Turbo Expanders: Dwelling on Efficiency

By P. Westermann P.E.

Since the early 1960s, turbo expanders have been increasingly used in hydrocarbon gas processing plants. The other primary market application of turbo expanders is for the production of industrial gases, such as oxygen. The production of industrial gases might not typically be recognized as essential to hydrocarbon engineering. However, reducing the production costs of industrial gases is fundamental to the viability of efficient and environmentally responsible global energy solutions, such as oxygen-based synthesis gas production and the liquefaction of natural gas using nitrogen as a refrigerant. The turbo expander efficiency gains achieved in industrial gas turbo expanders can also benefit hydrocarbon gas process plants. As aerodynamic efficiency improvements drive expanders to thinner, longer blades, strength and natural frequency considerations become critical in the design of turboexpander rotors. Reliable use of a higher efficiency turbine design is feasible by restricting specific ranges of constant machine speed during the startup.

Separating Efficiently

Today's cryogenic air separation plant uses a turboexpander to produce the low-temperature (cryogenic) refrigeration for the fractional distillation and liquefaction of air (-196 °C). A 100% efficient (isentropic) expansion extracts the maximum possible energy from the gas as the pressure is dropped, typically through a radial in-flow turbine. Power extracted from the turbine gas stream usually drives an integral-shaft booster compressor to "pre-boost" the turbine. The booster compressor is specifically sized to load the turbine at the optimum speed at the design process conditions.

Electricity is the chief cost of production in the industry gas industry. The amount of electricity used per Nm3 of gas produced is basically a function of the thermodynamic efficiencies of the compression and expansion of gas. Therefore, improving the compressor and turbine efficiencies has been paramount to directly reducing the cost of the product; i.e., the oxygen, nitrogen, and argon gas. Studies commonly reveal that, due to the energy invested to produce cryogenic temperatures, a point increase in turbine efficiency is economically equivalent to four or five points in the booster compressor efficiency.

Booster compressors have process conditions similar to many commercial radial out-flow centrifugal compressors. Therefore, numerous tools and resources are available for improving the compressor aerodynamic and mechanical design. On the other hand, the expander turbine's high pressure ratio and cryogenic process conditions pose rather unique challenges in the optimization of both efficiency and mechanical reliability.

The Art Of Design

For over forty years, ACD LLC has strived to continuously improve the efficiency and mechanical reliability of cryogenic turbo expanders. The design is a synergy of streamline analysis programs, Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), 5-axis machining capability, a framework of field-proven designs, and an invaluable database of cryogenic performance tests. Using these tools, ACD is able to provide the highest efficiency possible while maintaining reliability and unit life.

In addition to evaluating the aerodynamic performance effects of geometrical modifications, CFD is an indispensible tool for analyzing the interaction between the inlet guide vanes and the turbine wheel blades. The resulting fluctuating pressure field for a high pressure ratio turbine is shown in Figure 1. Although the amplitude of the excitation force is relatively small at operating speeds, the particular number of nozzles and blades can generate an excitation that matches the natural frequencies of the turbine wheel.

Figures 2 and 3 show natural frequency mode shapes for a blade and disk mode, respectively, which were determined by Finite Element Analysis (FEA). These natural frequency mode shapes are relatively simple and easily analyzed. There are numerous other natural frequency modes that must be reconciled while optimizing the aerodynamic design within the required operating speed range. A shrouded turbine wheel may be used to optimize, eliminate, and move natural frequencies out of the operating speed range. The shrouded turbine wheel is typically

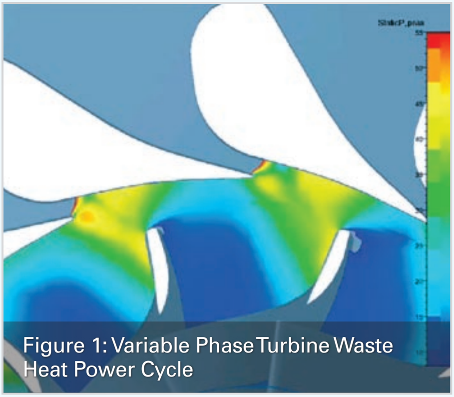

Figure 1: Variable Phase Turbine Waste Heat Power Cycle

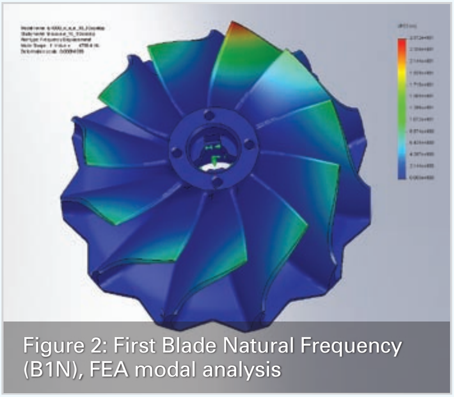

Figure 2: First Blade Natural Frequency (B1N), FEA modal analysis

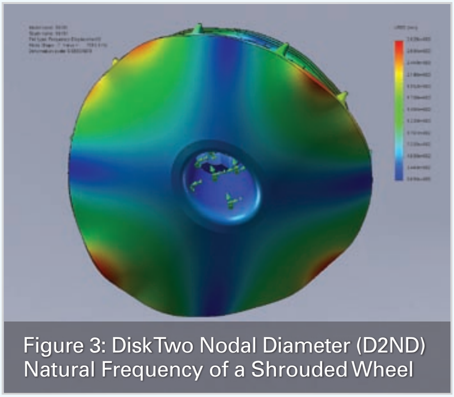

Figure 3: Disk Two Nodal Diameter (D2ND) Natural Frequency of a Shrouded Wheel

Figure 4: Single Piece 5-Axis Machining of Shrouded Expander Wheel

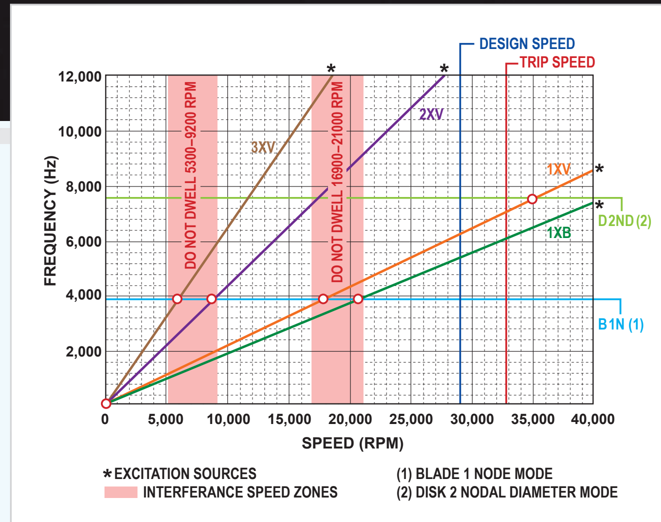

Figure 5: Campbell Diagram

5-axis machined from a single-piece forged aluminum biscuit as shown in Figure 4. Shrouded wheels, however, are a significant cost increase and not always required for acceptable operating ranges.

The excitation of potentially damaging wheel natural frequencies and their source of excitation are determined using a Campbell[1] diagram. The vertical axis of the Campbell diagram is for the wheel natural frequency and the horizontal axis is for the rotor speed. The problematic turbine wheel natural frequencies are plotted as horizontal lines. Excitation sources are a function of rotational speed, such as multiples of the number of vanes and blades. These diagonal lines intersect the wheel natural frequencies at the operating speeds that must be avoided. These intersections are referred to as "interference speeds." A typical Campbell diagram is shown in Figure 5. The excitation sources are multiples of the number of inlet guide vanes (1xV, 2xV, 3xV) and the number of wheel blades (1xB). Dwelling at a constant speed within the two speed ranges, identified as "Do-Not-Dwell" zones, will cause resonance and rapid accumulation of damaging fatigue cycles. For example, at a 6,000 Hz natural frequency, a million fatigue cycles accumulate in less than three minutes.

Constant speed operation at interference speeds causes an essentially unbounded amplification of the excitation stresses in the turbine wheel. The crystalline structures of metals possess virtually no internal damping to dissipate the excitation energy. When the frequency and shape of the excitation match that of the natural frequency, the condition is referred to as resonance[2] . The more closely the frequency and shape of the excitation directly match that of the natural frequency, the higher the amplification factor. For this reason, the lower order natural frequency mode shapes are easily excited by low number multiples of the number of vanes and blades.

Numerous test methods allow verification of the natural frequencies and mode shape of a turbine wheel. The simplest and least comprehensive method consists of mounting the wheel on a shaker-table with pickups to measure the response of the blades and wheel. Typically, the response spectrum exhibits the characteristic high amplification factor and the narrow frequency band of the undamped natural frequency resonance[3] .

Ramping Up To Efficiency

After a considerable amount of engineering and design iterations, an aerodynamically efficient turbine design will likely still have some interference speeds between zero and the trip speed. Fortunately, resonance can be minimized by accelerating or decelerating through these speed zones. For a turbine designed with a conservative speed margin from the design speed, the low inertia rotor allows the turboexpander to quickly pass through the interference speeds to prevent damaging resonance.

If the process requires unrestricted operating speeds from zero to the trip speed, i.e., operation at speeds far from the specified design and off-design cases), there are engineering solutions to protect the turbine's mechanical integrity. The wheel's natural frequencies can be increased by thickening the blades and modifying the wheel's disk and hub profile. This compromise, however, results in a less efficient aerodynamic design.

As the demands on industrial gas turbo expanders rise, cryogenic equipment manufacturers must meet the design challenge. Aerodynamic efficiency improvements can be mechanically reliable if careful study of excitation and natural frequency is performed. Observance of "Do-Not-Dwell" zones offers additional room for turboexpander advances.

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