

## Nursing an Unreliable Boiler Feed Pump Back to Health

William Marscher and Eric Olson, Mechanical Solutions, Inc., Whippany, NJ

An electric power generating plant located in the Northeastern U.S. had suffered through chronic boiler feed pump failures for eight years. The plant's difficulties had begun once the particular generating unit that was involved was switched from base-load to modulated-load operation. In fact, the longest period of operation that the pump had been able to log between major rotor element overhauls was only five months.

The pump OEM had been contracted to resolve the problem under the condition that any solution would be paid for only after it was demonstrated to be successful. Based on detailed vibration signature testing and subsequent hydraulic analysis, the OEM decided that the internals of the pump were not well enough matched to part-load operation. Consequently, the pump OEM had proposed replacing the rotor element with a new custom-engineered design.

Although the pump problem displayed some of the characteristics of a critical speed issue, both the OEM and the plant management were confident that this could not be the source of the trouble. The reason was because previous carefully performed rotor dynamics analyses had indicated that the factor of safety between running speed and the predicted rotor critical speeds exceeded a factor of two. However, the financial risk that was associated with relying solely on the hydraulic and the rotor dynamic analyses was considerable. The combined financial exposure to the plant's owners was approximately \$350,000. Because of this significant expense, MSI engineers were invited to provide the generating plant's management with a "third-party" opinion about the source of the boiler feed pump's repeated failures and how to resolve them efficiently.

To assess the cause of the chronic machinery malfunctions, MSI performed experimental modal evaluations of the boiler feed pump (Figure 1) using its proprietary time-averaged pulse (TAP™) technique. TAP incorporated time-averaging statistics to improve the signal-to-noise ratio rapidly under operating conditions. Time averaging reduced the amplitude ratio of the random naturally excited vibration versus the impact-coherent vibration during signal processing. This greatly emphasized the effect of the "bump" while the machine continued normal operation.

The critical speeds of all rotating machinery can be determined under operating conditions with this technique so that impact or "bump" testing for natural frequencies can be conducted without shutting down the machines. With TAP, an impact or bump test properly accounts for the boundary conditions that are set up by the operating condition. This feature

is especially advantageous for multistage, high-energy, variable-speed pumps, where the rotor-dynamic characteristics are speed and load dependent. Moreover, an existing or potential problem can be identified without any downtime of the tested pump or nearby equipment; this can provide a very important advantage in a broad range of applications and industries.

TAP is superior to "waterfall" or "cascade" plotting, the most common method of determining critical speeds. This consists of a succession of spectra as the rotating machine runs up to full speed or coasts down between the operating and static conditions. The TAP technique eliminates the problems that often lead to incorrect conclusions being drawn from a cascade plot. These may include:

- The dynamic coefficients of bearings and annular seals (Lomakin effect) can be substantially different between the transients of start-up and shut-down versus steady-state operating condition.
- The excitation source and magnitude is unknown. Therefore, the frequency response cannot be quantified in terms of the damping at each natural frequency to determine if it is critical or not.

The experimental modal testing performed while the machine operated quickly established that one of the rotor-critical speeds of the pump actually existed far from where it had been predicted to be. That particular critical speed had dropped into the pump's running speed range of 4,900-5,750 RPM. The unintended shift in critical speed appeared to be the sole cause of the boiler feed pump's reliability problems (see Figure 2).

Analyses were then conducted to help identify the source of the shift in the rotor-critical speed. A number of "what-if" iterations were performed using the OEM's rotor-dynamic computer model (Figure 3). These were verified with a similar model that was constructed by MSI engineers using the ROMAC (rotating machinery and controls) software code from the University of Virginia's ROMAC Industrial Research Program. The analytical results from both models consistently showed that the particular rotor natural frequency value and the rotor mode deflection shape could best be explained by improper operation of the pump's coupling end bearing.

Therefore, the coupling end bearing of the boiler feed pump was removed and was thoroughly inspected. Inspection revealed that the end bearing had a critical clearance that deviated far from the designed value. Ultimately, the discrepancy in the clearance was found to have been caused by a drafting error on the end bearing's manufacturing drawing, meaning that the mistake was carried over each time that the end bearing

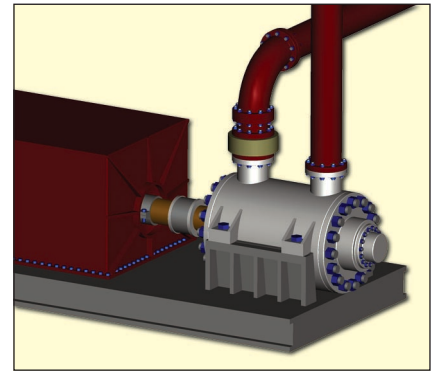


Figure 1. Steam-turbine-driven, barrel-type, main boiler feed pump.

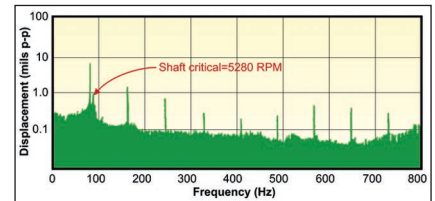


Figure 2. The 0-800 Hz (0-48000 RPM) vibration spectrum of boiler feed pump operating at 4900 RPM before any equipment modifications.

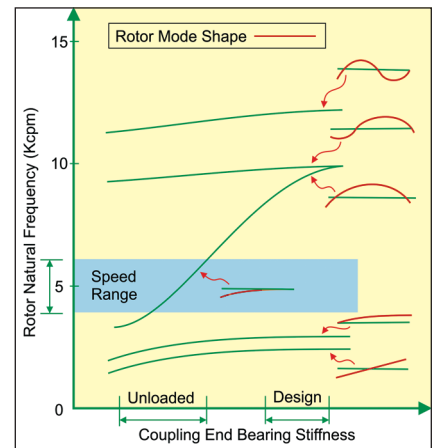


Figure 3. Results of "what-if" rotor dynamic analysis of boiler feed pump.

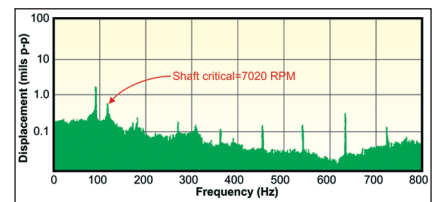


Figure 4. The 0-800 Hz (0-48000 RPM) vibration spectrum of the boiler feed pump operating at 5750 RPM after pump's end bearing was modified.

was repaired or was replaced. Installing a correctly constructed end bearing shifted critical speed of the rotor upward to very near its expected nominal value (Figure 4) and well out of the pump's operating speed range. The boiler feed pump prone to failure has since run for more than three years without need for an overhaul. Identification of the root cause of the pump failures eliminated considerable expense.

For more information on this case history or consulting services offered by Mechanical Solutions, please visit [www.mechsols.com](http://www.mechsols.com).

# Centrifugal Compressors – Past, Present and Future

Michael J. Lucas and George M. Mankos

Ingersoll Rand Industrial Technologies, Davidson, North Carolina

Founded in 1905, Ingersoll Rand has been building air compressors for more than 100 years. The history of Ingersoll Rand traces back to original patents for rock drills, which were powered by steam and soon afterward by compressed air. Ingersoll Rand products and tools have been used on some of the world's largest projects, including the Panama Canal, the Hoover Dam, the New York subway tunnels, airports, and more recently the world's largest hydroelectric project, the Three Gorges Dam project in China.

Over the years, Ingersoll Rand has designed and built axial flow compressors, reciprocating compressors, screw compressors, and centrifugal compressors. Some of these compressors have been recognized as the world's largest air compressors ever built. These compressors are used for many purposes such as transporting natural gas, drilling, producing food and beverages, pharmaceuticals, and manufacturing air tools. Air compressors play an important part in the operation of factories, and for this reason, Ingersoll Rand customers depend on these machines to run continuously without interruption.

## How Does It Work?

A compressor is a device that delivers a gas at a higher pressure than naturally exists in the atmosphere. Air is a compact and powerful medium used to transmit power that can be used for a variety of purposes. Typical uses include but are not limited to power air tools, pneumatic cylinder actuation, hoists and lifts, transportation medium, fermentation, and combustion.

Air can be compressed using two basic methods – positive displacement and dynamic compression. In the positive displacement method, air is trapped in a closed space and then reduced in volume to increase the pressure. Typical positive displacement compressors are reciprocating piston, rotary screw, scroll, lobe, hook and claw, and sliding vane.

Dynamic compressors are rotary flow machines that rapidly accelerate the gas (air) through rotating elements. Typical dynamic compressors are centrifugal, axial, and mixed flow.

## Why Centrifugal?

Centrifugal compressor technology has been around for more than 100 years but has been limited mostly to process applications due to initial cost. It is the preferred method of compression when the highest reliability and absolute best air quality is required. Centrifugal compressors became popular during the 1960s with the advent of the integrally geared design. The integrally geared design utilizes compression elements placed around a rotating bull gear allowing for the pressure to be multiplied

independently of the previous stage. Ingersoll Rand was the first to pioneer a fully packaged integrally geared design. Only a few companies at the time possessed the technological expertise to create such a machine. Since its introduction, more than 20,000 Centacs have been shipped and installed world-wide.

Why do customers prefer centrifugal to other compressor technologies? The first reason is dependable long life due in part to an inherently simple, rugged design. There are only three moving parts: a bull gear and two rotating impeller assemblies. Fewer moving parts means less opportunity for something to fail. Moreover, centrifugal compressors are not subject to the an-

nual overhaul requirements customary with other technologies. Ultimately, centrifugals ensure greater availability for production use and lower maintenance costs.

The second reason is the dynamic compression process itself. In dynamic compression, the air is compressed by converting velocity energy imparted by the impeller to pressure energy without any contact between mechanical components. The design ensures 100% oil- and particle-free air. It is not uncommon for a centrifugal compressor to run at least 7 years without needing to be overhauled. Unlike positive displacement technology, compression components do not wear.

The third reason is that centrifugals maximize energy efficiency by using multiple stages in conjunction with constant pressure control operation. Three stages of compression improve efficiency by dividing work evenly across each stage. Lower

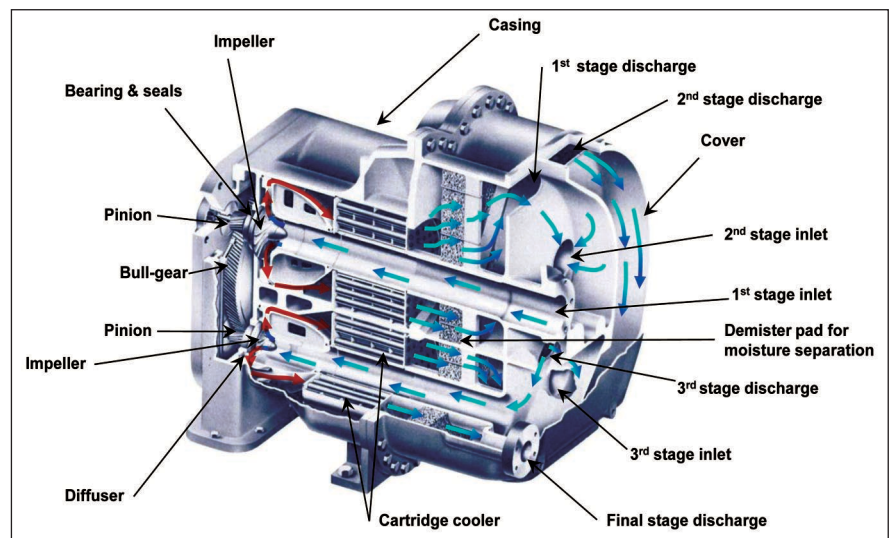


Figure 1. Original 1967 Centac.

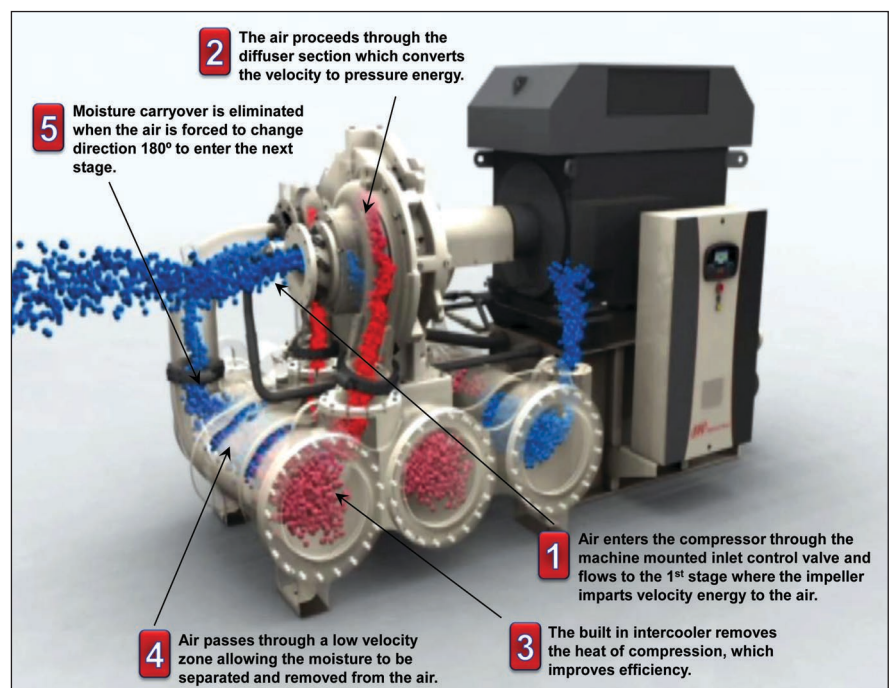


Figure 2. Essential features of compressor configuration.



compression ratios are borne by each stage, resulting in lower operating temperatures, and ensuring that cooler air moves from one stage to the next. The compressor produces air more efficiently, and requires less mechanical power and less energy.

In 1967, Ingersoll Rand released the first fully integrated centrifugal compressor. This line of compressors was referred to in the industry as the “centac” product, and has been in production for more than 40 years. A centac is a constant-pressure, variable-volume flow machine unlike reciprocating or screw compressors, which are fixed-volume flow machines. Since dynamic compressors are designed for a pressure, they vary the flow to meet the demand. Therefore, there is no need to operate in a pressure band with a centrifugal. Volumetric machines often operate in a pressure band set artificially higher than the required system pressure; this differential wastes energy, since the compressor overshoots the required delivery pressure.

The fourth reason is space. No other technology can offer the space-saving at-

tributes of a centrifugal compressor. The ultracompact, space-saving design lends itself well to flexibility. A centrifugal unit is capable of delivering twice the flow for the same amount of floor space as opposed to competing technologies.

Customers demand reliability. Customers depend on a mature product that has been validated at Ingersoll Rand test facilities. Customers prefer not to stock replacement parts (even key parts) to maintain continuous operations. Instead, customers depend on Ingersoll Rand’s customer service and support worldwide to keep them operational. One of the features engineers strive for compressor design is minimizing part count. The fewer the parts, the more reliable the product becomes.

Another approach to ensure reliability is by testing and continuous monitoring. Testing and validation is comprised of operational tests that address specific areas such as:

- Aerodynamics performance
  - Impeller geometry – validation of models generated using computational fluid dy-

namics to verify flow, pressure, turndown range and efficiency

- Stage matching
- Impeller and diffuser combinations and optimization
- Heat exchanger
  - Cooling water to control air temperature performance
  - Condensation removal efficiency
- Rotor dynamic performance
  - Stability (critical speeds and resonances)
  - Unbalanced response and coast down
  - Vane passing frequencies and other high frequency drivers
- Mechanical testing
  - Bearing stability and damping
  - Vibrations of compressor components
  - Oil and package subsystem reliability and performance
- Acoustic performance.

Overall system validation also includes a separate set of tests conducted to simulate operation of the compressor in an environment that approximates a typical real-world compressor. This includes a rigorous duty cycle of starting and stopping as well as load/unload operation at a variety of set pressures using cycling valves.

Recently, Ingersoll Rand has launched a new line of centrifugal compressors known as the Centac C-Series. This compressor represents a fourth-generation of centrifugal compressor platforms that will replace current models and form the core of a family of innovative products. C1000 is unique for many reasons – it represents a major departure from the traditional design, development, and manufacturing approach of the past.

The changes began early during the development phase. During initial framing of the C1000, Ingersoll Rand implemented a new tool called Outcome Driven Innovation™. The ODI process analyzes the customer’s expectation of performance outcomes. In the past, product development was driven by framing requirements from an internal point of view and was limited in understanding customer expectations. The new

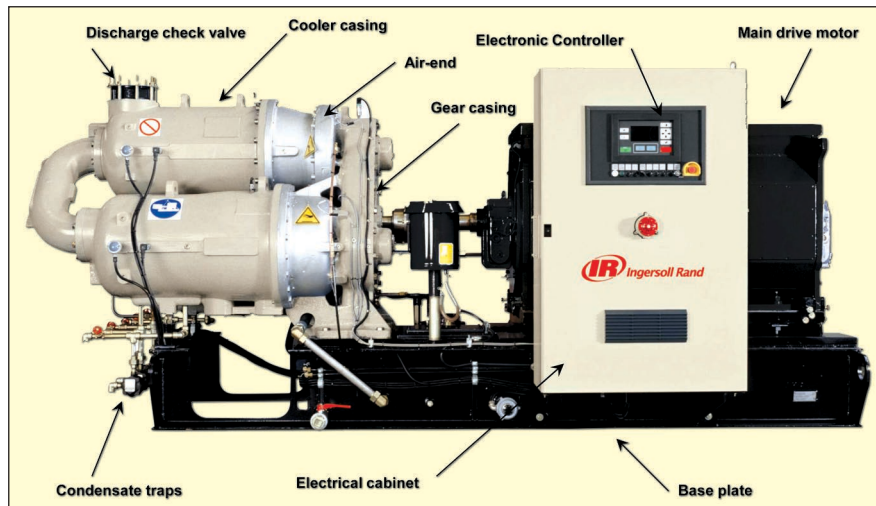


Figure 3. Legacy centrifugal compressor design (C950).

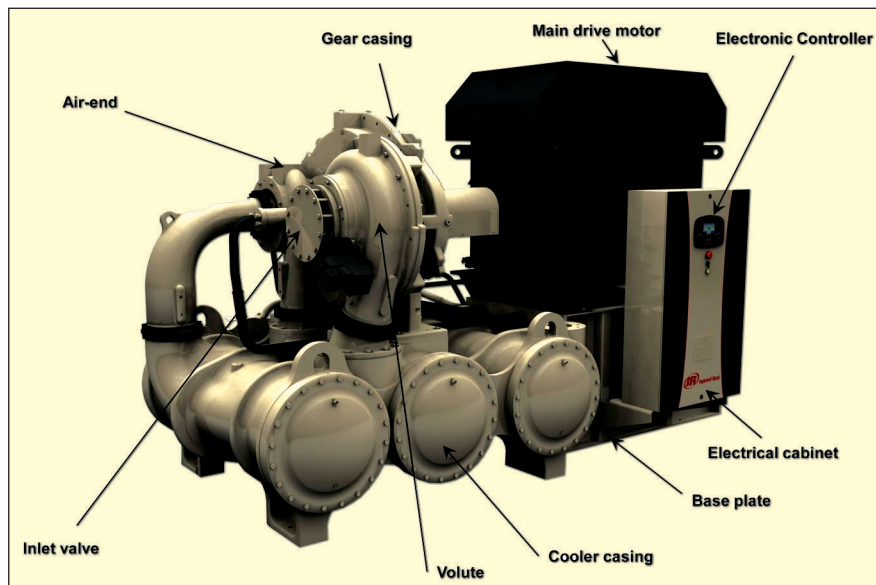


Figure 4. New compressor platform design (C1000).

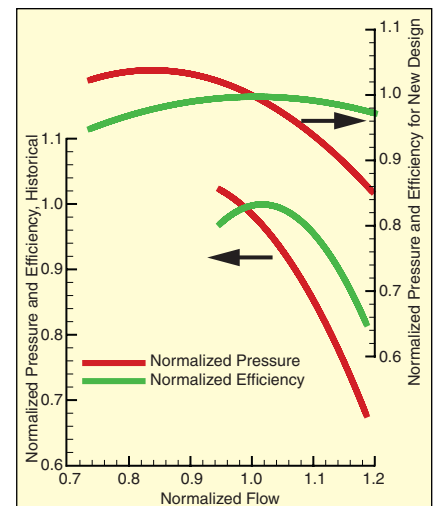


Figure 5. Normalized pressure and efficiency versus flow.

process focuses on how customers measure success when executing tasks they are trying to achieve with the product. Using the “outcomes” as inputs to the development process eliminates much of the variability in product framing.

The C1000 is the first of a line of compressors currently under design at Ingersoll Rand. It has the following performance specifications:

- 800-1300 kW (1100-1750 HP)
- Two or three stages of compression
- Pressures from 3.5-10.3 barg (50-150 psig)
- Air/gas flow capacities 127-212 m<sup>3</sup> /min (4500-7500 cfm)
- Water cooled – water in tube coolers
- 50 or 60 Hz
- 4160-10,000 volts

The new platform has many distinctive features that separate the current design (Figure 4) from its predecessors (Figure 3). For example, the compressor has a new system of coolers. It is three-stage machine and

produces approximately 7000 cfm of air.

Centrifugal compressors are designed for peak efficiency at a specific operating point. However, the new design approach also considers off-peak performance, as many applications have demand characteristics that necessitate the maintenance of good efficiency beyond the design point. The aerodynamic design of the C1000 compressor was produced by state-of-the-art software and modeling to ensure a desired performance of range and efficiency.

The aerodynamic strategy for the C1000 has shifted from designing the stages to operate at a high efficiency over a range of flow conditions. The compressor range between stall and choke are shown in Figure 5. The idea behind the C1000 is to have relatively high efficiency and flow range for turndown. This means that the stage curve has to have a broader range between stall and choke. This is illustrated by the red (pressure ratio) and green (efficiency) curves. To do this, the aerodynamic components have to

be designed with this in mind, specifically low-solidity diffusers that are well matched to volutes and impeller tip conditions.

Mechanical subsystems have to be designed to be robust and reliable. Bearings were designed for stability over a range of drive speeds, while offering very low friction losses. Gears are designed according to AGMA standards to meet requirements for long life and durability. Coolers are a high-maintenance item when water quality is not optimal. Compressed air cooling systems are designed to be maintenance friendly using a mechanically cleanable tubular design (Figure 4). The coolers can be cleaned in place for quick turnaround. The lubrication system and package are designed with a small footprint to ensure minimal use of factory space and for compact overseas container shipment.

Ingersoll Rand continues to innovate after more than 100 years in the compressed air industry. For more information, please visit [www.ingersollrandproducts.com](http://www.ingersollrandproducts.com).