How Plant Rotating Equipment Resonance Issues Can Affect Reliability and Uptime

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Detecting the cause of machinery vibration can sometimes prove elusive. If you have had your switchgear fail due to exciter bolt tension[1], or have ever sought to diagnose high vibration levels that have appeared with no apparent cause, or come and go in seemingly random intervals, or have always exceeded their twin machine that is "the same", you may have encountered resonance. If you have pushed a child on a swing, you have certainly experienced resonance first-hand. The child swings at a natural frequency, and you continue to add a small amount of force at each cycle, increasing the height, or amplitude, of the swing. The same holds true for rotating machinery, which we will explore in detail below.

Nuclear power plants are special and unique, particularly with regard to baseload providers. Nuclear capacity factor, or power produced vs. capacity, far exceeds other sources of baseload generation, sometimes by a factor of two (Figure 1). In an effort to stay competitive with fossil fuels, there is need for even higher levels of uptime, particularly as refueling outages shorten and forced outages become intolerable. With this reduction in downtime, there is less opportunity to chase elusive resonance-based vibration problems with a trial-and-error approach, making it increasingly important to understand what resonance is, recognize how to diagnose it, and know the tools at your disposal to remedy it.

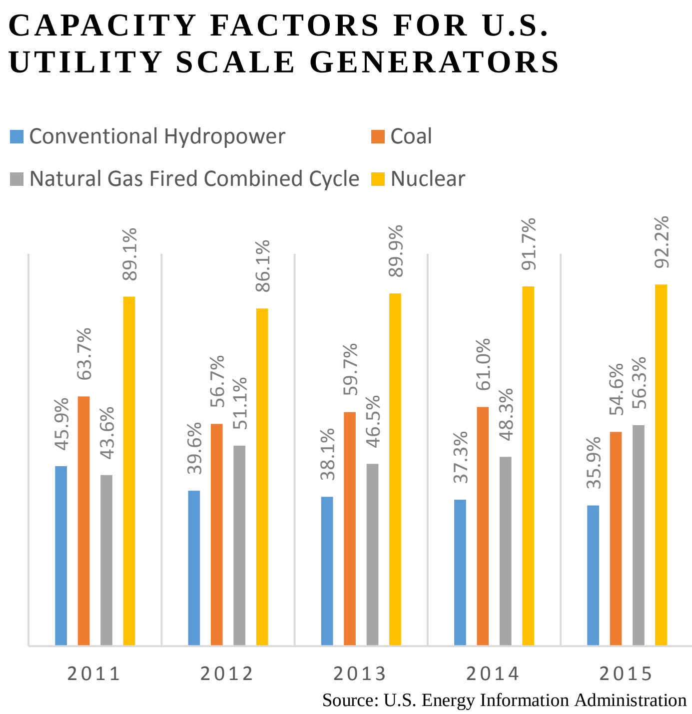

Figure 1. *Nuclear power's capacity factor far exceeds other major sources of grid power, and is continuing to push even higher*

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[1] For a fascinating case study on resonance, please visit: http://www.mechsol.com/case-study/resonant-room-acoustics-exciting-destructive-vibration-at-a-nuclear-power-plant/

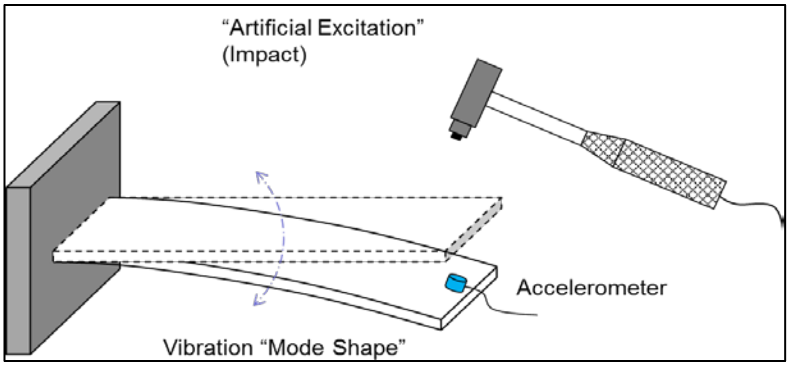

Figure 2. *Impacting an object will cause it to vibrate at its natural frequency according to its mode shape*

In order to understand resonance, it is essential to first understand natural frequency. Natural frequency is the frequency, or number of cycles per unit of time, at which an object will vibrate when excited by an external force (Figure 2). For example, a bell will ring (vibrate) at a certain pitch (frequency) when rung (excited by an external force). These ringing frequencies are dependent on the square-root of the ratio between the stiffness and mass of the system (i.e. structure or rotor). Changing these variables will cause the natural frequency to change as well. The same holds true for all objects, though thankfully most do not vibrate in the audible range of frequencies. Components of rotating machinery, including the rotor, casing, piping and supporting structure, all have natural frequencies. When damaging vibration does occur, it usually only involves the lower range of a system's natural frequencies.

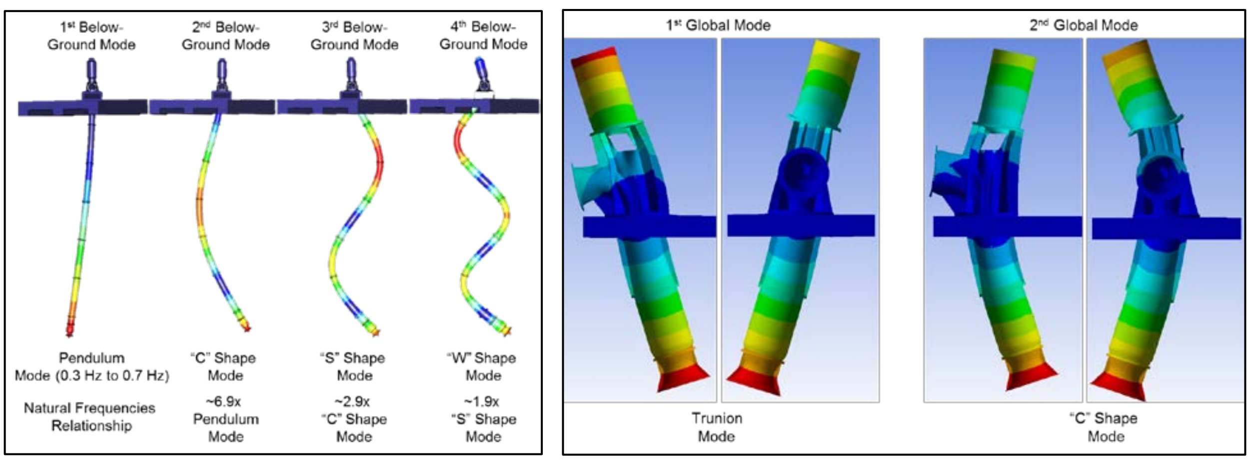

Figure 3. *Mode shapes describe the pattern of vibration movement. Their names are often descriptive of the characteristics of motion.*

The object's oscillation will move according to a "mode shape", or pattern of back and forth motion. These mode shapes can be classified into categories for typical structures, and are often descriptive of the type of motion (Figure 3). You will note from the images that the location of the vibration measurement will have considerable variance based on the mode shape. For example, in Figure 3, the second example from the left for a pump with a deep setting, the "C" shape mode, would have maximum displacement at the midpoint of the column, whereas the same measurement point would show very little displacement for the "S" shape mode to the right under similar overall displacement conditions.

Resonance occurs when the natural frequency is being excited by a force with a similar frequency. If the object does not have adequate damping to offset the effects of the excitation force, the object will begin to amplify vibration at its natural frequency (Figure 4). These sources of excitation are often associated with the operation of the rotating machinery, such as the speed of the rotor (residual imbalance) and its harmonics (e.g., misalignment), vane pass frequency, rubbing, gear mesh frequency, etc.

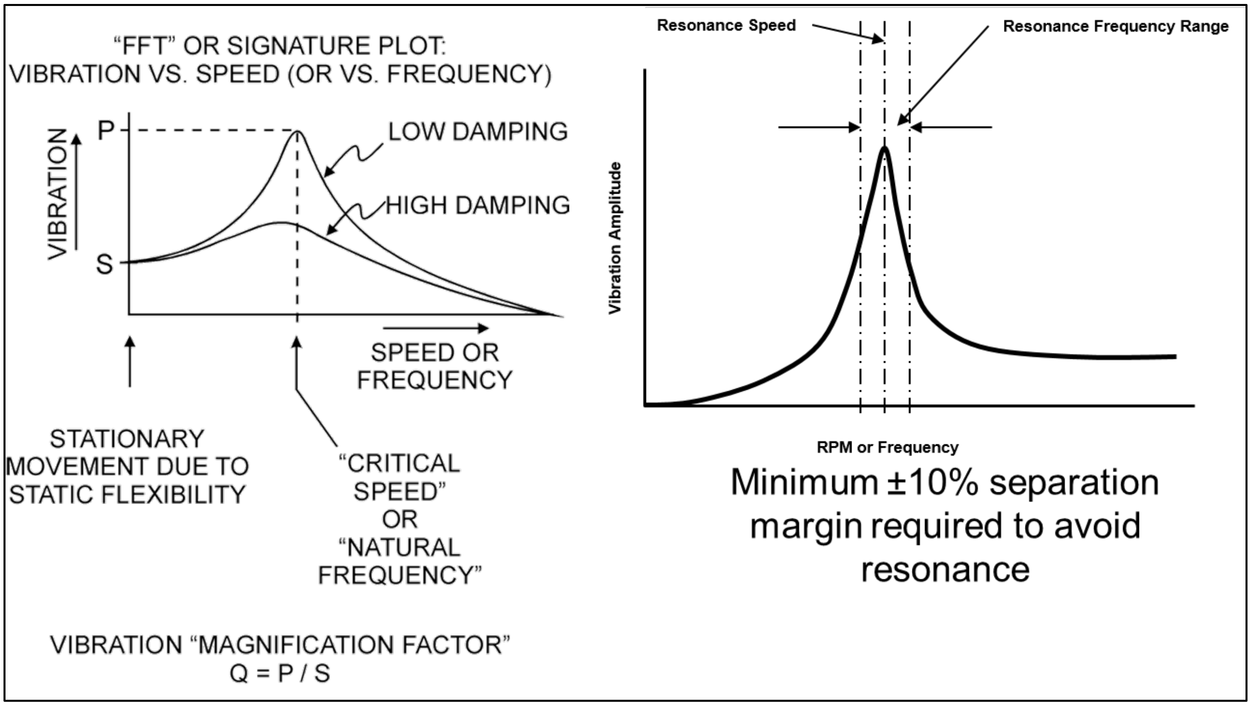

Figure 4. *Natural frequencies of rotating machinery can be excited by the operating speed of the machinery. Inadequate damping will allow the vibration levels to increase.*

Fortunately, it is possible to detect the natural frequencies present in your rotating machinery. Similar to the bell example, the machine can be impacted with a special hammer equipped with a load cell (force measurement sensor). Then the vibration response is measured at strategic points on the machine to determine the response to this measured force. These vibration responses are then processed to display the amplitude across a frequency spectrum, with the broadband peaks in the frequency domain signaling a natural frequency (Figure 5).

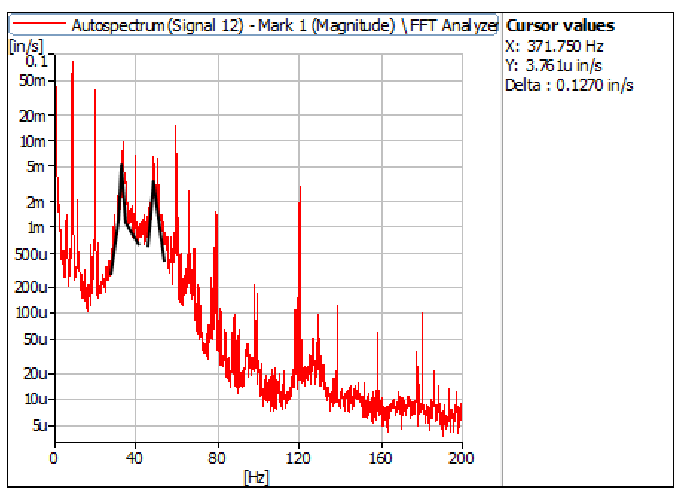

Figure 5. *Vibration spectrum indicating broadband peaks indicative of potential natural frequencies present in the machine if the amplitude (y) axis is on a log scale.*

Common causes of resonance conditions are numerous, and many are typical within the nuclear industry. In general, there are two major causes: 1) a shift in natural frequency or change in operating speed, or 2) insufficient analysis of new machinery installations or machine retrofits to determine natural frequencies in advance of online operation. For example, as plants age, the structural stiffness of the machine may change, or the foundation may weaken or crack, shifting the natural frequencies downwards. Frequent maintenance provides opportunity for changes in tightness between components. Such a machinery train may be considered "alignment" or "balance" sensitive when in reality the maintenance team is fighting a resonance problem (making rotor vibration sensitive to imbalance). Solutions to other problems may shift a natural frequency into a problematic region. New replacement systems may not have a system-level analysis done to determine their installed natural frequency (different weight or stiffness). Switching motor drivers to variable-frequency drive (VFD) may allow the machine to operate at a speed that now excites a natural frequency that before was safely away from the operating speed. A different coupling will change a shaft system's rotordynamic natural frequencies (lateral and torsional natural frequencies).

Solutions to resonance problems usually involve shifting the natural frequency that is being excited, rather than altering the exciting force (i.e. operating speed, misalignment, vane pass frequency, etc.) Generally, this is done by either increasing or decreasing the stiffness of the system, or by adding or removing mass to or from the system. Changing the stiffness can be accomplished by adding or removing braces, brackets and ribs, boxing in I-beams, or by adding bolting connections. Changing the mass is typically done by adding lead weights or a tuned mass damper at specific locations. It is important to note that while this can be done in a trial-and-error approach, it is possible and cost effective to engineer a specific solution to a) make sure it will work, and b) ensure it doesn't create additional problems.

The authors' company has diagnosed and resolved hundreds of resonance conditions associated with rotating machinery, many of which have been within the nuclear industry. What follows are three examples of resonance problems, including how each was diagnosed, and the recommended solution.

Example 1. Feedwater Pump Driver

For this plant, the motor of one of the Feedwater Pump was experiencing high vibration with varying amplitude at the same frequency as the operating speed (1x rpm). The running speed was 3,570 rpm, which translates to a frequency of 59.5 Hz. The 4000 HP motor had been maintained off-site and was recently re-installed.

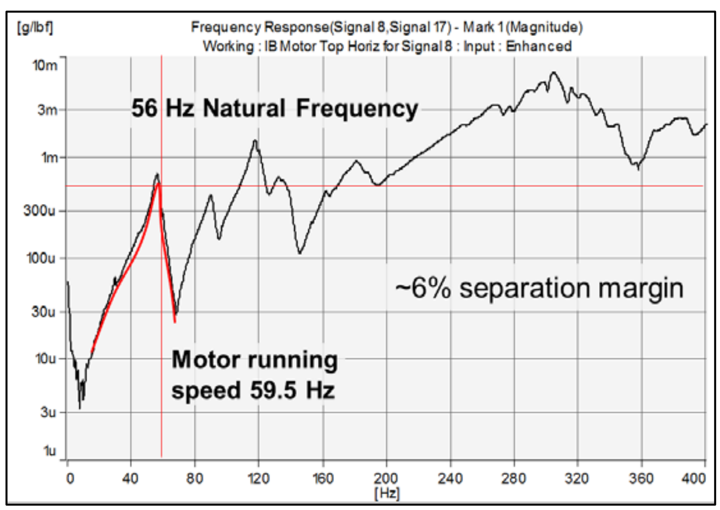

Figure 6. *Impact testing revealed a natural frequency only 6% below the running speed, indicating a resonance condition*

Impact testing of the pump and motor, to determine their natural frequencies, revealed a natural frequency at 56 Hz, with only about 6% separation from the running speed (Figure 6). Additional Operating Deflection Shape (ODS) testing at the operating speed frequency revealed the baseplate was separating from the foundation (Figure 7). This was due to a "soft-foot" condition, whereby the baseplate's connection to the foundation was loosening due to delamination and aging of the foundation. The resultant reduction in stiffness had shifted the main structural natural frequency downward, close to the 1x rpm frequency.

Recommended solutions included verifying the torque and stud fit of the motor mounting bolts, particularly on the corner where soft-foot was evident. As an added measure, it was recommended to add additional lag bolts to secure the baseplate at the problem corner. And finally, it was suggested the plant re-grout the entire baseplate at the next available opportunity. Each of these recommendations was designed to shift the natural frequency back up away from the operating speed by increasing the overall stiffness of the machine.

Example 2. Emergency Diesel Generator

In this situation, one of the Turbochargers on an Emergency Diesel Generator was experiencing increased vibration in the axial direction. This excessive vibration was causing additional looseness in the system, with resultant leaking of the turbocharger's cooling piping and flanges. The 6 MW diesel had a running speed of 514 rpm, which translates to 8.57 Hz. Also of note, twice the running speed, or "2x rpm", was 17.1 Hz. Twice the running speed often has substantial force associated with it in a reciprocating unit, where harmonics of the running speed can be exciting forces of structural natural frequencies.

Impact testing of the turbocharger revealed a natural frequency of 18.25Hz, with only 6.7%

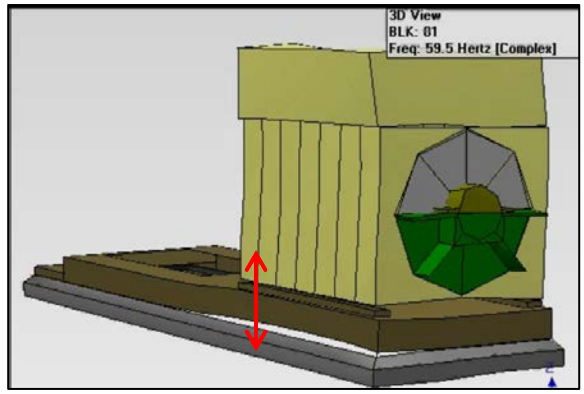

Figure 7. *ODS analysis revealed that the baseplate was separating from the foundation*

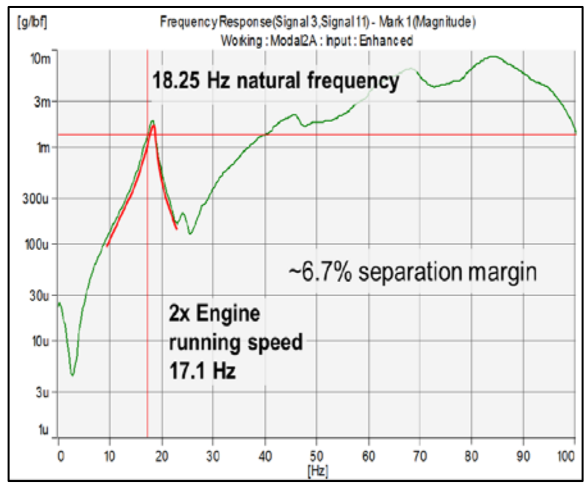

Figure 8. *Impact testing revealed a natural frequency only 6.7% removed from the running speed, indicating a resonance condition*

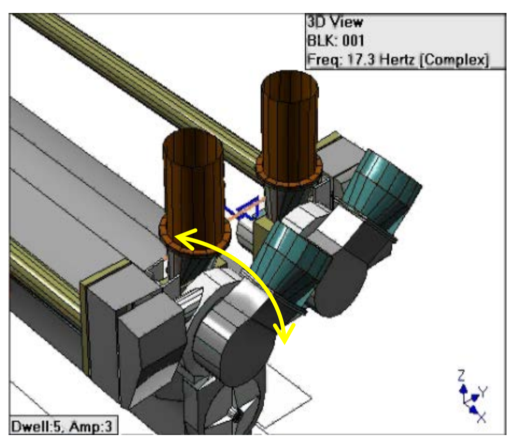

Figure 9. *Modal analysis demonstrated significant rocking motion in the turbocharger assembly*

separation margin from the 2x rpm, or 17.1 Hz (Figure 8). Analysis at the 2x rpm frequency revealed excessive rocking motion of the entire turbocharger assembly, and looseness of some of the components (Figure 9). It is important to note that an operating forced response test yields an animation called an operating deflection shape, or "ODS". This exaggerated and to scale motion animation displays the mode shape information in an easy to observe format. However, the motion often does not translate to a still image very well.

Fortunately, the solution was a simple one: verify and tighten the turbocharger connections to the diesel. These loosened connections, likely a result of recent maintenance, had shifted the natural frequency to within range of the 2x rpm frequency, creating a resonance condition.

Example 3. Safety Related Core Spray Pump

Ever since this Core Spray Pump had been installed, it had higher axial vibration levels than its sister pump. The 500 HP motor-driven pump had a running speed of 1,780 rpm, which is 29.7 Hz. Testing on the baseplate by the plant indicated there were possible voids in the grouting.

Experimental Modal Analysis (or impact) testing with the pump operating was used to determine natural frequencies of the pump and revealed several notable frequencies. One in particular was at 27Hz, with only 9% separation margin from the operating speed of 29.75Hz (Figure 10). ODS analysis at the operating speed demonstrated considerable looseness in the middle section of the baseplate, causing the motor to rock axially (Figure 11). The figure shows displacement information using the color spectrum, where the red end of the contour plot denotes maximum displacement. The top front edge of

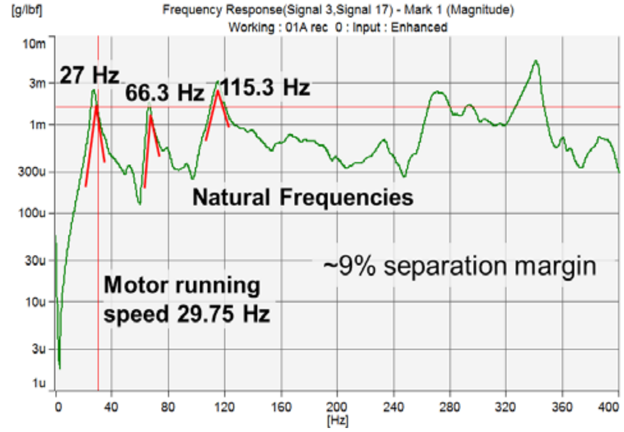

Figure 10. *Impact testing revealed a natural frequency only 9% removed from the running speed, indicating a resonance condition*

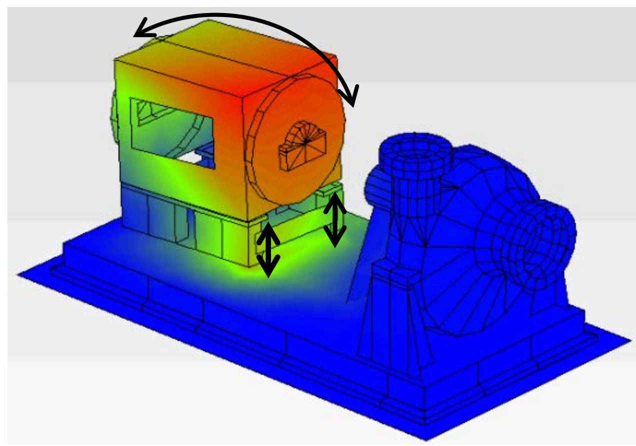

Figure 11. *ODS analysis showed significant axial rocking motion of the motor due to baseplate flexibility*

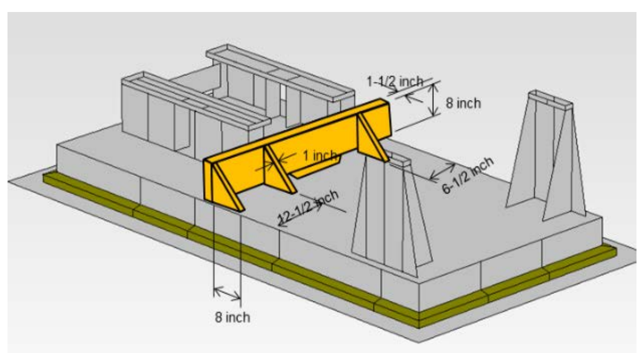

Figure 12. *Brace recommended to add immediate stiffness to baseplate*

the motor was rocking back and forth due to excessive flexibility of the baseplate, shifting the natural frequency down in proximity to the running speed. In addition to recommending the plant fill the grout voids at the earliest potential opportunity, an engineered solution consisting of a brace across the baseplate was provided that could be immediately installed (Figure 12).

Summary

Resonance is a challenge within the nuclear industry, and will continue to be so as plants age and components are maintained and replaced. Understanding the concept of natural frequency and how it can shift will give technical personnel an important tool in diagnosing challenging vibration problems. Solving resonance problems is not a routine troubleshooting task, and requires specialized test and analysis that can benefit from specialists trained in acquiring the necessary data and interpreting the results. Additionally, modern analysis tools can reduce the risk of installing a resonance problem before machinery systems are manufactured (or retrofitted) and installed. The specialized testing can also be used to determine the safe operating time remaining for a system that is suffering from a resonance issue. Actionable, well-defined solutions should be sought and expected when dealing with a resonance condition, making sure the plant stays up and running until the next scheduled outage.

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