Undergraduate Turbomachine Design Using CFD and 3-D Printing

John Abbitt
University of Florida

Abstract

For the past year, Mechanical & Aerospace Engineering students at the University of Florida have been designing and manufacturing impellers for a centrifugal fan. The method is taught in our Thermo-Fluids Lab and Design class and involves using Euler's Turbomachine Equation and creating velocity diagrams to predict performance. A limitation of the Euler Turbomachine Equation is that it is based on a finite control volume analysis which prescribes blade angles at the entrance and exit of the impeller, but provides no information on the number or geometry of the blades within the impeller. Another limitation of the equation is that it assumes an infinite number of blades of zero thickness that results in uniform flow at the inlet and the exit, while a real impeller has a distinct velocity profile in between each blade that leads to losses not predicted by the equation. Recently, the department obtained a computational fluid dynamics (CFD) program which allows students to use a differential control volume method to analyze the interior of the impeller region. The program was introduced to the students in the Fall 2014 semester. The students now use the program to improve their impeller designs. Once the designs are optimized using the software, the students manufacture their impeller using a 3-D printer, and then test the impeller in the lab fan performance apparatus. The results of their efforts as well as the issues involved in managing such a project with about 125 students per semester will be discussed in this paper.

Keywords

Centrifugal fan, 3-D printing, design, Solidworks, Pumplinx

Introduction

Turbo-machinery design is taught to both Mechanical and Aerospace engineering students at the University of Florida in a senior level course called EML4304C Thermo-Fluids Design and Lab which is an advanced fluid mechanics and thermodynamics course. There are usually 100-120 students enrolled in the class which is offered three times a year. Pre-requisites to this class include Fluid Mechanics, Thermodynamics, and Computer Aided Graphics & Design. About three weeks of lecture as well as two optional workshops are dedicated to turbomachinery analysis and design. In addition, there are two lab periods that involve characterizing two centrifugal pumps by measuring head rise, and brake and water horsepower over a range of flow rates and rpm, and then plotting performance curves of both forward and backwards facing impellers. For the last three semesters, the final project in the class has involved designing, building, and testing a pump impeller.

In the lectures for this course, turbomachinery design is focused mainly on centrifugal pumps, and, in particular, there is a discussion on the performance of backwards facing, radial, and forward facing blades on a pump impeller. The discussion in the textbook shows that the performance curve of an impeller with a backwards facing blade should give a negative slope when plotting head rise versus flow rate of the pump.[1] Similarly, a radial blade should generally give a slope of zero over its range of operation, and a forward facing blade should give a somewhat positive slope. The reader is led to believe that impellers with the blade geometries described will always behave according to these generalizations. To support this discussion, typical performance curves are provided in the various widely used textbooks. A representative performance curve is shown below.

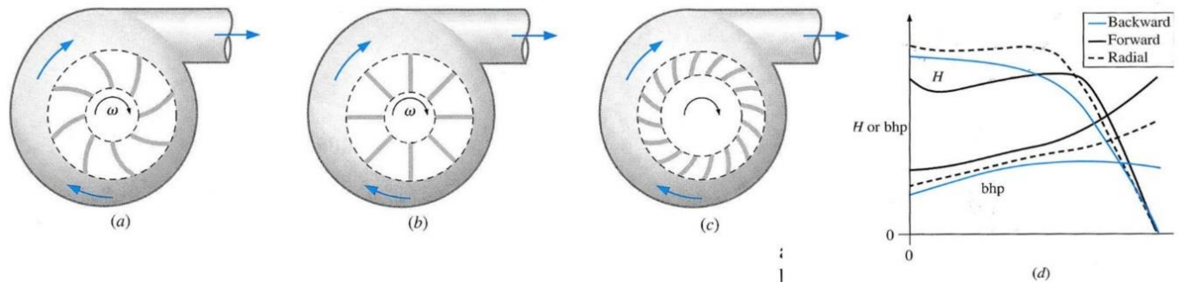

Figure 1. This is a diagram from the course textbook, and shows the three types of blade configurations available. Backwards-facing are shown in (a), radial blades are shown in (b), and forward-facing are shown in (c). Figure (d) implies that these are typical performance curves for each of these configurations.[1]

Students in the class study Euler's Turbomachine Equation which predicts the head and thus the performance of an impeller. Euler's Turbomachine Equation is:

$$H = \frac{1}{g}\left(V_{t,1}\,\omega r_1 - V_{t,2}\omega r_2\right)$$

where H is the head added to the flow, g is gravity, $V_{t,1}$ and $V_{t,2}$ are the tangential components of the flow at the inlet and outlet of the impeller, r_1 and r_2 are the radii of the inlet and outlet of the impeller, and ω is the rotational speed.[2] The tangential components of the velocity V_t depend on the blade angles of the impeller. For the ideal case, $V_{t,1}$ is set to zero since it is assumed that the tangential component can never produce negative head. The ideal case gives the maximum possible value for head, and the flow rate at this condition is said to be the "design" flow rate.

For an ideal flow, Euler's equation predicts a linear relationship with flow rate with a negative slope for backwards facing blades, a slope of zero for radial blades, and a positive slope for forward facing blades. The curve from the textbook is shown in Figure 2.

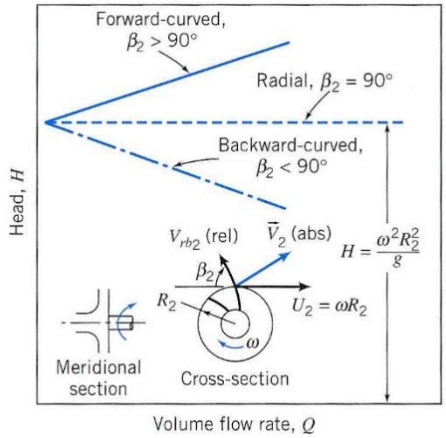

Figure 2. Idealized relationship between head and volume flow rate for centrifugal pump with forward-curved, radial, and backward-curved impeller blades. The implication is that forward-curved blades will always yield a positive slope, the radial blades will yield a zero slope, and backward-curved blades will yield a negative slope.[3]

While not explicitly saying so, the analysis leads the reader to believe that the slope of the performance curve of a pump with an impeller with a backwards facing blades will always be negative, and the slope of the performance curve of an impeller with radial blades will be flat over a wide range of flow rates, and the curve for the forward blade will have a positive slope.

Unfortunately, if the flow rate is not at the design flow rate, the tangential component of the velocity at the inlet is not zero as assumed in the development of the analysis. The curves in Figure 2 assume the tangential component of the velocity at the inlet is zero at all points which in actuality is not the case. That means the predicted slope of the performance curve should occur only at the design flow rate, if at all. Another problem is that the Euler Turbomachine Equation assumes an infinite number of blades that give perfect control of the flow, and that the blades are infinitely thin so there are not losses due to friction at the blade walls. In reality, since there are a finite number of blades, control of the flow is less than ideal which leads to what are called "circulatory" losses, and the friction at the wall leads to what are known as "passage" losses.

In the Thermo-Fluids lab, students use TecQuipment MFP106 Centrifugal Fan to collect experimental data and plot the performance curves over a range of flow rates and rpms. There are two sets of experimental apparatus which are referred to as modules. Each module is set up with one of the different blade angle options. When these modules were obtained, it was planned to re-enforce the concept of the shapes of the performance curves for the different configurations. However, in all cases, the actual slope of the performance curves is similar over a wide range of flow rates for all impellers, and certainly do not reflect the shape of the curves described in the textbooks. The explanation by TecQuipment about this discrepancy is as follows:

"In an ideal fan or pump the impeller (β_2=90°) should give a constant pressure even though flow increases, but forward and backward curved impellers produce an increasing or reducing

pressure as flow increases. In actual fans and pumps, many different factors affect this theoretical difference, so pressure always increases with flow."[4]

If the statement above were true, there would be no reason to study Euler's Turbomachine equation since it would have no value in predicting the performance curve. Since the author of this paper was not ready to reject the conventional wisdom described in the textbooks, further study was conducted to determine the discrepancy.

It was decided to try to design and build an impeller in-house to achieve specified performance curves. It has been determined that it is practical to manufacture impellers using 3-D printers available in our department. It was decided to build a prototype for the impeller with blade angles customized for the lab apparatus. A blade angle β_1 of 29˚ was chosen for the inlet, and a blade angle of β_2 of 31˚ was chosen for the outlet. These angles are both backwards facing, and were chosen to give a negative slope for the performance curve. This performance curve is shown in Figure 3. The next step was to draw the impeller in Solidworks. The drawing of the impeller is shown in Figure 4.

For the Fall 2014 students, the class began using a CFD pump simulation software package called Pumplinx which was created by the Simerics corporation. This program is a 3-D CFD tool that provides for virtual testing of any type of pump system. With Pumplinx, students can see the flow field within the impeller including pressure distributions and velocity vectors. Using the software, students were able to determine where flow separation occurred, and were able to modify the geometry to avoid separation and obtain the specified performance curves. The due date for results of the simulation was not until after this paper was submitted, but results will be available at the conference presentation. From informal discussions with students about their design, it appears Pumplinx led to important changes in their designs that led to significant improvements in performance.

The next step was to print the impeller in the 3-D rapid-prototype machine. The impellers are made of ABS plastic. The plastic seems to hold up well, even at 3500 rpm. We have now conducted several hundred runs and have had no mechanical failures. The actual impeller is shown installed in the apparatus in Figure 5.

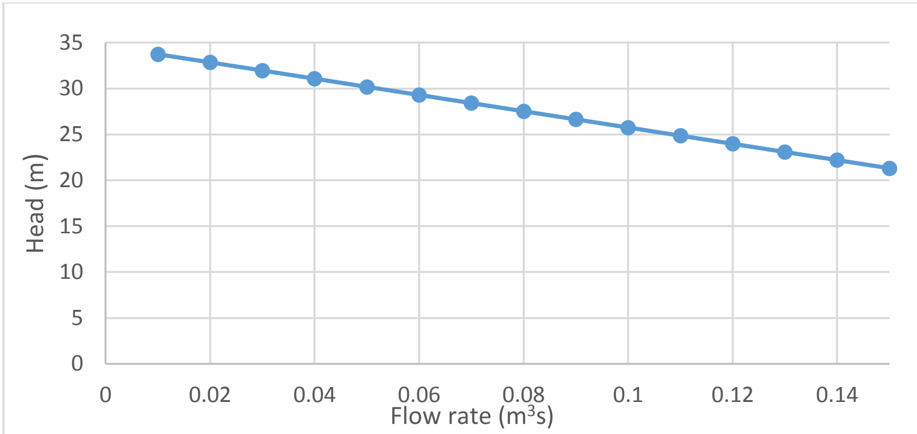

Figure 3. The performance curve of head vs flow rate at 1841 rpm calculated from Euler's Turbomachine equation is shown here. The blade angles were chosen to give a negative slope.

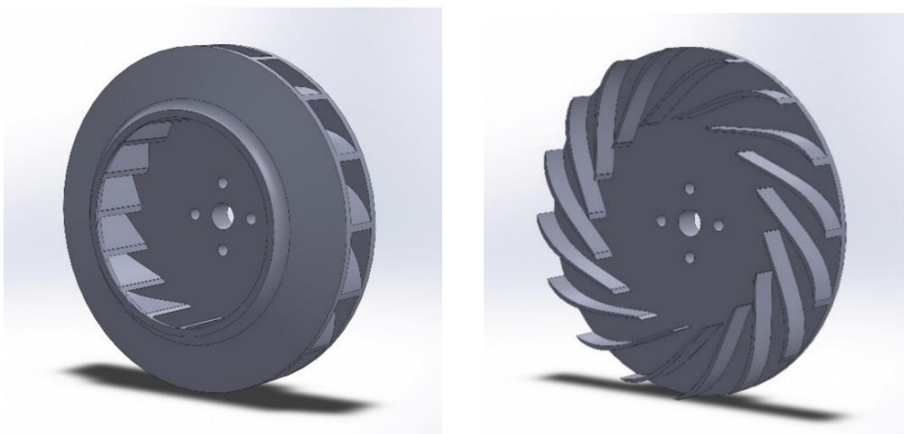

Figure 4. Solidworks drawings of impeller. The image on the left is the complete impeller. The image on the right is a cut-away that shows the blade configuration.

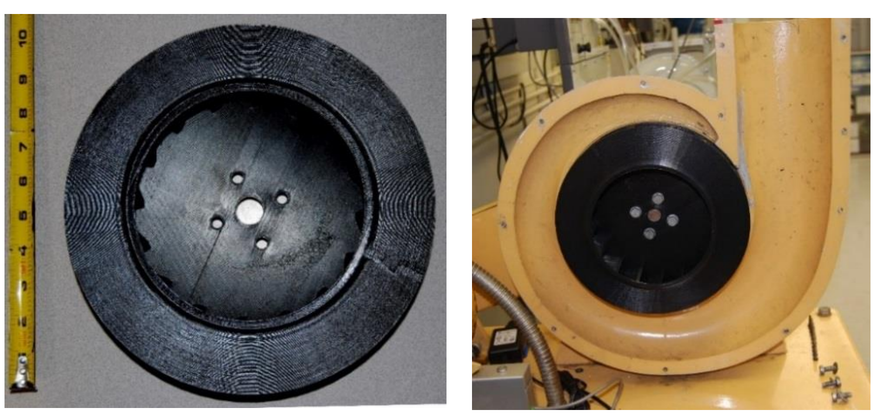

Figure 5. On the left is shown the model built using the 3-D printer. The image on the right shows the model installed in the test apparatus.

Test results

To date, the students have built and tested approximately 48 impellers. The results of one of our early tests is shown here. The results of a test conducted at 1841 rpm is shown in Figure 6. The useful range of the impeller was defined to be the flow range where the slope was negative. In the useful range, the predicted values of head compare well with the measured values.

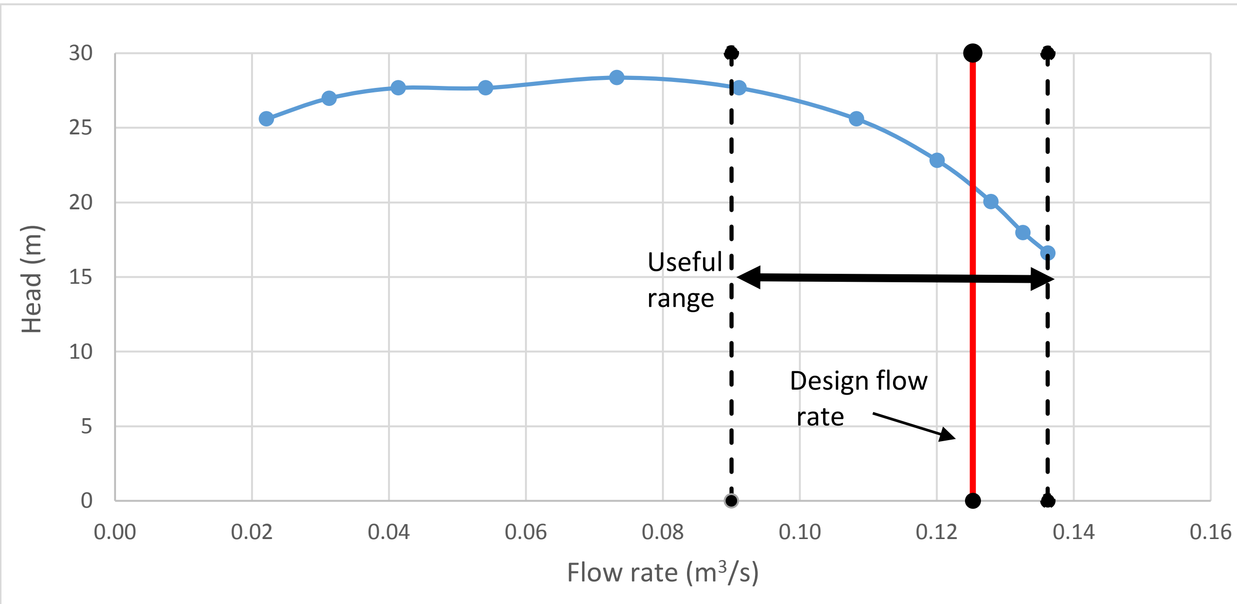

Figure 6. Shown here is the measured performance curve for an impeller with $\beta_1 = 29^\circ$, $\beta_2 = 31^\circ$, rpm = 1841. The useful range is defined at the range in which the slope is negative, and the heads are similar to the predicted values shown in Figure 3.

Integration into Design Component of Course

The purpose of this project is to improve the course/lab that students take to learn elementary impeller design. As mentioned earlier, this course ends with the students completing a design project. As a result of the progress made with the construction of the impeller with the 3-D printer and the Pumplinx software, students this semester were able to design, build, and test an impeller that produced a specified performance.

Final Remarks

At the time this paper was submitted, students were completing their final reports for the project. There seems to be much interest and enthusiasm in the project so far, and it appears that students are achieving the specified curves. The project is interesting, and pulls together concepts from manufacturing, thermal system analysis, CFD, and design in an engaging format. Results from the project will be available by the time of the conference, and the results will be presented then.

References

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[2] Cengel, Yunus A. and Cimbala, John M., *Fluid Mechanics*, McGraw Hill, United States, 2006, pg. 758.
[3] Fox, Robert; McDonald, Alan; and Pritchard, Philip, *Introduction to Fluid Mechanics*, Wiley, United States, 2006, pg. 500.
[4] *MFP Centrifugal Fan Module User Guide*, TecQuipment Ltd, Great Britain, 2011, pg 20.

John Abbitt

Dr. Abbitt received his Ph.D. from the University of Virginia in 1991. Prior to that he served as a P-3 and T-28 pilot in the U.S. Navy. He is now a Senior Lecturer at the University of Florida where he teaches three courses, EML4304C (Thermo-Heats Design and Lab) and EML4147C (Thermo-Fluids Design and Lab), and EAS4939 (Experimental Aerodynamics).