Training program for researchers in design and manufacturing of experimental prototypes for fluids engineering using additive technologies

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Abstract: Experimental testing is one of the pillars in Fluids Engineering research. The arrival of rapid prototyping, and especially, Additive Manufacturing (AM), has revolutionized this field, allowing fast and flexible prototype manufacturing. Among these technologies, Fused Deposition Modelling (FDM) allows to fabricate complex parts using light, resistant, composite materials at a very affordable cost. To harness the full potential of this technology, the fluid dynamics engineering research group (GIFD) of the University of Oviedo started a training program for researchers in this area. This rich and complete program is presented herein, emphasizing its elaborate methodology and highlighting the successful case-studies derived from its application. Knowledge and integration of this technology has granted the capability of self-manufacturing customizable, low-cost experimental prototypes with adequate mechanical properties and accuracy, which produce high-quality results. Additionally, it has widened remarkably the possibilities of experimental research, resulting in a significant increase of experimental publications.

Keywords: Experimental prototypes, Additive manufacturing, Fused deposition modelling, Training techniques, Design for manufacturing and assembly.

1. Introduction

Experimental tests are considered one of the most important study methods in Fluids Engineering research as they provide valuable, reliable data, which is often used for the validation of analytical and computational models. Within the experimental testing phase, dimensional analysis is one of the most common methodologies, which allows testing scaled prototypes at conditions equivalent to those of the real-scale prototype and extrapolate the results. In this context, prototype manufacturing entails a tremendous challenge, as they are on-demand single parts, subjected to design changes and usually feature complex geometries. These characteristics make conventional prototype manufacturing an extremely expensive and time-consuming process.

In the past, experimental prototypes in fluids engineering were frequently handmade by skilled craftsman in materials as balsa wood, with its limitations in manufacturable geometries, shape accuracy and material properties (the last often improved adding composites as fiber glass) [1]. On the other hand, when metal parts were required, they were manufactured by means of conventional processes as forging,
casting, welding, and folding, usually demanding customized tooling equipment. These are methods which require machining and post-processing after fabrication through different operations (drilling, turning, milling and grinding) to achieve the desired geometries with an adequate surface finish. Furthermore, these processes involve high initial cost and require professional operators; frequently being profitable only for mass production, not for a limited number of parts. Additionally, they do not allow easy implementation of design changes, which is a key aspect at prototype stage.

Nevertheless, with the arrival of rapid prototyping, and especially Additive Manufacturing (AM), the scenario has changed radically, allowing quick physical model production directly from Computer Aided Design (CAD) data files. These extremely flexible technologies can adapt to design changes without need of customized tooling or cost increase, and have a wide range of materials [2].

Within AM, Fused Deposition Modelling (FDM) has become an extraordinarily useful tool for experimental testing, allowing affordable fabrication of complex parts with light, resistant, composite materials [2]. Furthermore, there is Computer Aided Manufacturing (CAM) software available which reduces the need of technical knowledge needed to use the technology.

With the aim of harnessing the full potential of this technology, the fluid dynamics engineering research group (GIFD) of the University of Oviedo started in 2018 a training program for their researchers in this field. The main objective of this work is to show the benefits and applications of incorporating AM and more specifically FDM, as a resource for experimental research in Fluids Engineering, sharing the methodology used to address this task, as well as the results and experience obtained.

2. Methodology

After the expiration of Stratasys’ patent describing the basics of FDM in 2009, there was a massive and continuous price drop in commercial 3D printers. Hence, in 2015, with 3D printing at user reach, a PhD student at the University of Oviedo, acquired a BQ WitBox to try the technology in the field of OWC turbines. In his thesis and subsequent papers, he reported very good agreement between experimental and numerical tests, validating the technology for its use in this field [3]. Based on these works the GIFD decided to incorporate its first 3D printer in 2016. The first machine purchased was “The Beast v1.2” from Cultivate3D, a large DIY kit printer (figure 1(a)) whose main specifications, and those from the following machines, are detailed in table 1. Given the good preliminary results with this technology, the GIFD decided to set up a 3D printing cluster in 2017, starting with the purchase of a BCN3D SIGMAX dual extruder printer (figure 1(b)).

![The Beast v1.2 from Cultivate3D. (b) BCN3D SIGMAX. (c) HTA3D P3Steel.](image)

Figure 1. (a) The Beast v1.2 from Cultivate3D. (b) BCN3D SIGMAX. (c) HTA3D P3Steel.

Once the technology was established, the next step was to open it up for all GIFD researchers to use in their fields. For this purpose, two intensive courses of 30 and 14 hours respectively were taught. A summary diagram of the contents and methodology used in the training program is shown in figure 2.
First one was a one-week 3D printing course, which was given in collaboration with Prodintec foundation (now part of Idonial) and MediaLab. Prodintec technicians were in charge of providing the theoretical part of the course. They gave a seminar in their facilities and a guided tour, showing the students the different existing technologies, their practical applications, and their industrial machines at work. The rest of the course took place in the university, with an introduction to FDM by MediaLab covering: the fundamentals and working principles, available materials, 3D model databases and different machine types and components. Finally, researchers were tasked with assembling and operating a series of DIY kits of Prusa i3-type printers from the brand HTA3D (figure 1 (c)), to achieve first-hand knowledge of the technology. In addition, after the course, they were added to the GIFD 3D printing cluster.

The second course was intended to deepen in FDM, but it also kept a brief introduction to additive manufacturing for researchers who did not take the first course. This course focused on teaching a systematic proceeding to the researchers and building a solid base from which they could grow by themselves. The course was divided in three modules:

The first module covered a brief summary of what was taught in the first course. After, researchers were assigned projects to work in during the course.

The second module faced in depth the topic of design for manufactur ing and assembly (DFMA), which is one of the keys to exploiting the full potential of FDM technology [4]. First, some general rules DFMA applied to FDM technology were given, as for example: rounding edges when possible in the XY plane, to avoid mechanical and thermal stress concentrators [4]. Then, a strong emphasis was laid in designing 3D parts for a specific part orientation, taking into consideration surface finish requirements or mechanical properties [5]. DFMA of problematic part features was also revised, as how to make overhangs or “bridges” printable or designing strong durable joints [6]. A strong effort was put in exemplifying every theoretical principle with its practical application to a technical part. Furthermore, as a practical exercise, attendants were tasked with redesigning some of their project part features to improve manufacturing and assembly.

Table 1. Equipment specifications and characteristics.

| 3D printer       | Build Volume (mm) | Hot End | # hot ends | Extrusion type | Architecture |
|------------------|-------------------|---------|------------|----------------|--------------|
| The Beast v1.2   | 470×435×690       | E3D v6  | 1-4        | bowden         | cartesian    |
| BCN3D SIGMAX     | 420×297×210       | BCN3D   | 2          | bowden         | cartesian    |
| HTA3D P3Steel    | 200×200×210       | E3D v6  | 1          | direct         | cartesian    |

Figure 2. Summary diagram of the contents and methodology used in the training program.
The third module started covering the operation, calibration, and basic maintenance of the machines. Then, the topic shifted to material properties and appropriate material selection for each application, focusing specially on experimental prototypes for fluid engineering. Next, process parameter selection was addressed from a systematic approach, identifying part features which drive certain process parameters, as for example: details in the Z direction which require lower layer height [7]. To minimize process parameter setting adjustments, a series of predefined profiles were created for part families based on those characteristics. Additionally, a complete, methodical guide on problem diagnostics and solving based on part inspection was taught, and the course ended with the researchers fabricating their projects. As a tool for continuous improvement and targeting future courses, a feedback loop was implemented by means of an anonymous quality survey, whose results indicated a high level of satisfaction with the course (9.8/10).

3. Successful case-studies

After taking the courses, researchers were able to apply the new resource to their investigations. This section shows a diverse selection of successful case-studies in which FDM was applied by the researchers not only for manufacturing experimental prototypes, as airfoils or even complete turbines, but also for a great number of auxiliary systems.

3.1. Auxiliary systems

3.1.1. Aerodynamic balance orientation system. Experimental characterization of airfoil profiles is one of the active research lines of the GIFD research group. For this purpose, lift and drag coefficients are measured with an aerodynamic balance for a range of attack angles and at different Reynolds numbers. Achieving the correct positioning of the airfoil at different attack angles is a difficult and tedious task, which researchers of the group were able to overcome with the design and FDM manufacturing of a worm drive orientation system (figure 3(a)).

3.1.2. Probe positioning system. One of the most common aerodynamic measurements are wake velocity profiles, which usually require a high number of measurement positions. The probes must keep the same calibration angle and measurements are usually performed in two or three dimensions. The acquired knowledge allowed the design and FDM fabricating of a simple, yet efficient, mechanical probe positioning system (figure 3(b)). By means of a crank-pulley-wire-slider system, the desired linear displacement is achieved by a revolution of the pulley, which has the adequate diameter. This system allows correct probe positioning and quick and comfortable displacement, with the implicit precision enhancement and test time optimization.

3.1.3. Epicyclic gear train. A planetary gearing system with gear ratio of 10:1 was designed and FDM fabricated (figure 3(c)) to be used in wind tunnel experiments. It is coupled with a small vertical axis turbine (shown further on) to reduce the starting torque required and make the turbine model rotate easily. In fact, fabricating this gear train system using FDM added more flexibility, allowing the use of the same arrangement to multiply the velocity in another application (gear ratio of 1:10) by only printing one additional part, which was able to change the positions of both the drive and driven gears.

3.1.4. Venturi tube. The Venturi tube is one of the most widely used devices for measuring the flow rate through a pipe and is present in most experimental tests involving this kind of flow. For this reason, a Venturi has been built (figure 3(d)), measuring 1200mm in length and 350mm in diameter at its widest part and consisting of 17 glued parts. For it to perform accurately, it has been designed in accordance with the UNE-EN ISO 5167-4 standard and calibrated based on the velocity profile at the outlet to calculate the real flow rate, giving a discharge coefficient of 0.99.
3.2. Airfoil profile fabrication

3.2.1. Aerodynamic studies. As it was previously mentioned in sub-subsection 3.1.1, experimental airfoil characterization is an active research line. The new knowledge and availability of FDM technology has allowed an important cost reduction in airfoil profile prototype fabrication. For example, a methacrylate airfoil prototype which was bought some years before, cost 20 times more than an equivalent in-house FDM fabricated airfoil (figure 4(a)). Also, it has increased the research possibilities since, more complex geometries can be fabricated, and design changes can be easily and quickly implemented because the researchers control the whole process. Furthermore, results show that the technology is valid for this application, as obtained data matches the bibliography one. An example is shown in figure 4(b) comparing experimental data from an experimental FDM flat plate prototype and the theoretical results obtained by analytical methods available in [8].

3.2.2. Vertical Axis Turbine prototypes. FDM fabricated airfoils have also been applied to the manufacturing of vertical axis turbine prototypes, for wind energy (VAWTs), as well as for tidal currents (VATTs).

In the first field, an existing scaled VAWT prototype for wind tunnel testing, which had broken due to extreme centrifugal forces, was redesigned and FDM technology was used for the airfoils and several of its components. Knowledge from part orientation was applied in the manufacturing of the blades, achieving an increase of 43.4% in bending resistance and a 61.5% in strain and shifting fragile behaviour to ductile at fracture. The results were obtained from the 3-point bending test of 2 blade section specimens, manufactured with the same process parameters, but different layer orientation (figure 5 (a)).
Also, a well optimized topology of the critical features such as joints allowed the new prototype to be tested at the required rotational velocities. Furthermore, the cost of the new blades was astonishingly lower, only 2% of the original ones. After 2 years of being used in demanding experiments with high rotational velocities the prototype (figure 5 (b)) has proven to be a great application of this technology. The results and experience gained by its testing have led to start the manufacturing a real-scale prototype for field experiments.

Figure 5. (a) 3-point bending test of 2 blade section specimens with same manufacturing parameters but different layer orientation. (b) FDM turbine prototype.

In the other field, several prototypes of Vertical Axis Tidal Turbine (VATT) have been manufactured and tested successfully inside a water channel [9] (figure 6 (a), (b)).

Figure 6. (a) VATT prototype tested in water channel. (b) Close-up of other of the designs manufactured.

The proposed models worked properly under the continuous hydrodynamic loading, without any change in the design nor the properties during months of experiments. In addition, one of the experimental requirements was to change the turbine position along a vertical axis, thanks to the FDM, a slotted collet (collet chuck) mechanism was fabricated and equipped with the VATT to achieve more than one vertical position. Also, other accessories were fabricated to complete the turbine support system, including bearing beds and shaft holders. In fact, testing these kinds of turbines inside channel was not limited only for straight blade type, but also it was extended to helical blade models. The flexibility and ability of generating complex shapes of FDM allowed the fabrication of helical turbine
models with different helix angles (30°, 45°, 60°, 90° and 120°) to be tested and evaluated inside the water channel.

3.3. OWC turbine prototypes
One of the GIFD's lines of research focuses on turbines for harnessing wave energy. Within this line, an axial turbine has been designed and built, completely inside the laboratory and without external help. Constructive design copies real gas turbines and was based in a previous work found in the bibliography [10]. Figure 7(a), (b) shows the exploded view, as well as the real turbine.

![Figure 7](image1.jpg)

**Figure 7.** (a) Exploded view of the turbine. (b) FDM axial turbine prototype.

A research work has been published on this turbine [11] in which the experimental-numerical validation can be seen, a sample of this data is shown in figure 8. As it can be seen, FDM technology gives great results in the field of fluid mechanics.

![Figure 8](image2.jpg)

**Figure 8.** Numerical model validation through experimental testing of FDM prototype (Torque coefficient vs. Flow coefficient).

4. Conclusions and Future Works
A rich and complete training program in AM, and more specifically FDM for researchers in the field of fluids engineering, has been shared in this work, emphasizing its elaborate methodology and highlighting the successful case-studies derived from its application. Researchers which were new to this technology have now become experienced users with great skill.
Integrating this technology and knowledge in this research area has granted the capability of self-manufacturing customizable, low-cost experimental prototypes with adequate mechanical properties and accuracy, and which produce high-quality results. Additionally, FDM is being used to improve the experimental procedures and even to produce ad hoc equipment. The possibilities of experimental research have been widened remarkably and it is expected that this will result in a significant increase in number and quality of the experimental publications in the near future.

Given the success of integrating FDM and the expected academic outcome, betting on this technology can be taken as an investment for the future. This opens the door for investing in other AM technologies, as Stereolithography (SLA) or Selective Laser Sintering (SLS), whose interest for this application has yet to be analyzed.

Additionally, the evaluation system implemented in the courses indicated that the training methods were adequate, and it will enable the continuous improvement of the training program, which given its success will continue in the following years.

Acknowledgements
The authors wish to thank the support of: MINECO, Spain [ENE 2017-89965], MECD, Spain [FPU15/04375], Ministry of Higher Education and Scientific Research, Egypt, GRUPIN [IDI/2018/000205], University Institute of Industrial Technology of Asturias (IUTA) and Ayto. Gijón [SV-18-GIJON-1-05], and the collaboration of Prodintec (Idonial) and MediaLab (Univ. Oviedo).

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