A BASIC DESIGN-BUILD-TEST EXPERIENCE: MODEL WIND TURBINE USING ADDITIVE MANUFACTURE

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ABSTRACT

This paper describes a project undertaken by most first-year Engineering undergraduates at Lancaster University in which they are set the task to design, build and test a scale-model wind turbine.

Working in pairs, the students are able to make design decisions on the blade geometry and the number of blades on the turbine. Utilising fused-deposition modelling (FDM) additive-manufacturing (AM) technology, students are able to produce their turbine blades by additive manufacture, which has provided an opportunity to greatly improve the accuracy and finish of the model aerofoils that students can produce, as well as ensuring geometric repeatability of blades on the same hub. It also allows students the capability to produce concave surfaces on the underside of their blades, which was almost impossible when producing the blades by hand methods.

The performance of the model turbines fabricated using the AM technique has been noticeably better than that of models produced by hand, the previous method. Introducing the AM method has also given an extra educational dimension to this design-build-test project.

In this project, students learn about aerofoils and simple aerodynamics and mechanics. The project introduces them to testing and measurement methods, as well as to the advantages and limitations of the particular AM technology used. For testing, the model turbine is mounted in a wind tunnel on a simple dynamometer, allowing different levels of torque to be applied and the speed of rotation to be measured, for a variety of air speeds. Students are encouraged to plot dimensionless performance curves of power coefficient against blade-tip-speed ratio. Using these figures, they can then predict the performance of a full-size rotor with similar geometry.

KEYWORDS

Aerofoil, airfoil, additive manufacture, wind turbine.

INTRODUCTION

Design-build-test projects have formed an important part of the curriculum in all years of undergraduate programmes in the Engineering Department at Lancaster University ever since the foundation of the department in the late 1960s [1]. All of these programmes are grounded in engineering science, but the philosophy from the outset has been that graduates should be practised in applying this science fruitfully to real engineering problems. Inevitably, such real problems are never fully defined, and do not have unique ‘right’ solutions: the students have to learn to make engineering decisions on the basis of incomplete information. They also need to realise that costs and the need to conserve resources are important considerations in any engineering project. Accordingly, many of the design-build-test projects include economic considerations of some aspects.

A project undertaken by most students in first year is to work in small teams to design, build and test a model wind turbine. The maximum diameter is 200 mm, so that the turbines can readily be tested in a small wind tunnel; but within this constraint there is much scope for students to make choices. Being mostly fresh out of school, the students generally find making decisions on the basis of incomplete information quite uncomfortable. However, the need to do this occurs often in real engineering situations (and indeed in life), so the ability and confidence to make such decisions is an important and useful skill.

This philosophy is very much in line with the CDIO approach, as set out for example by Crawley *et al* [2] and Hugo & Goodhew [3]. However, this project, being at first-year undergraduate level, is relatively constrained: the diameter of the model turbine is restricted and the test set-up is fixed, so the freedom to conceive different turbine designs is somewhat limited. What is more, there has never been any intention to operate the turbine outside the laboratory, although students are encouraged to use the test results from the model as the basis for a prediction of the performance of a full-size turbine of similar geometrical design.

REVIEW OF PREVIOUS WORK

Making aerofoils by additive manufacture

There is a growing body of literature reporting the manufacture of lightly-loaded aerofoils by AM methods.

In the USA Stamper and Dekker fabricated a wing from ABS (Acylonitrile Butadiene Styrene) material in order to compare it with an aluminium one of the same cross-section [4]. Because the ABS wing was built up in layers, it was rough compared to the aluminium one and its performance was not as good. However, once its surface had been smoothed, the lift and drag curves were found to approach those for the aluminium wing.

In Germany, AM methods have been used to fabricate aerofoils with embedded sensors, to form aerodynamic components of racing cars [5]. In this case, AM was used because it readily allowed the aerofoil profile to be altered to incorporate the sensors - but it is clear that the aerofoil functioned well even though it was made by a layer-lamination method, and as such its surface will have been relatively rough.

At Lancaster University, a model of a vertical-axis tidal power device has been manufactured, based on a multi-element aerofoil profile [6]. In this case the multi-element profile was optimised using CFD, taking into account the very different Reynolds number value for tidal devices from the more familiar NACA aerospace geometries. The profiles were fabricated using the stereolithography AM technology, with pressure tappings designed into the profiles and incorporated at the outset. The final multi-element device was tested in a water flume in the Engineering Department's laboratory.

CDIO projects based around aerofoils

At a number of universities and colleges, aerofoils have played a significant role in CDIO design-build-test projects.

In the Department of Aeronautics and Astronautics at MIT, groups of students worked to design and build at full scale the aerofoil rear wing of a racing car with its supports, using a CNC foam cutter [7]. The resulting wing was then tested in the wind tunnel to measure the lift and drag forces. This work was aimed to support the learning objectives of the CDIO initiative, as well as using up-to-date technology including AM. Student feedback was firmly positive.

At Newcastle University, UK, second-year students taking Engineering Design undertake team projects to design and build a wind turbine from a fairly free choice of components [8]. Learning is open-ended. Lectures are given by staff in an impromptu manner in response to students' requests. High levels of student satisfaction are reported.

In Portugal, at Instituto Superior de Engenharia do Porto, first-year engineering students work in teams on a CDIO project to build a vertical-axis wind turbine, mainly from parts 'from the junkyard' and also by adapting suitable rotating electrical machines [9]. Surveyed after this experience, the students felt that projects of this kind were important 'for better learning outcomes and collaborative multidisciplinary issues'.

The student project at Lancaster University has evolved from one where the blades were made completely by hand. In the first stage of evolution, the blades were fabricated by AM and mounted on radial rods retained in a brass hub [10]. This had the drawback that the blade angle could easily be set up incorrectly. In the present arrangement, the blades are built with their end fittings incorporated, so that the blade angle is fixed.

DESIGNING AND BUILDING THE MODEL WIND TURBINE

For the design and implementation of their model wind turbine, students at Lancaster University work in groups of two or three. The time allocated for the exercise totals 15 hours, consisting of five three-hour practical sessions over a period of five weeks, together with a small number of associated lectures. In this fairly concentrated period a number of useful learning outcomes are achieved.

Power available in a moving fluid - Betz limit

The final part of the practical work undertaken by the students, once they have completed the manufacture and assembly of their model wind turbine, is to assess its performance by testing in the wind tunnel, and to compare the power captured with the theoretical maximum. The students therefore need to be able to estimate how much power is available in the wind that passes through an area A perpendicular to the wind direction.

This entails calculating the kinetic energy in the air passing through the area A per unit time, and then appreciating that it is impossible to capture all of this energy, otherwise the air would be stationary behind the turbine. Clearly the air must move away to make way for air following on behind.

The energy E that would pass through area A in a free stream is thus

$$E = \tfrac{1}{2}\rho A u^3 \qquad \text{(Eq 1)}$$

where ρ is the density of the air, and u is the air speed. The German engineer Betz showed in 1919 that the maximum proportion of this energy that can be captured is 59% - see for example ref [11].

Tip-speed ratio

The first design decision that students need to 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. At a lower ratio than this, too much air passes between the blades without contributing its energy to the power capture; at a higher ratio, the wake from one blade interferes too much with the flow around the next one. In North America, two-blade rotors are common; the optimum value of λ 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 to make a two-blade rotor for these reasons, although some make three-blade rotors, and those who like to challenge convention manufacture one-blade rotors with a counterbalance mass. In commercial practice, there may be good reasons to choose any one of these: a low-speed rotor when high torque is needed, e.g. to drive a reciprocating piston pump directly; a three-blade medium-speed rotor because they avoid most of the problems of periodically-varying loads and are pleasing aesthetically; or a two- or one-blade high-speed rotor to minimise the cost of the blades and step-up gearbox that is needed to drive the generator.

Angle of attack, relative velocities, and the need to twist the turbine blades

The blades of horizontal-axis wind turbines have aerofoil profile. The students can use any aerofoil shape, 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 [12]. Here the students can choose values 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 a simulator to check the performance of their chosen aerofoil, and alter the values in pursuit of improved performance if they wish.

For each aerofoil profile, the lift force increases with the angle of attack up to a certain point. Beyond this, the lift suddenly drops as the 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 quite sudden, so these advanced shapes are less forgiving than the simpler shapes.

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

Due to 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 w 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 of incidence φ of the air on the blade along its whole length, the blade must therefore be twisted.

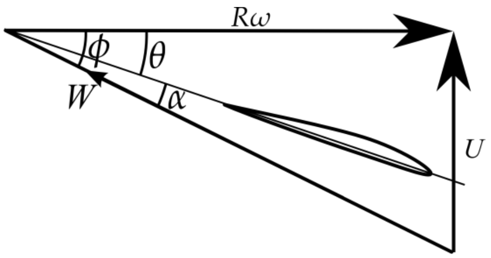

Figure 1: Velocity triangle at radius R

Manufacturing considerations

The FDM technology can produce accurate shapes in the two-dimensional horizontal layers (slices), but in the vertical direction the part produced is discretised into layers of finite thickness, and ridges appear at the edges of the layers (known as stair-stepping). If a blade is built laid horizontally, it will have ridges running along the length of the blade, perpendicular to the air flow, and this is likely to compromise the performance of the aerofoil [4]. If the blade is built standing vertically, the ridges will be parallel to the air flow, which should be more acceptable. Furthermore, a blade built in the vertical orientation requires less support structure (required to support overhanging structures or geometric features) than one built horizontally. However, the horizontally-built blade will have greater strength in the longitudinal direction, which is the direction of the bending stresses. Figure 2 shows blades as they come from the FDM machine, with the support structure still in place.

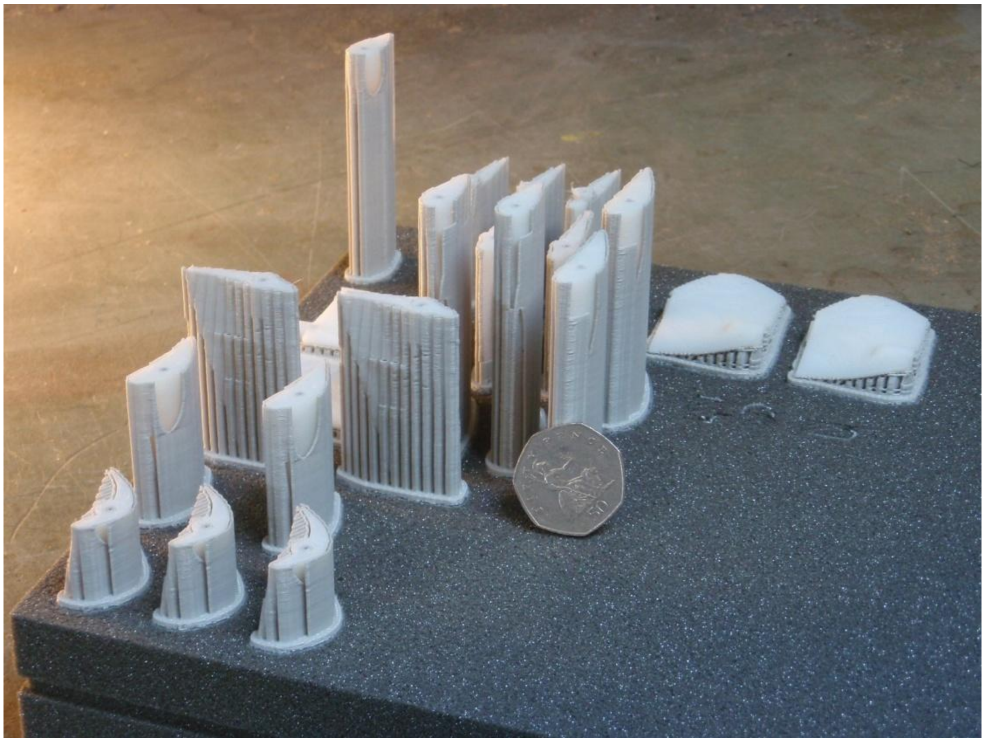

Figure 2. A bank of just-built model turbine blades on their platen, with the support structure still in place

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

The correct aerofoil shape has a thin trailing edge, tapering away theoretically to nothing. However, the FDM AM process has some difficulty in reproducing such fine features as this, a drawback of the extrusion/deposition process - it yields only a weak raggy edge. To overcome this, students are asked to thicken the trailing edge in the CAD model before committing to manufacture; they then have to remove this additional material thickness later in post-processing operations, including a combination of filing and abrasive finishing using sandpapering.

Finishing and balancing

To achieve a smooth surface on the blades and hence low drag, the students are recommended to fill the surface with a two-part car-body filler, before sanding it to a smooth finish. The students have to take care not to sand too vigorously, in order to preserve the geometry of the aerofoil.

Before testing the rotor in the wind tunnel, it must be static balanced, using a dummy shaft and knife-edges. For the purposes of manufacturing the geometries required in this project, the AM process is generally accurately repeatable, so usually the rotors are very nearly in balance, and all that is required is to remove a little material from the tip of the blade on the heavy side.

A finished rotor is shown in Figure 3.

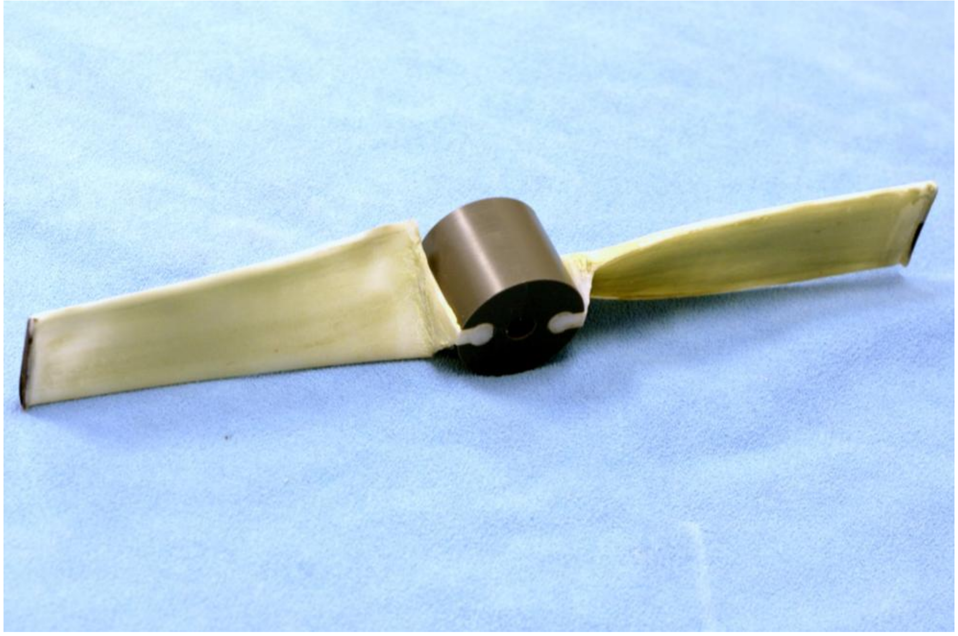

Figure 3. A finished model wind turbine ready for testing

Testing and reporting

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. The power coefficient is the ratio of the power produced by the turbine to the power available in the wind (Eq 1). For a given rotor, these curves should be approximately the same, regardless of the air speed. The students can use these results to predict the performance of a full-size wind turbine with a geometrically-similar rotor.

Each student presents an individual report, containing a record of the experimental measurements and calculations, the performance curves, calculation of the size of rotor needed to generate 1 kW in steady wind of standard speed.

CONCLUSIONS: Learning outcomes relevant to CDIO syllabus

From this design-build-test experience on a model wind turbine, a range of learning outcomes are achieved.

- Students learn about the behaviour of fluid passing around an aerofoil, including the generation of lift and drag. Because the wind turbine rotor is itself rotating, the students learn about relative velocities, how the angle of the relative velocity varies with the radius, and that the blade has to be twisted to maintain constant angle of attack and hence good lift performance all along the blade. In designing their model turbine, they use their early understanding of fluid flow, including the boundary layer and its attachment to or detachment from the surface of the aerofoil shape, and the relationship between the force on the foil and the change of momentum of the air flowing around it. These are important ideas in mechanics, and are part of core engineering knowledge for all engineers [CDIO syllabus 1.2]
- The students are able to choose the number of blades on the rotor in order to give high-torque or high-speed turbine performance, and they have the opportunity to experience this in practice when they test their own rotor.
- As the blades are fabricated using an AM technique, students are able to achieve quite accurate aerofoil profiles and profile angles along the blade. However, for best performance they need to address any surface imperfections generated as a result of the AM process, typically through manual finishing methods.
- When testing the rotor, the students learn about the use of the wind tunnel, including the instrumentation. The testing of the turbine, using a simple dynamometer and a wind tunnel, involves a number of simple instruments. Students need to make allowance for common problems such as friction in the dynamometer bearings, and for experimental errors in determining the air speed in the tunnel from readings on an inclined manometer. All of this introduces engineering reasoning through experimentation [CDIO syllabus 2.1 and 2.2]
- Students work in teams of two or three, and because there is some time pressure they quickly find that they need to divide tasks between them in an efficient and effective way so that the overall aim can be achieved in the time available [CDIO syllabus 3.1]
- In this exercise, students learn of the advantages of presenting their measured results in terms of dimensionless ratios - the power coefficient and the tip-speed ratio - and how

these dimensionless results can be used to predict the performance of a wind turbine of a different scale. In the final part of their individual report, they are required to use the dimensionless power coefficient and tip-speed ratio to predict the performance of a full-scale wind turbine of the same geometric shape. This is a powerful technique that is often not well understood, even by professionals, and it is good to introduce it at this early stage of the undergraduate course. [CDIO syllabus 1.2]

This wind turbine exercise packs a great deal of educational value into a relatively short and economical project - and usually students find it enjoyable.

REFERENCES

[1] French, M.J., "Nature and Rationale of the Undergraduate Course", internal note, Department of Engineering, Lancaster University, 4 May 1972.

[2] Crawley, E., Malmqvist, J., Östlund, S., and Brodeur, D., Rethinking Engineering Education, the CDIO Approach, Springer, New York, 2007 (ISBN 978-0-387-38287-6).

[3] Hugo, R., and Goodhew, P, "The CDIO Approach to Engineering Education: 4. Designing and Integrating Design-Implement Experiences" (revised June 2010), CDIO Knowledge Library, Cambridge, MA; CDIO Worldwide Initiative. http://www.cdio.org; hugo@ucalgary.ca; goodhew@liv.ac.uk.

[4] Stamper, R.E., and Dekker, D.L., "Utilizing rapid prototyping to enhance undergraduate engineering education", 30th ASEE/IEEE Frontiers in Education Conference Paper F3C-1, Kansas City, MO, USA, October 18-21 2000.

[5] Klaeger, U., and Hoffman, A., "Using intelligent prototypes to improve the aerodynamic design of race car aerofoil profiles", Virtual and rapid manufacturing, Proc 3rd International Conference on Advanced Research in Virtual and Rapid Prototyping, Leiria, Portugal, 24-29 September 2007.

[6] Quayle, S. D. and Rennie, A. E. W., "Integrating computational fluid dynamic and prototyping technologies in the investigation of multi-element profiles for a high-lift variable-pitch vertical-axis tidal power generator", International Journal of Agile Systems and Management, Vol. 2 no 2, pp 222-236, 2007.

[7] deWeck, O. L., Kim, I.Y., Graff, C., Nadir, W., and Bell, A., "Engineering design and rapid prototyping: a rewarding CAD/CAE/CAM and CDIO experience for undergraduates", Proceedings of the 1st Annual CDIO Conference, Kingston, Ontario, Canada, June 7-8, 2005.

[8] Joyce, T., Evans, I., and Pallan, B., A Student-Led Design Course Related to Sustainable Engineering, Case Study, Higher Education Academy Engineering Subject Centre, available at www.engsc.ac.uk/downloads/scholarart/100119-**joyce-case-study**.pdf

[9] Neves, B.C., and Guedes, P.B., "Spinning new engineering students' minds", Proceedings of the 6th International CDIO Conference, Ecole Polytechnique, Montreal, June 15-18, 2010

[10] Widden, M., and Gunn, K., Design-build-test of model aerofoils for engineering education using FDM, Virtual and Physical Prototyping, vol 5 no 4, December 2010, pp 189-194

[11] Walker, J.F., and Jenkins, N., Wind Energy Technology, John Wiley & Sons, Chichester, 1997

[12] Jacobs, E.N., Ward, K.E. and Pinkerton, R.M., "The Characteristics of 78 Related Airfoil Sections from Tests in the Variable-Density Wind Tunnel", National Advisory Committee for Aeronautics, USA, 1933

Biographical Information

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