DESIGN AIDS MANUFACTURING

CUTTING COSTS TO ENHANCE PRODUCT SUCCESS

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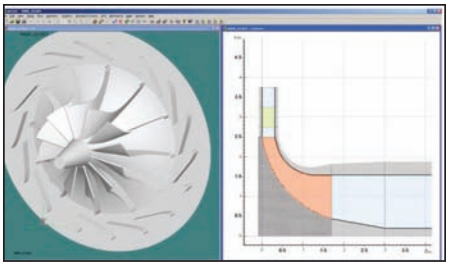
Design for manufacturing is a critical factor in overall product success. Oftentimes, engineers become too focused on performance-related numbers, such as efficiency, and lose the big picture of what is needed in a truly successful design. After all, efficiency is merely one facet in determining overall product cost and viability. Controlling all costs associated with a product is essential for commercial success.

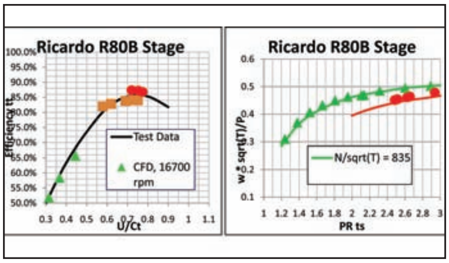
Consideration of manufacturing concerns in the earliest stages of design can yield significant benefits downstream. Generally, these are surprisingly easy to accommodate, with little or no sacrifice in stress allowances or aerodynamic performance.

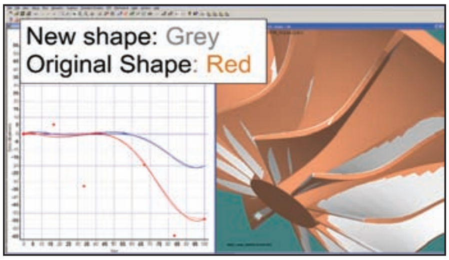
Engineers need to work with product managers and manufacturing teams to produce the most successful designs. Ultimately, the best design is one that leads to the highest commercial success of the product, and not just the highest efficiency. Successful companies form integrated teams that consider all of the relevant factors for product success at the earliest stages.

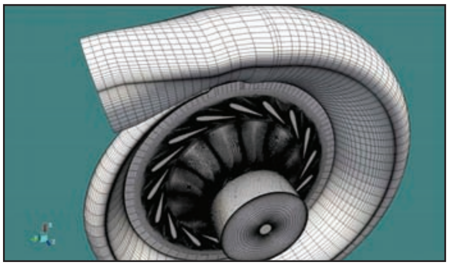
Development costs and schedules can easily spiral out of control when each discipline works in isolation, with little knowledge or concern about what happens when the job is thrown over the cubicle wall to the next group. Inevitably, the designs cycle back for costly reiterations in these situations.

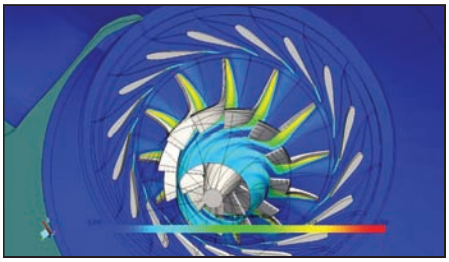
With computer-aided design systems, it is now possible to consider many of these possibilities in the first steps of development. Using an efficient method to layout potential geometries, coupled with effective analytical models, is key to achieving this success. Equally important is understanding how small changes up front can lead to big benefits downstream in the manufacturing process.

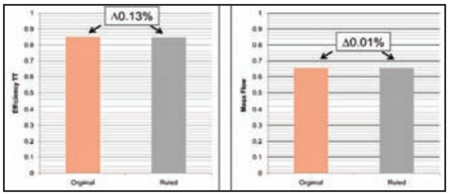












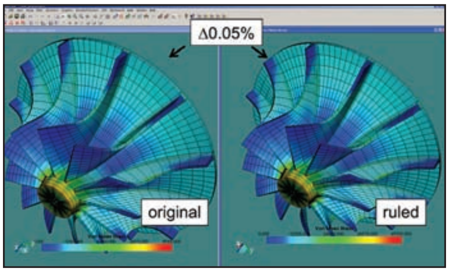


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Figure 1: Geometry of the Ricardo R80B radial turbine

Figure 2: CFD results (open symbols) overlaid on test results (solid lines) for the original turbine geometry

Figure 3: Overlay of original and modified rotor designs

Figure 4: Full-stage CFD grid used in the analysis

Figure 5: Entropy distributions of the flow field at approximately mid-span for the modified radial turbine rotor. Note the high losses that are typically generated at the leading edge of the rotor

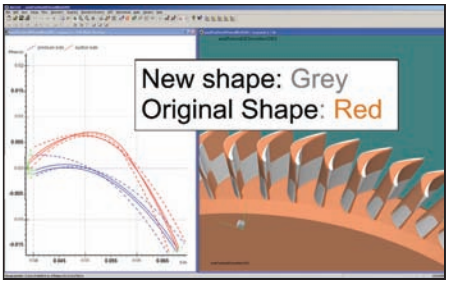
Figure 6: Comparisons showed only modest reductions in performance in the more easily manufactured rotor

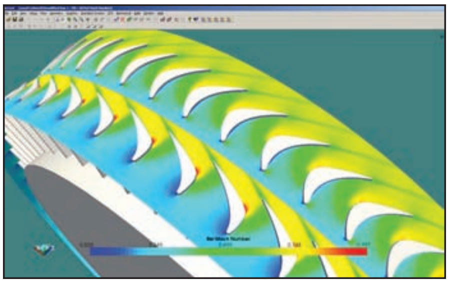
Figure 7: Comparison of FEA results showing maximum stress levels at the trailing edge and little variation between designs

Manufacturing constraints

The shape the designer ultimately chooses must be compatible with the manufacturing process used. A common method used in the industry is flank milling, which uses the side of a cutting tool to carve away the blank into the desired shape. For this to work, the surfaces have to be represented as a series of straight lines. These straight lines are roughly perpendicular to the joining surfaces and are called quasi-orthogonal lines. Although composed of straight lines, the resulting shape is generally a curved surface in three-dimensional space.

Computer-Aided Manufacturing (CAM) methods are used to guide the cutting tool in a 5-axis milling machine.





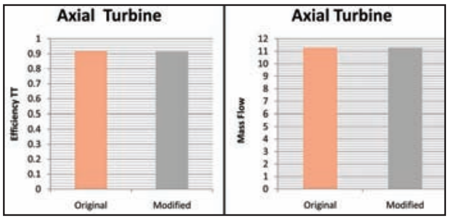


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Figure 8: Original twisted blade (dashed line, grey) compared to the simpler extruded design (solid line, red)

Figure 9: Relative Mach number distributions at roughly 70% span

Figure 10: CFD comparison of aerodynamic performance

Failure to represent the surfaces with true quasi-orthogonals forces a more tedious and slower point-milling method. Five-axis machining methods tend to dominate the compressor industry and the lower temperature regions of turbines. Improved cutting methods, more accurate geometry results, and the superior surface finish are favoring 5-axis machining in other industries that have traditionally used casting.

Casting methods come with their own unique restrictions. Chief among them is the ability to pull the mold from the product. Various methods and ranges of costs exist to accomplish this. State-of-the-art methods require complex three-dimensional calculations to determine if proper clearances are present to free the casting as the molding components are pulled and twisted away.

At the heart of any viable design method is the ability to define and manipulate the geometry in a convenient way. Ideally, the Computer Aided Design (CAD) system would hold the geometry to a predetermined parameterization that is compatible with the manufacturing method needed. Several CAE products are available specifically for turbomachinery to do this. The most advanced allow a range of different parameterizations and provide modeling methods that give clear feedback on performance, which enables the designer to make the optimum trade-offs on performance, stress levels, overall geometric constraints, and manufacturing costs.

In order to demonstrate some of the simple principles of design for manufacturing, two sample cases are demonstrated below. Each of them will be modified in a specific way for better manufacturability. The results will show how easy it can be to reduce manufacturing time and costs, and how small the sacrifices in stress levels and aerodynamic performance can be. These cases are:

- A radial turbine modified to conform to a quasi-orthogonal definition for flank milling
- An axial turbine rotor significantly reshaped to allow an inexpensive, extruded type of blade

Maintaining performance

Radial turbines historically have used casting to produce rotors. Today, 5-axis machining is increasingly being used. This raises an issue with the way radial turbine blades have traditionally been laid out. Stress concerns tend to dominate in radial turbines. The high temperatures found in turbines tend to push the structural limits of the material. Also, aerodynamically, turbines are inherently less sensitive than compressors.

For these reasons, radial turbines generally have a "radial" blade definition, where the blades radiate out directly from the axis of rotation. This limits all of the stresses in the blades to pull-stress from the centrifugal forces of rotation, which essentially eliminate bending stresses. This minimizes overall stress levels, albeit with a significant reduction in the degree of freedom the designer has to work with. A radial blade may or may not be suitable for casting, but it is mathematically impossible for it to take on a ruled element shape necessary for 5-axis flank milling.

To bypass this problem, we will break with engineering tradition and lay out a new design based on pure quasi-orthogonal lines for efficient 5-axis machining. Our baseline design is one of the famous Ricardo series of radial turbines extensively tested and documented in the 1950s and 1960s (Figure 1).

Figure 2 shows the Computational Fluid Dynamics (CFD) results for this turbine compared with test data. Not only do the CFD results show an excellent comparison to test data, they also show how conveniently the performance correlates with the velocity ratio (U/c), defined as the tip rotor speed divided by the ideal velocity expended out to the exit pressure. The various flow points and rotational speeds all tend to fall on this single line; hence, it is the preferred method of plotting performance. The excellent comparison between the test results and analytical solutions gives a high degree of confidence in quantifying the performance change for the design modification.

Comparison of the baseline design (red) to the modified design (grey) in Figure 3 shows little difference in the overall shape. As long as key parameters, such as radius and inlet and outlet blade angles are kept unchanged, the geometry can be reparameterized with remarkably little change in overall shape. Although the final shape is only modestly changed in three-dimensional space, the new geometry can now be produced much more efficiently by 5 axis machining

Next, we will confirm that these geometric changes are structurally and aerodynamically small as well. We will use CFD (Figure 4) and Finite Element Analysis (FEA) again to quantify the impact of the geometry change. Figure 5 is a snapshot of the grid around the nozzle blade and a further perspective of the mesh for the entire stage used in the CFD. This solution used a total of nearly 600,000 grid points and ran for about five hours. Figure 5 shows a plot of entropy distribution from the modified geometry solution.

The bottom-line change in performance was small for this example. Only about one-tenth of one percent of efficiency was lost with this design modification (Figure 6) . In reality, the change would most likely result in a net gain on the test stand. No attempt was made in the CFD to account for the higher quality surface finish that would result from this manufacturing process. This benefit would most likely outweigh the tiny loss in efficiency from changing the gross blade shape.

How do the stress levels compare? This is most critical, since controlling the stress levels is the primary motivation for using a purely radial blade layout. The results of FEA analysis show only an extremely small variation in the case: less than one-tenth of one percent. Looking deeper into the results, we can clearly see why.

The pure radial and modified ruled-element lines are essentially the same at the trailing edge. In other words, they are mathematically identical at that location, since they happen to have the same orientation. By contrast, the leading edge defining lines (top of Figure 7) are 90 degrees apart, and the resulting shape is quite different. Because the maximum stress level is at the base of the trailing edge, it stands to reason that the stress levels will be similar as well.

A big change in shape

The second case is a radical departure from the previous case in which there was only a subtle difference in shape (and ultimately performance). However, in this case, there is a significant difference in shape (Figure 8). The question then arises: Is this more significant change acceptable?

The baseline shape of this turbine rotor blade is a fairly typical twisted design. The modified design is without twist and can potentially be manufactured in a simple extrusion-type process for blading with high aspect ratio, such as this example.

Again we use CFD to quantify the difference aerodynamically. FEA analysis will be bypassed in this case, since twist imposes additional stresses on the blade and the modified untwisted design is virtually guaranteed to have a lower stress level.

CFD results of relative Mach number for this single-stage turbine are shown in Figure 9. Note that the modified blade shape is the rotor (downstream blade), while the upstream stator on the left has been unchanged in this study.

Once again, the penalty paid for this geometric change is surprisingly small, about one-quarter of one percent in overall stage efficiency. The mass flow change at the fixed pressure ratio is less than one-tenth of one percent (Figure 10).

Whether or not such a change makes sense from a product value point of view depends on the circumstances. Most likely, a one-quarter percent drop in efficiency would be unacceptable for a high-performance aircraft engine. On the other hand, a small-scale turbine in a highly price-competitive market could certainly benefit from reduced manufacturing costs.

Note: All figures in this article are from Concepts NREC's Agile Engineering Design System.

References

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