides a taste of real engineering design. (Those who like it get more excited about their curriculum choice; those who don't like it may choose a different major sooner.)

(3) It helps develop teamwork skills. (These design projects usually are intended for teams of two or more.)

(4) It helps develop manual technical skills. (Today it seems that entering engineering and technology students are more likely to be familiar with computers than with wrenches, saws, soldering irons and measuring instruments.)

Some projects intended or touted as design projects turn out to involve a great deal of creativity but little or no design. The venerable "egg drop" is one example. Students may have a great time inventing ways to package an egg so that it will survive a drop from the top of the school building, yet be completely incapable of estimating G forces during deceleration, or even the velocity at impact. Neither is required to produce a winning design.

In a good design project, success will depend partly on creativity, but also to a significant extent on data collection, analysis and tradeoffs.

The windmill design project described here is one of the educational modules developed as part of NSF-ATE Project No. DUE-9454547, a grant titled "A Partnership for Excellence in Engineering Technology Education". It has been used three times in an Engineering Design and Graphics course at Penn State's York Campus. This course traditionally has been used only for Engineering students, but a study performed under the NSF ECSEL Project has concluded that there are no significant problems with mixing Engineering Technology students into these classes.

THE PROJECT

The version presented here is both rearranged and severely abbreviated from the fully-documented version. The full version provides a set of handouts for the students to follow and separate background information for the instructor explaining why the project is designed the way it is, how to make the test stand, what difficulties may arise, etc. Here that separation between student and instructor sections is ignored.

Equipment needed:
- Wind source (100W fan will suffice; larger is better)
- Windmill test stand (chuck to hold windmills, torque-loading system, speed-measuring system)
- Adjustable windmill (1-6 blades, variable angle & radius)
- Windmill materials (hubs, shafts, blade materials, etc.)
- Tools (Scissors, pliers, glue, etc.)

Introduction to the project:
- Establish teams.
- Discuss power as the goal of the design.
- Discuss parameters that affect windmill performance.
- Provide a handout detailing the project, including reporting requirements.

Introduction to the hardware:
- Show students the windmill test stand and adjustable windmill.
- Demonstrate how the windmill is adjusted and mounted in the test stand.
- Demonstrate how a torque loading is set.
- Give each team an opportunity to make speed and torque measurements.

Objective 1 – Plot speed vs. blade angle:

The first lab assignment (outside of class, unless test equipment is available to all teams simultaneously) is to measure and plot windmill speed as a function of blade angle, through a

180 degree variation of angle. Fixed parameters include blade radius and fan/windmill positioning. The resulting plot must have enough data points to allow for smooth, accurate interpolation.

Objective 2 – Plot torque vs. speed:

The second lab assignment is to measure and plot the relationship between speed and torque loading, from no load to stall, for one fixed blade angle. Enough data must be collected for smooth, accurate interpolation.

Objective 3 -- Design of the most powerful windmill:

Using data collected for the first two Objectives (plus any extra data from non-required tests), students must design and build the most powerful windmill possible, within the given limits. (A fan source limits effective windmill size; limited materials and/or tools avoid unfair advantage for those with access to better resources.) Student teams also must predict their maximum power.

Testing of windmill designs

In-class testing is done cyclically among the teams, allowing one trial at a time per team. Each trial consists of these steps: mount the windmill; set the torque loading; turn on the fan and record the maximum speed; calculate the power.

For each successive test, a team may modify the windmill (if possible) and select a different torque loading.

(In one class where this testing was done, student teams earned points in four categories: highest power prediction; highest power achieved in any trial; ratio between predicted and achieved power nearest unity on the first trial; and ratio nearest unity on the last trial.)

RATIONALE AND FEATURES

Algebra and physics

This project is based on simple but nontrivial physical principles. It can be used with great success at course levels ranging from introductory algebra to college engineering design. As long as units are consistent, students can multiply any measure proportional to speed by any measure proportional to torque and get a consistent measure of power. On the other hand, students can be asked to measure everything in real units, performing appropriate conversions, and be virtually compelled to understand the definitions of mass, force, torque and power.

Lab technique, design of experiments

Unlike many labs in which all the necessary procedures are laid out step-by-step, here the teams are allowed to devise their own techniques for setting blade angle, to take measurements in any sequence they desire, and to decide as they see the data just how many measurements they should take and where data points should be added. The desired end results (smooth and accurate plots) drive the procedures. The open-endedness of the labs allows sloppy teams to fail to recognize a very significant anomaly: windmill speed is not a symmetrical function of blade angle! (Because an ordinary fan produces a swirling flow, a windmill will rotate much faster with the fan than counter-rotating.) On the other hand, having the freedom to design their tests leads some teams to waste time measuring unnecessarily close data points.

Teams are not asked to measure the effect of additional windmill arms, changing the effective radius or varying the shape or size of the blades; nevertheless, such parameters could have a significant effect on performance, and could be measured easily with the modular, adjustable windmill. Additional effort is quickly repaid with additional knowledge about windmill design.

Data analysis

Because both zero load and excessive (stalling) load produce zero power, maximum windmill power always is achieved with some optimal intermediate load. Because the test procedure allows only a limited number of tries, it is important for teams to know ahead of time their expected performance and how it should change with changes in load or other adjustable parameters (if any). Teams that have not properly analyzed the data they collected will be "flying blind" when trying to improve their initial performance.

Ideally, the test equipment should be unavailable for the week before the in-class testing, to minimize trial-and-error design and maximize analytical design based on experiments with the standard adjustable windmill.

THE TEST STAND

The windmill test stand is an upright rectangular frame of 1x2 pine boards joined by simple bolts and wing nuts for easy disassembly, with a bottom crosspiece and diagonal bracing strings to hold it upright. Mounted on that frame are the windmill chuck, speed instrumentation and torque instrumentation.

Windmill chuck

A cheap drill chuck is threaded onto a long bolt for an axle. The axle passes through two ball bearings which are clamped to a small supporting board, and the board is screwed to the frame with the axis horizontal. This makes the test stand adaptable to any windmill mounted on a horizontal axle, up to the capacity of the chuck.

Speed instrumentation

A bicycle "computer" provides very convenient instrumentation for measuring rotational speed. A magnet intended for a bicycle wheel can be taped to the chuck, and the sensor mounted on the frame near where the magnet passes. With a little calculation, an artificial wheel diameter can be entered into the bicycle computer so that its km/hr or mph reading provides RPM or some other convenient speed reading directly. (In one class the student teams were asked to calculate that wheel diameter.)

As a lower-cost alternative, a low-friction pulley can be mounted on the frame, and a rubber band can be run around that pulley and the shaft of the chuck. The windmill and chuck may be spinning too fast to count revolutions, but a dark mark on the rubber band will pass by only once every ten or twenty revolutions of the chuck. (This must be calibrated; it is the ratio of shaft circumference to the mounted length of the rubber band.)

Torque instrumentation

The torque measurement technique developed for this project is simple but accurate. A parallelogram is constructed of two center-pivoted horizontal beams and two vertical strings connecting the ends of the beams. One of the strings is wrapped once around the shaft of the chuck so that rotation of the windmill tends to pull the string down. A weight attached to or vertically aligned with the opposite string balances that force. The pivot of the upper beam is attached to a fixed support, and the pivot of the lower beam is attached to a variable load. (In practice, usually a hand pulling down on a short bungee cord.)

If the variable force pulling down on the lower beam is too light, there will be little friction on the shaft and the opposing weight will prevail. If the variable force is too strong, the string will wrap tightly about the shaft and lift up the weight. When that variable force is just right, the weight and the frictional force will be in balance and the beams can be kept horizontal. Under that condition, the tangential frictional force on the shaft will equal the force of whatever weight is placed on the other end of the beams, and torque on the shaft can be calculated from that weight and the known
diameter of the shaft.

This technique requires no measurement of the force on the central pivot, no calibration, and the actual coefficient of friction between the string and the shaft is immaterial. (In fact, if the force required on the bungee cord to balance the beams is uncomfortably large, the string can be wrapped around the shaft two or more times, without changing the procedure or calculations at all.)

THE ADJUSTABLE WINDMILL

A modular, adjustable windmill is made from an axle, a hub, arms and blades. The hub has an axial hole and six equally-spaced threaded radial holes. The axle is a bolt or short section of threaded rod. The arms are sections of threaded rod as long as desired, with nuts to lock them into the hub and to lock the blades to the arms. Each blade is simply two squares of mat board or heavy cardboard, taped at opposite edges and sprung apart slightly to slip it over the arm. Washers spread the load where nuts on the arm hold the blades in position. (Lighter metal, folded over the blade edges, probably would be even better.)

The windmill described here can have any number of blades from one to six (with appropriate counterbalancing, in the case of one or five). The blade radius can be adjusted from snug against the hub to the maximum length of the arms. Blade angle can be adjusted very easily. (In fact, lock nuts or some tape may be necessary to prevent movement during use.) In addition, the standard square blades can be replaced by blades of virtually any size or shape.

APPLICATIONS

This project has been used in a freshman design course for engineers, but has been designed for much broader application. The full document (available from the authors) suggests applications ranging down at least to junior high school.

For younger students, it can be productive to begin with the creative activity of building windmills from simple materials such as paper or plastic plates, bowls, cups and spoons, with tape and glue. Testing those windmills (for unloaded speed) begins to reveal some of the principles of windmill design. (One young student designed for strength, with two flat strips of plastic passing at an angle completely through a hub. When neither his first attempt nor his second, with one strip tilted the opposite way, would turn, he realized that a twist was needed in each blade.)

Expansion into other aspects of the curriculum is possible with assignments relating to literature, history, ecology, power generation and even web-searching. The hands-on aspect appeals to all ages, and the links to power generation and ecology provide relevance.

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