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USE OF FDM IN AN UNDERGRADUATE STUDENT PROJECT: DESIGN, BUILD AND TEST A MODEL WIND TURBINE

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Abstract: *Most undergraduate practicals at Lancaster University, UK, take the form of short projects. These give students the opportunity to make design decisions, to observe directly the consequences of these decisions, and to compare the performance of the item with the original design specification. Students are motivated more strongly by these projects than they are by standard labs where they only have to take measurements. Using ALM techniques provides an opportunity to extend the scope of these projects. This paper describes one such project: to design, build and test a model wind turbine. Use of fused-deposition modelling (FDM) has much improved the accuracy and performance of the turbine blades that students can produce, and has increased the educational value of the project.*
Key words: *engineering education, FDM, aerofoil*

1. INTRODUCTION

Almost all undergraduate engineering and science courses require students to do practical work. The aims of this may be to introduce techniques, instruments and equipment; to illustrate points from lectures; to give students the experience of working in teams or groups; or other aims; (Hale, 1964); (Beard & Hartley, 1984).

Academic staff sometimes provide fairly detailed instructions, which set out what the experiment is about, what measurements should be taken, the content of the report, and when it should be completed and handed in. This prescriptive approach fails to develop the important skills of planning the work and making decisions about what should be done. It ensures the important technical content is covered, but it is not very stimulating or motivating for the students.

An alternative way of arranging practical work is through design-build-test projects. This way of setting lab work has been used in all undergraduate years in the Engineering Department at Lancaster University since its foundation in 1968 (French, 1972). Recently, it has become popular in university engineering education internationally (Crawley et al, 2007).

This paper describes one of the projects undertaken by first-year students at Lancaster: to design, build and test a scale-model horizontal-axis wind turbine.

2. MODEL WIND TURBINE PROJECT

Working in pairs, first-year Engineering students at Lancaster University are set the task of designing, building, and testing a model wind-turbine rotor, as the practical part of a module entitled Energy Technology and Sustainability. The aim is to achieve high performance, as measured by the power coefficient of the model machine. A measure of the turbine's effectiveness, the power coefficient is the ratio of the power captured to the power available in the wind that would pass through an area equal to that traced by the turbine rotor.

The blades of modern high-efficiency wind turbines are aerofoil sections. Due to the rotation of the turbine, the speed of motion of the blade at radius R is $R\omega$, where ω is the angular velocity. The wind speed is U, in the axial direction. The velocity triangle for the blade at this radius (Figure 1) shows that the direction φ of the velocity of the air relative to the blade depends on the ratio of U to $R\omega$; thus it varies with the radius R. To maintain a constant angle φ of incidence of the air on the blade along its whole length, the blade must therefore be twisted.

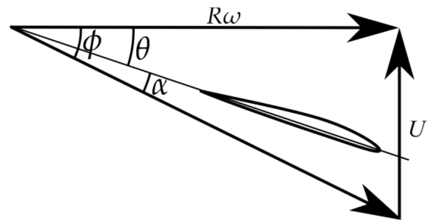

Fig. 1. Velocity triangle for a blade at radius R

Until recently, students made up their turbine blades from sheet pvc, heating them for twisting in a special jig which allowed students to set up their own chosen twist angles. Inevitably, this technique was imprecise. The Engineering Department has now set up an ALM facility, and this has greatly extended the opportunities available for interesting student projects. In particular, we can make up much more accurate model wind-turbine blades for this project.

2.1 Wind turbine design decisions

The first decision that students make in their blade design is the tip-speed ratio λ of the rotor; this is the ratio of the speed of the blade tip as it rotates to the speed of the wind. Closely related to this is the decision on the number of blades in the turbine rotor.

Most modern wind turbines in Europe have three blades, and in this case the optimum tip speed ratio is in the range 6 to 7. In North America two-blade rotors are quite common; the optimum λ value is then as much as 9.

For work at model scale, two-blade rotors use less material and so are cheaper to make. They are also easier to balance. Most students choose a two-blade rotor for these reasons - although some make three-blade rotors, and some ambitious students make one-blade rotors with a counterbalance mass.

The second important design decision is the choice of the aerofoil shape. The students can use any aerofoil profile, provided they document the selection in their report. However, they are advised to base their aerofoils on the NACA4 standard, developed by the US National Advisory Committee for Aeronautics (Jacobs et al, 1933). Data on the shapes of these aerofoils is made available in electronic form. Students are able to choose values for parameters such as the chord length, the blade thickness, and the camber (i.e. the curvature of the centre-line of the blade). They can then use the free on-line simulator *Javafoil* (Hepperle, 2008) to investigate the performance of the aerofoil.

For each aerofoil profile, the lift force increases with the angle of incidence, but only up to a point: beyond this, the lift force suddenly drops, as the air flow stalls, separating from the upper surface of the wing shape. Some advanced aerofoil shapes allow quite large incidence angles before the onset of stall - but the loss of lift when stall occurs can be very sudden, so these aerofoil shapes are less forgiving than the simpler shapes.

By being involved in these decisions, students learn that compromise is inevitable in engineering design.

2.2 Generating the geometry file

Once they have made the design decisions for their wind-turbine rotor, students can create the geometry file using a solid-modelling package. At Lancaster, we use SolidWorks, but other packages could be used equally well.

The blades need to be attached to the hub by some means. In 2009, each blade was attached to a radial steel rod, and the rods were held in holes in the cylindrical brass hub by grub screws. This was not wholly satisfactory, because it was difficult to set and maintain the blade angle accurately.

For 2010, a wholly-RP method of location was introduced. A cylindrical feature was added to the inner end of each blade, and this fitted into a round recess machined into the hub (Figure 2), which this year was made of pvc. As these parts are a good fit, no screws or other fixing was needed.

One question was how to achieve the thin trailing edge needed on the aerofoils. At first we tried to do this directly on the ALM machine, but inevitably ended up with a very weak and raggy edge. To overcome this, the students were asked to thicken the trailing edge in SolidWorks before manufacture; they then have to remove the added thickness later, by a combination of filing and sandpapering.

2.3 Manufacturing considerations

The FDM machine can produce very accurate shapes in the horizontal layers, but in the vertical direction the body is discretised into layers of finite thickness (0.254 mm in this case), and ridges appear between the layers. If a blade is built up in the horizontal position, if will have ridges running along the length of the blade, perpendicular to the air flow, which is likely to compromise the performance of the aerofoil (Stamper & Dekker, 2000). If the blade is built in the vertical position, the ridges will be parallel to the direction of air flow, which should be more acceptable.

A blade built in the horizontal position requires more support structure, and so consumes more material than one built vertically.

On the other hand, a horizontally-built blade will have greater strength in the directions subject to largest stresses.

The cost of the material is significant. As an incentive to students to be economical, the marking scheme for this project includes a sliding scale for marks to be added (or subtracted) if the blades are particularly light (or heavy).

2.4 Finishing and balancing

As they come from the ALM machine, the blades are rough and so unlikely to perform well in the wind tunnel. It is possible to smooth them using sandpaper or wet-and-dry paper, but pits in the surface will remain. The students were therefore recommended to fill the surface with a two-part car-body filler, before sanding it to a smooth finish. Care is needed with this, so that the geometry of the aerofoil is preserved.

Under test in the wind tunnel, the rotors can rotate at up to 5000 rev/min, or more if the students are not cautious. The rotors produced by ALM are much better balanced than the earlier ones produced by hand work, but it is still important to check the balance and correct it if necessary.

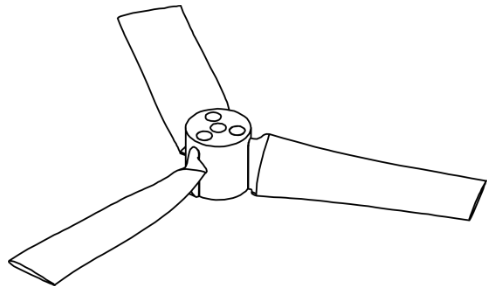

Fig. 2. A finished model wind-turbine rotor made in 2010

Static balance, using a dummy shaft and knife edges, is sufficient because all the rotating mass lies very close to a single plane. Usually, all that is needed is to remove a little material from the tip of the blade on the heavy side.

3. TESTING

For testing, the model rotor is mounted on a dynamometer in a small wind tunnel. Torque is applied by a simple Prony (friction) brake. The rotor speed is measured using a non-contact instrument such as an optical tachometer or a Hall effect sensor.

The students are advised to plot dimensionless performance curves, of the power coefficient against the tip-speed ratio. For a given rotor, these curves should be approximately the same, regardless of the air speed.

They can then use these results to predict the performance of a full-size wind turbine with a geometrically-similar rotor.

4. CONCLUSION

The introduction of ALM techniques into this model wind-turbine project has allowed students to make up more accurate models. They can select an aerofoil shape and choose values for the chord, the blade thickness, the camber etc, with confidence that these values will be realised quite closely in their model blades. Testing their model turbine rotors in the wind tunnel gives them the opportunity to compare their experimental results with predictions. The students also gain experience of a very useful ALM technique.

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