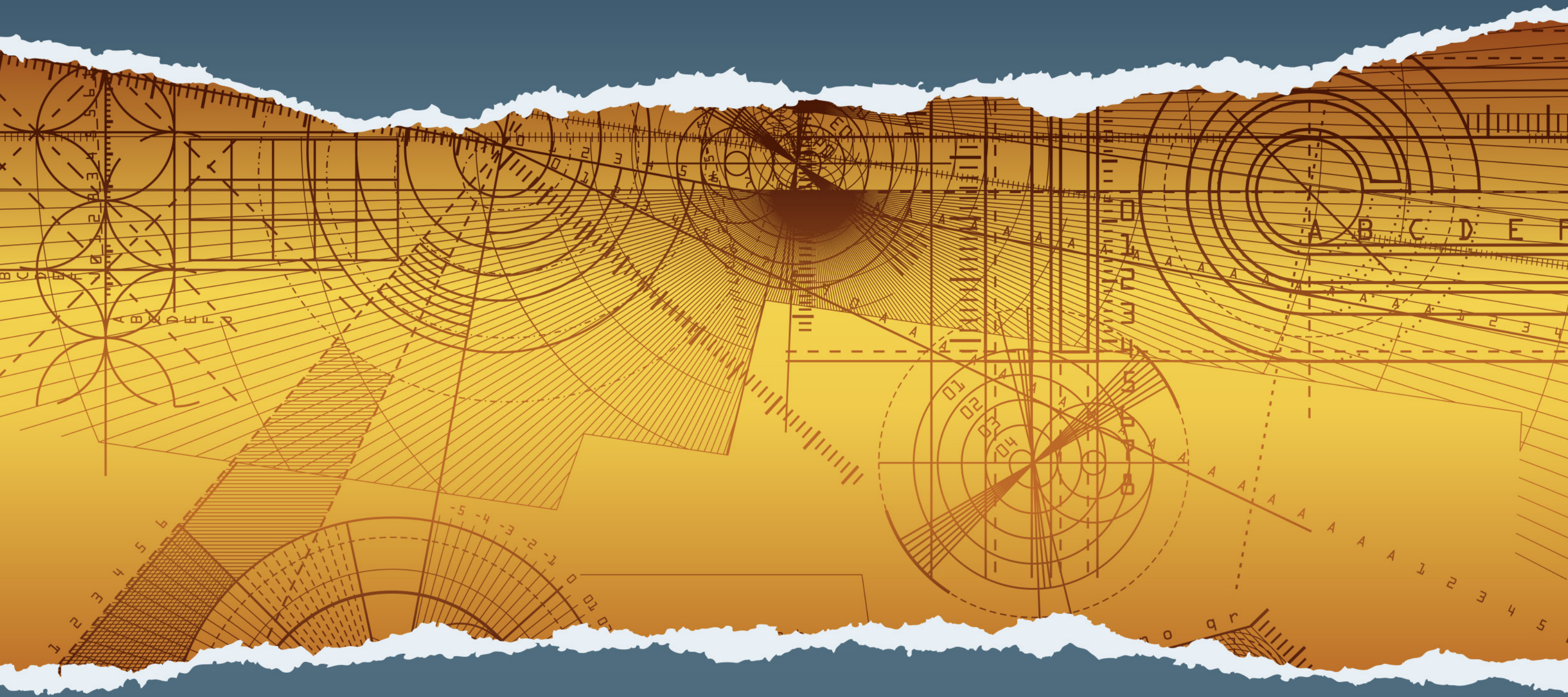

ENGINEERING A NEW GENERATION OF ROTOR

Justin Fleming and Paul Wells, Mitsubishi Heavy Industries Compressor International Corp., USA, explain the choice faced by hydrocarbon processing plant owners between replacing or upgrading rotors in centrifugal compressors and the best way to reduce maintenance expenditure over the long-term.

The heart of every piece of turbomachinery is its rotor; the rotating element inside the machine that delivers to or absorbs energy from the working fluid. In the hydrocarbon sector of the turbomachinery world, these machines are usually centrifugal compressors and pumps, which deliver power to the gas or fluid. Because of the integral nature of these rotors to downstream operations, historically speaking the overwhelming majority of a hydrocarbon processing plant owner's centrifugal compressor maintenance expenditure goes towards rotor repair.

There are many different phenomena and environmental factors that impact rotors, giving rise to various failure modes. Considering these rotors are large pieces of metal rotating at high revolutions per minute (RPM), a significant degree of stress is developed within the rotor, which inherently carries potential for catastrophic failures. In some hydrocarbon processes, rotors operate in harsh chemical

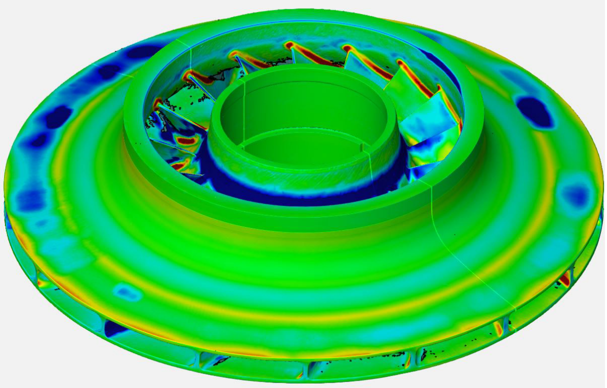

Figure 1. 3D model vs 3D scan – surface deviations.

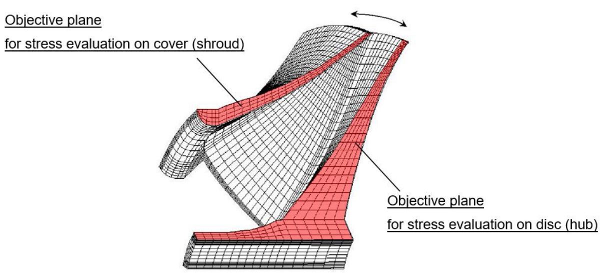

Figure 2. Cover and disc mesh with objective planes for stress analysis.

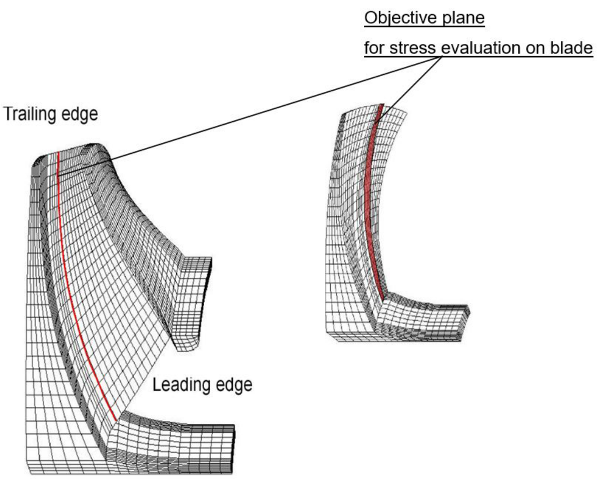

Figure 3. Impeller blade mesh with objective planes for stress analysis.

environments, which when coupled with the high stresses from rotation, can cause a failure through a mechanism known as stress corrosion cracking (SCC).

The true cost of working with ageing infrastructure

Currently, there are few new hydrocarbon processing plants being constructed in the US, therefore most plants are antiquated, operating with older technologies, machines, and processes which can, and often do, experience mechanical problems. With reduced maintenance budgets, operators are forced to continue replacing failed parts and enduring mechanical reliability issues and/or machine failures, turnaround after turnaround. Dependent on the parts replaced, this approach can be quite costly.

If machinery vibrations reach high enough levels, operators are forced to shut down the machine. When these critical pieces of machinery go offline, opportunity in production and generating potential revenue go with them. Often times, with a unit shut down due to high vibration, the machine's rotor needs to be removed from service and replaced with a spare rotor, which equates to more costs to the customer. Some operators lose more than US$1 million/day in production costs. The costs to an outside field service provider to perform the rotor change out scope could easily surpass US$1 million for a 14-day duration. It is easy to see that having these costs pile up, turnaround after turnaround, can be quite a burden on an end user. If these antiquated parts are not upgraded, but are continually replaced each time, the end user could face expenditures upwards of US$60 million over the designed lifetime of the machine.

When a plant operator makes the decision to shut down, it is always a huge financial commitment that must be planned according to market conditions and the overall profitability of the company. Turnarounds are usually planned to occur every four to five years, and many times problems like a failed rotor are only recognised once a turnaround is in progress. In these scenarios, operators are taken by surprise, and are left with no other option than to rely on their spare rotor and send the failed rotor off to be repaired or replaced. This 'boom and bust' cycle can be eliminated if thorough root cause investigation and engineering design expertise can be leveraged in an upgrade activity. The price associated with the upgrade pales in comparison to the potential costs over the lifetime of the machine.

Case study: air compressor rotor failure due to liquid ingress

Mitsubishi Heavy Industries Compressor International Corp. (MCO-I) has two major businesses, new unit and customer service. The new unit business is solely focused on selling new compressors into the market whereas the Customer Service Business (CSB) deals with all other aspects of the compressor after it ships from MCO-I. This includes redesigns, upgrades, overhauls, field service, shop repair services, and technical support. MCO-I's well-established relationship with a major downstream customer of the new unit business led to an opportunity with that customer in the service business. MCO-I CSB was invited to bid on manufacturing a replicated, but upgraded, rotor to solve a recurring failure in a rotor in air service.

Designing an improved rotor

The customer had a history of impeller failure due to SCC arising from liquid coolant leaking into the compressor from the process intercoolers. MCO-I was requested to reverse engineer the existing rotor and to design a new replacement rotor to be used within the existing casing and internals. The original rotor's assembly type, impeller method of

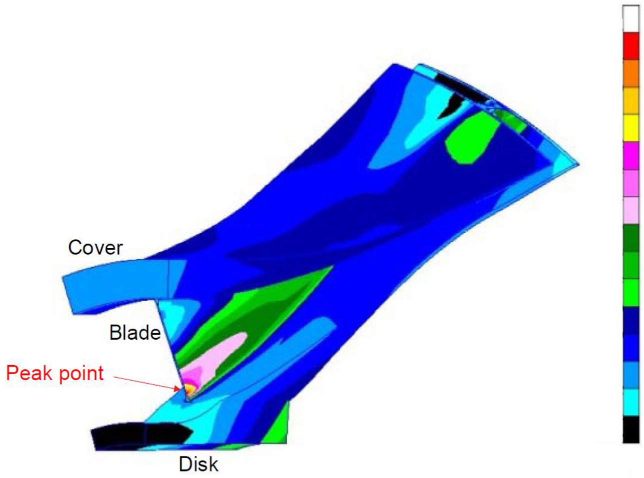

Figure 4. Stress map of impeller blade area.

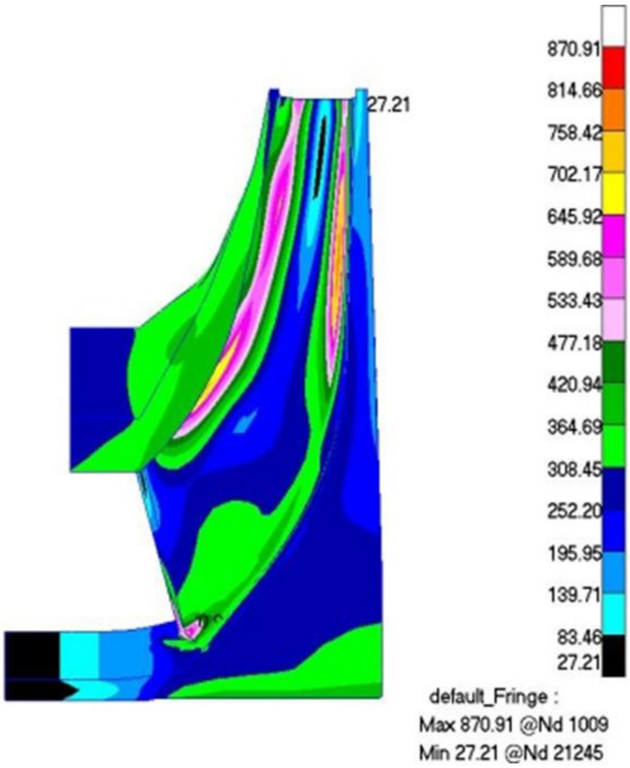

Figure 5. Finite element analysis stress analysis map.

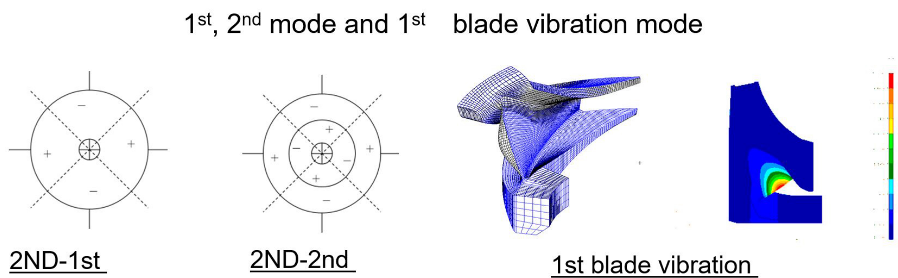

Figure 6. Natural frequency mode shapes and vibratory stress plot.

construction, and metallurgy were studied. Given the original design, MCO-I developed a new, improved rotor in accordance with the latest design and manufacturing standards, offering advancements over the original design.

The compressor increases air pressure from its inlet condition to some higher-pressure point required by the process. Most hydrocarbon process compressors are designed for very specific process conditions, i.e. temperature, pressure, flow rate, humidity, molecular weight, etc. In this particular instance, the customer's compressor was experiencing corrosive liquid ingress, which was degrading the health of the rotor. Corrosive agent will naturally attack low-alloyed steels over time, and when coupled with the high stresses generated while operating, a conducive condition for stress corrosion failures is formed.

This customer experienced multiple failures in its compressor since the unit was originally commissioned in the 1970s. Every time the rotor was changed out, another field failure occurred some years later, and the cycle continued. It stands to reason that if the compressor was designed to only move air, then the process conditions should be rectified to remove the liquid phase from the compressor. However, this is a significant undertaking, involving a huge amount of capital investment, lost revenue in downtime and lost production opportunity. With limited support from the rotor's original equipment manufacturer (OEM), consequently this customer was forced to keep replacing the damaged rotor with its spare at every turnaround opportunity (every four or five years) and purchase replacement parts as required.

Ultimately, the customer was not satisfied with the solutions posed by the OEM and so elected to source an upgraded rotor through a different supplier.

A new approach

The customer asked a variety of suppliers to provide a bid for a replica rotor, requesting a material upgrade option as a solution to the failure issues from the liquid ingress. MCO-I's approach was to offer not only a replicated rotor to match the performance of the original rotor, but upgraded in both material of construction and manufacturing methods in accordance with present MCO-I best practices. Since the original rotor was manufactured in the 1970s, technologies, manufacturing processes and standards have improved substantially. After the rotor components were received by MCO-I, each component was carefully inspected and 3D models were generated from the original geometries. The latest MHI design and manufacturing concepts were then applied to the 3D models to create the improved rotor. The customer was ultimately offered an upgraded replacement rotor that was no longer a replica of its original rotor, but fully upgraded in regards to corrosion resistance and reliability. A technical report on the design was produced and addressed with the customer, who eventually elected to move forward with the MCO-I upgraded rotor design.

Identifying upgrades

Materials

SCC is a common problem in hydrocarbon processes and occurs when a material susceptible to SCC combines with a high level of stress and a corrosive environment. If just one of these elements is changed, SCC will cease to be a problem. It was found that the base metal of the impellers as originally designed was susceptible to SCC. The compressor was originally designed to be in a non-corrosive environment: air. Given the nature of the failure, and the metallurgical reports performed by others during previous failures, MCO-I recommended a material that has superior corrosion resistance and strength compared to the original base material. A martensitic precipitation-hardening stainless steel was chosen for the final design, which also was an upgrade to the rotor's manufacturability.

Manufacturing

It was observed that the original manufacturing methods were quite antiquated. In its original manufacture, there was an unavoidable slightly uneven distribution of impeller blades relative to each other. Given the advancements in manufacturing and 50 years of technological improvements later, position accuracy and control can ensure even distribution of impeller blades around the disc, increasing even flow characteristics around the impeller and leading to higher stage efficiency.

Mechanical reliability

One of the most important considerations for a plant engineer is mechanical reliability, which encompasses vibration, metal temperatures, etc. If a machine is performing well, but is exhibiting elevated vibration, it could be an indicator that something is internally wrong in the machine. If left unabated, these elevated vibrations could exacerbate into a failure over time.

This rotor's upgraded design is estimated by its rotor dynamic analysis to exhibit extremely low vibration levels throughout its speed range with a variety of unbalance cases compared to the relevant industry/design standards. The material upgrade and the high mechanical reliability performance are just a few of the reasons the customer decided to choose MCO-I's upgraded rotor design.

Generating value through upgrades

The rotor design was changed to ensure a well-performing rotor over its operating range from both a mechanical and metallurgical perspective.

The situation encountered by the customer described in this article is not an isolated event; it is in fact an industry-wide issue relevant to everybody who works with turbomachinery. The upgraded rotor discussed in this article provides an example of how it is possible to find innovative solutions to extremely complex problems within the hydrocarbon industry.