Teaching Turbomachinery Analysis using 3-D Printing Technology

***John Abbitt*[1], *Shannon Ridgeway*[2]**

Abstract – The authors are exploring an interactive way to teach turbomachinery design. The present method is taught in the Thermo-Fluids Lab and Design class (EML4304C) using Euler's Turbomachine Equation along with velocity diagrams to predict performance. There are associated labs where students measure the performance of centrifugal fans, one with a backwards-facing impeller, and one with a forward-facing impeller. The measured performance of the current impellers does not agree well with theory, and it was discovered the design flow rates for the blade configuration of the impellers in the lab was much greater than what could be achieved with the available brake horsepower. To remedy the situation, it was decided to build new impellers with more favorable blade angles. In the Fall 2013 semester, a prototype pump impeller was designed in Solidworks, a 3-D drawing program, and was constructed out of ABS plastic using a 3-D printer. This prototype was installed, and measured performance curves are much closer to theory than the previous impellers were able to achieve. The process of building of the impeller was very instructive, and it was decided to have students in the class design and build their own impellers this semester, and test their design on the fan performance apparatus.

Keywords: turbomachinery, centrifugal fan, 3-D printing, design, Solidworks.

INTRODUCTION

Turbo-machinery design is taught to both Mechanical and Aerospace engineering students at the University of Florida in a fourth-year 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 two and one half weeks of lecture 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. The final project in the class has typically involved designing a pump-piping system for a set of performance specifications that vary each semester. This final design project has been purely analytic, but it was desired to develop a project that would also involve building and testing a design which is the motivation for the project described in this paper.

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, as per the textbook, a radial blade should generally give a slope of zero over its operation range, 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.

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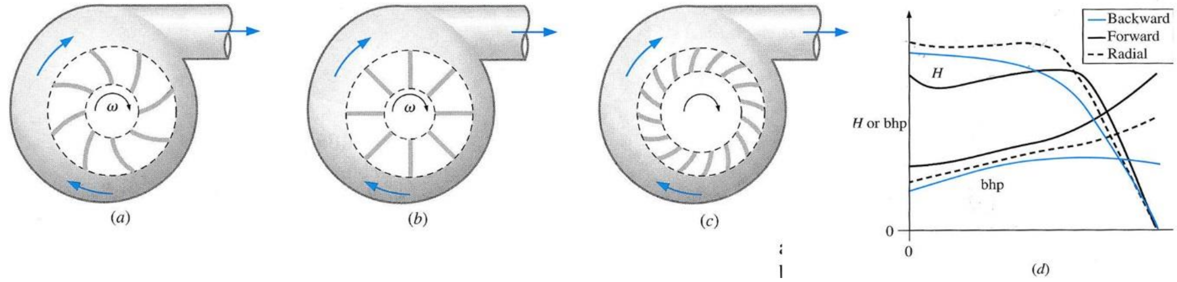

Figure 1. This is a diagram from the course textbook, and shows the three types of blade configurations available. Backwards-facing are shown in (a), radial blades are shown in (b), and forward-facing are shown in (c). Figure (d) implies that these are typical performance curves for each of these configurations.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

Students in the class also study in detail Euler's Turbomachine Equation which predicts the head, and, thus, performance of an impeller, behaves according to blade angle. 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 below.

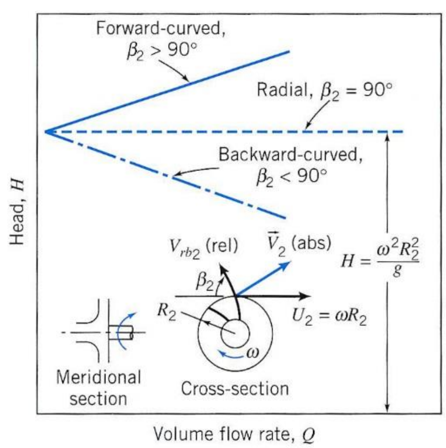

Figure 2. Idealized relationship between head and volume flow rate for centrifugal pump with forward-curved, radial, and backward-curved impeller blades. The implication is that forward-curved blades will always yield a positive slope, the radial blades will yield a zero slope, and backward-curved blades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

There are several observations that should be made about the analysis. First, while not explicitly saying so, the analysis leads the reader to believe that the performance curve of a pump with an impeller with a backwards facing blades will always be negative, and 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.

The second observation which is if the flow rate exceeds the design flow rate, the tangential component of the velocity at the exit will go negative. This is not physically possible, and the analysis breaks down at this point. Therefore, the useful range of the pump will be near the design flow rate.

In the Thermo-Fluids lab, there are three sets of TecQuipment MFP106 Centrifugal Fan Modules where students collect data and plot the performance curves over a range of flow rates and rpms. Each of the three modules is set up with one of the different blade angle options. When these modules were obtained, it was planned to re-enforce the shape of the performance curves for the different configurations. However, in all cases, the actual slope of the performance curves is positive 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 authors were not ready to reject the conventional wisdom described in the textbooks, further study was conducted to determine the discrepancy.

The inlet and exit blade angles of the existing apparatus of the backwards facing impeller was measured. The performance curve predicted by the Euler Turbomachine equation was plotted for these blade angles, and it was found that the slope of the curve for these backwards facing blades was indeed positive. In fact, by adjusting the inlet and exit blade angles while still maintaining a backwards geometry, it was possible to get any slope desired, positive or negative. TecQuipment was contacted to see if impellers were available that at least matched the theory taught in class, but the response was that it was cost prohibitive to do so. At that point, the authors considered designing custom impellers, and having them cast in a machine shop. That, too, was expensive, and there was no guarantee that our impellers would be any better than the ones already available.

It was at that point it was decided to try to design and build an impellers in-house. In the past few years as a result of the Computer Aided Graphics & Design class, students have become very proficient in using Solidworks which is a 3-D modeling program. The department owns several 3-D printers which have complemented the Solidworks class. It was decided to build a prototype for the impeller with blade angles customized for the lab apparatus. A blade 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.

Finally, the impeller was printed in the 3-D rapid-prototype machine. The original impellers that were part of the fan performance apparatus are made of metal. The new impeller is made of ABS plastic, and there was concern that the impeller would break apart at the higher rpms of the tests. However, three separate tests at 3500 rpm for twenty minutes have been conducted with no failures. The actual impeller is shown installed in the apparatus in Figure 5.

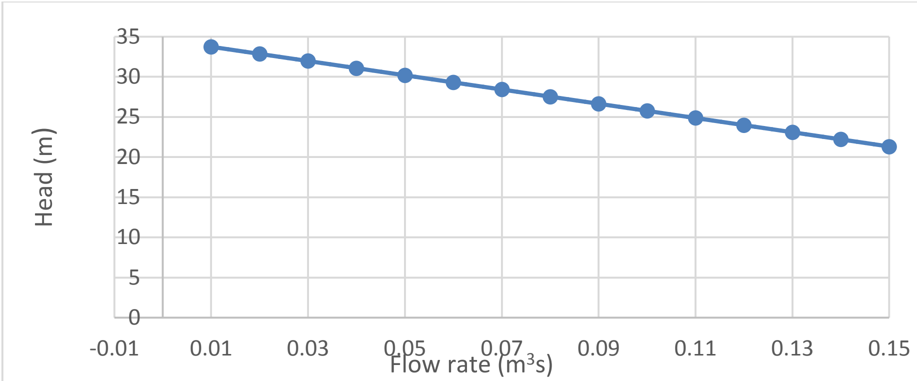

Figure 3. The performance curve of head vs flow rate at 1841 rpm calculated from Euler's Turbomachine equation is shown here. The blade angles were chosen to give a negative slope.

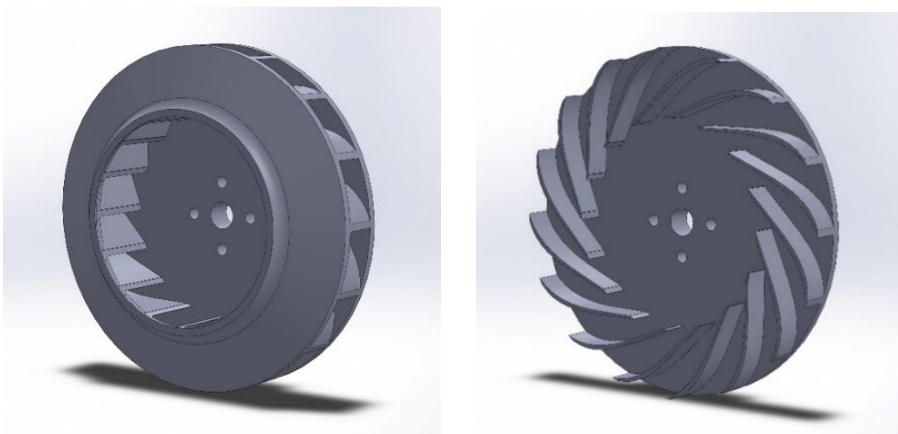

Figure 4. Solidworks drawings of impeller. The image on the left is the complete impeller. The image on the right is a cut-away that shows the blade configuration.

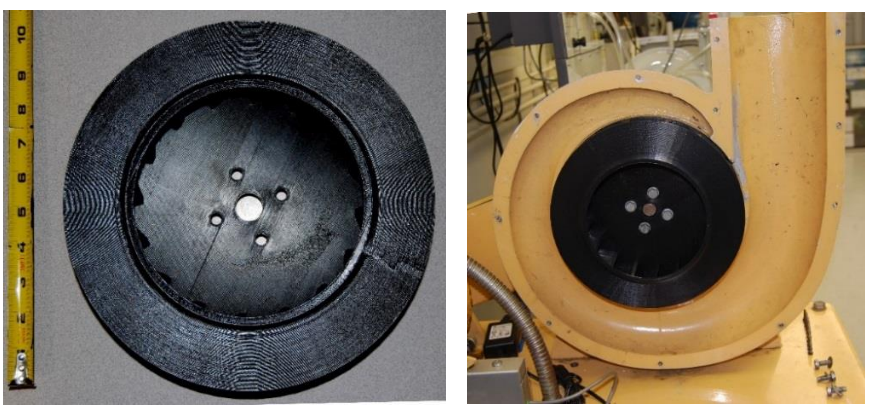

Figure 5. On the left is shown the model built using the 3-D printer. The image on the right shows the model installed in the test apparatus.

Test results

A test was conducted to measure the performance curve of the impeller that was constructed. The results of a test conducted at 1841 rpm is shown in Figure 6. Due to unanticipated less blockage in the inlet than expected, the design flow rate of the new impeller was still higher than what could be achieved, but it was closer to what we could achieve in the past. 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.

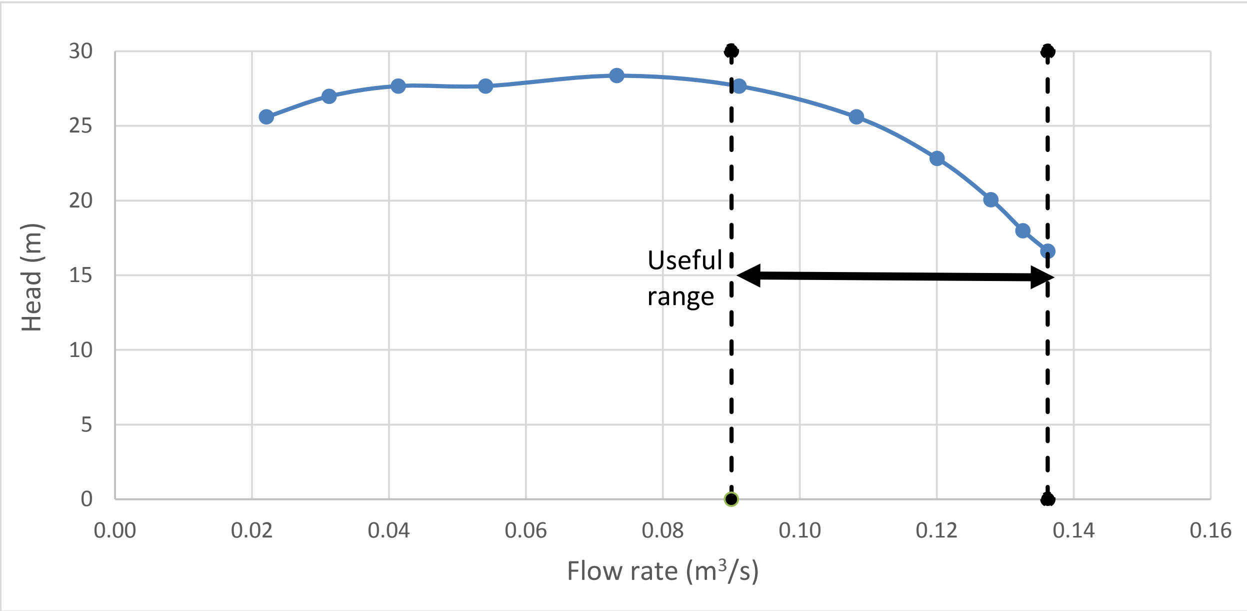

Fig 6. Shown here is the measured performance curve for an impeller with β_1 = 29˚, β_2 = 31˚, rpm = 1841. The useful range is defined at the range in which the slope is negative, and the heads are similar to the predicted values shown in Figure 3.

Integration into Design Component of Course

The purpose of this project is to teach 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, students this semester have been assigned a performance curve for a particular application for a centrifugal fan for their design project, and they are designing and building their own impellers. The students will then test the impellers in our fan performance apparatus and compare the actual performance with the predicted performance.

Issues

At this point, the major issue with this project is scheduling time on the printer. There are 112 students enrolled in the class divided into fourteen sections. The sections have eight students each, and the students are working in groups which means fourteen prototypes will have to be built. Each prototype takes about 40 hours on the printer to build. If similar projects are to be conducted in future semesters, an additional printer will be necessary.

Final Remarks

At the time this paper was submitted, students **were** just beginning to work on their impellers. There is much interest and enthusiasm in the project so far, and the authors are optimistic that students will be able to achieve results similar to their predictions. The project is interesting, and pulls together concepts from manufacturing, thermal system analysis and design in an engaging format. Most students should have completed their projects by the time of the conference, and the results will be presented then.

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