Implementing Compressor System Designs or Modifications
- The Devil is in The Details -

Recently our chief engineer had a little problem in our company lunch room. We have one of those coffee makers that is connected to the water supply so that you can brew coffee by just hitting a switch. You can also withdraw hot water from another tap on the machine. If you actually read the instructions, however, you are told that you should not draw hot water while coffee is being brewed, as the result will be a “short pot” of coffee. When our CE violated this rule, what actually resulted was what we might call a “long pot” - weak coffee all over the counter and floor! (It overflowed.)

There is a point to this anecdote, beyond embarrassing Brian Howes. A good machinery installation requires a good design and faithful implementation. In the kitchen accident, we had a problem on both counts - the design and the implementation were flawed.

In our experience at Beta Machinery Analysis, even when the design or re-design is not flawed, there are, all too often, problems due to implementation issues. What gets installed is not exactly what the analyst/designer intended.

When trying to ensure the reliability of machinery systems, there are some details that must be implemented as designed - no deviation.

What is required to make sure this happens?
- Clear communication by the analyst, emphasizing those details that must be followed faithfully.
- A genuine attempt by the fabricator to understand the design documents.
- No implementation "creativity", at least in the critical areas.

Consider the following example. In order to correct problems on a customer’s two throw compressor installation, Beta recommended a new suction bottle. The picture on the left shows the way this new bottle was initially installed. The photo on the right shows the way it was intended to be installed and the way it eventually looked. With the bottle installed in the axial direction of the compressor (left photo) vibrations were unacceptably high. With the bottle turned to the correct orientation, vibration level dropped by half.

This is an extreme example of the kind of discrepancy that can arise between what the designer intended and what gets built. We have encountered many other far less obvious examples, including:
- inadequate connection between scrubber base plate and skid: if the base plate warps when it is welded to the skirt, there will be poor contact between the base plate and the skid (or sole plate) and low stiffness. This can lead to large variations between the predicted scrubber mechanical natural frequency (MNF) and the measured scrubber MNF. Grossly excessive vibration can result.
- pipe bolt-up strain: if a pipe is not shimmed properly (i.e., when the unit is "hot"), before it is clamped down, the mechanical characteristics can change. Our experience is that piping with bolt-up strain is more likely to vibrate excessively.

One way to ensure that the implementation accurately reflects the intended design is to have a specialist on site to provide input on the implementation details.

In addition, there is a case for on site verification that the predicted behavior is achieved. For example, simple “bump” tests can confirm that the desired mechanical natural frequencies have been achieved; if not, immediate corrections can be made. This situation can and does arise due to implementation disconnects (a support not built as intended) or due to inherent design uncertainties.
Perplexing Variable Frequency Drive Vibration Problems

Recently, we have seen several vibration problems associated with variable frequency drives (VFDs). The common symptoms are:

- A fixed frequency of vibration (either torsional or linear/lateral/transverse), independent of shaft speed
- Amplification of torsional vibrations, particularly on the motor side of the system.

Significant time has been spent troubleshooting some of these cases, only to find out that simple changes to the software in the VFD system were available to eliminate the problems.

Case History 1

System Description

Eight motors driving cooler fans (8 blades) through cog belts. The VFD manufacturer did not supply the motors. See Figure 1 below.

Symptoms

Vibrations: The worst vibrations were in the east-west direction, which is the direction from the motor to the fan. The operating deflected shape (ODS) of the vibration exhibited a rotational motion about a vertical axis through the base of the motor.

The vibrations were so large that they were visible and so extreme that the system could not have been run for long. In fact, a motor bearing may have been damaged in the relatively limited testing that was done in the attempts to troubleshoot the vibration problem.

<table>
<thead>
<tr>
<th>System Test Description</th>
<th>Dominant Fixed Frequency (Hz)</th>
<th>Frequencies and ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 6, as found</td>
<td>20.8</td>
<td>Rated motor speed = 30 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Speed range = 5 to 30 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Belt ratio = 4.86:1</td>
</tr>
<tr>
<td>Unit 6 with Brace 1</td>
<td>22.3</td>
<td>7% increase in dominant frequency, but vibrations still very high</td>
</tr>
<tr>
<td>Unit 6 with Brace 1 and 8 fan blades removed</td>
<td>24.6</td>
<td>24.6/22.3 = 1.1 (Calculated TNF ratio with 4 and 8 blades = 1.1)</td>
</tr>
<tr>
<td>Unit 4, as found</td>
<td>21.56</td>
<td>Vibrations: 5.3 ips pk</td>
</tr>
<tr>
<td>Unit 4 with Brace 2 (tube)</td>
<td>20.5</td>
<td>Vibrations reduced to 1.6 ips pk</td>
</tr>
<tr>
<td>Unit 6 without VFD</td>
<td>n/a</td>
<td>Vibrations reduced to 0.32 ips pk</td>
</tr>
</tbody>
</table>

Table 1 summarizes the key vibration amplitudes and frequencies. The dominant frequency was observed after the speed increased to that frequency. After the speed increased further, the dominant frequency remained and only increased in amplitude as the motor speed increased.

Mechanical Natural Frequencies (MNFs): The relevant MNFs are shown in Table 2.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description of MNF</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>As found, 21.9, rotational mode about a vertical axis through the motor base, and 23.4 Hz</td>
</tr>
<tr>
<td>4</td>
<td>Brace 1, Not much change</td>
</tr>
<tr>
<td>4</td>
<td>Brace 2, 23.4 unchanged, and 27.6 Hz, rotational mode about a vertical axis</td>
</tr>
</tbody>
</table>

Torsional Natural Frequencies (TNFs): Not measured, but the calculated values were consistent with the linear vibration frequencies observed. See Table 3.

Table 3: Calculations of Torsional Natural Frequencies (Done after leaving the site)

<table>
<thead>
<tr>
<th>Stiffnesses Included</th>
<th>Inertia Included</th>
<th>TNF Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan shaft and belt</td>
<td>8 blades and motor</td>
<td>31.5</td>
</tr>
<tr>
<td>Fan shaft and belt</td>
<td>4 blades and motor</td>
<td>34.8</td>
</tr>
<tr>
<td>Fan shaft, belt and motor shaft</td>
<td>8 blades and motor</td>
<td>23.8</td>
</tr>
<tr>
<td>Belt</td>
<td>8 blades and motor</td>
<td>144</td>
</tr>
</tbody>
</table>

Electrical or Software Changes

The pulse frequency was changed from 1.5 to 3.5 kHz, based on advice over the telephone from the drive manufacturer’s representative. Subtle changes in the vibrations were noted, but the changes were of no practical significance.

The “load reactor” was removed from the electrical system, but no changes resulted.

The load reactor was returned, and the “line filter” was removed. The effect of this change was dramatic. The vibrations on the motor dropped to an acceptable level. Unfortunately, the line filter is required to protect the motor from overheating due to the harmonics in the power system.

The drive manufacturer had a software change available to correct the problem. This was installed and after some adjustments of parameters the vibration problem went away.

Conclusions

The presence of a torsional natural frequency in the system, in an apparently critical frequency range, caused motor speed fluctuations that sent current fluctuations from the motor to the VFD. The VFD and the electrical system combined to amplify the current fluctuations.

The mechanical natural frequency of the motor further amplified the vibrational response of the system.

Although the mechanical system responses had a significant effect on the frequency and amplitude of the vibrations, the fundamental cause of the high vibrations was a feed-back of energy from the VFD.
Case History 2

System Description

Two pipeline reciprocating compressors driven by synchronous motors. There is a large flywheel between the motor and the compressor. One VFD shared between the two motors, used as a soft start for the first motor which is switched to “across the line”, and then the second unit is started and run on the VFD.

The VFD manufacturers did not supply the motors.

Symptoms

Failures: Several motor shaft failures in the stub shaft area have occurred, caused by torsional vibrations and improper shaft materials.

Vibrations: Bearing housing vibrations are not high. Torsional vibrations (TVs) are an issue on the motor side of the flywheel. TVs are lower than predicted on the outboard end of the compressor, but higher than predicted on the outboard end of the motor.

The original symptoms were exhibited in the Unit 1 motor. As the speed was increased and the first torsional critical speed was excited, the TVs peaked and then stayed high at the TNF even though the motor speed was still increasing.

Unit 2 did not exhibit the “lock-in” TV at a fixed frequency. The amplitude of the TVs on the motor outboard was higher than predicted.

Mechanical Natural Frequencies: Not an issue in this case.

Torsional Natural Frequencies: The TNF measured in the field is as predicted using computer models. The damping used in the predictions is consistent with the damping measured in the field.

Mechanical Changes Attempted

The motor shaft material problems have been corrected. This had no effect on the vibrations, but will give better motor life.

Electrical or Software Changes

In a recent test, the VFD manufacturer made software changes to the drive. We are not privy to the changes made.

The result of the changes was that the two motors now behave the same when on VFD control. The “lock-in” constant frequency of TV no longer occurs on Unit 1.

The amplitude of TV at resonance is higher than predicted on both units at the front of the motor.

Conclusions

We believe that the compressor torque fluctuations cause speed fluctuations in the motor, which lead to current fluctuations, which cause speed fluctuations (another way of saying torsional vibrations) in the motor.

The flywheel apparently isolates the compressor from the torsional vibrations (torque fluctuations) coming from the motor. It was originally installed to isolate the motor from torque fluctuations coming from the compressor.

Designers of torsional systems can only assume the Variable Frequency Drives will not amplify the torsional vibrations in a system at this time. In fact, we have seen that amplification does occur. Therefore, the VFD manufacturer should tune the drive to match the electrical and mechanical system characteristics, eliminating the amplification.

Case History 3

System Description

Four Vertical Motors and Pumps. The VFD manufacturer supplied the motor.

Symptoms

Vibrations: Vibrations on the motor bearing housings show a fixed “lock-in” frequency at 19.75 Hz. This frequency stays constant as the shaft speed passes 19.75 Hz.

Occasional trips have been occurring due to high vibrations in the NDE motor bearing accelerometer on one of the units. Monitoring of the motor has not picked up a trip yet. It is suspected that the 19.75 Hz component increases when the trip occurs, although other problems may be present.

The amplitudes of vibration vary among the four units with the highest to lowest varying in proportion to the distance from the VFD.

Torsional Natural Frequencies: The third mode of the system is predicted to be at 6 times the measured “lock-in” frequency. This TNF has not been measured yet.

Conclusions

Based on other experiences with VFD vibration problems, the VFD manufacturer should be contacted and requested to tune the operating parameters of the system to eliminate the unusual vibrations.

Strange vibration problems causing machine trips will go away when a monitoring system is attached to a machine.

Lessons Learned

- A system approach to the design of a drive-motor driven machine may be helpful. The system should include an understanding of the torsional response of the mechanical system.
- A thorough start-up lateral and torsional vibration and current pulsation check for all systems with Variable Frequency Drives should be done.
- There is a coupling mechanism between electrical and mechanical systems through the torsional vibrations imposed on the motor by the system. Speed fluctuations of the motor may cause electrical currents to travel from the motor to the VFD, which amplifies the currents.
- There are different types of VFDs. Our limited sample suggests that Vector Control is better than Voltage-Speed Control.
- Some VFD manufacturers suggest that the VFD and the motor should be supplied by the same manufacturer, so that responsibility for the matching of the motor to the VFD is clear. We conclude that, as a minimum, when different manufacturers are involved, one of the manufacturers should be given the responsibility to ensure that the system design is correct.
A startup check should be considered, especially for high risk and/or high profile systems. Properly done, pulsation studies will do a good job of predicting and controlling pulsations, forces, vibration and stresses. But the analyst must necessarily make assumptions about stiffness, damping, and mass properties. As a result, there will be some uncertainty in the predicted pulsations, forces, vibration levels and stress. With the additional possibility of implementation errors, there can be significant potential for post startup problems. These can be headed off by a field startup check.

In one startup check, a resonant PRV was found. A correction was designed, implemented and verified with the analysts on-site.

What should be verified for a reciprocating compressor installation as part of a startup check:

- operating vibration levels, from which stress levels can be calculated. This should include small bore piping, which is not in the scope of a standard pulsation study, but will most likely be the first thing that fails if there is a vibration problem.
- pulsation levels to confirm that forces on piping, bottles and supports are acceptable
- foundation: inspection of grout, pile contact
- performance review to verify that power and throughput meet specifications. In some cases a detailed performance analysis including cylinder by cylinder horsepower, capacity, valve dynamics and efficiency can be justified.
- system integrity check involving a thorough inspection of clamps, bracing, bolts, flange alignment, wedge supports and any other potential failure sources
- torsional vibration, especially in motor drive systems, to ensure that torsional stresses are acceptable under all operating conditions
- alignment between driver and compressor

If needed, immediate on site corrections can often be made under the guidance of the startup analyst.

To summarize, reliable operation involves both good design and good implementation. Ensuring the latter requires a strong team approach between the analyst/designer and the people doing the fabrication. Keeping the analyst involved in the implementation can prevent expensive problems.

In lieu of sending cards, Beta has chosen to support local food banks.

It is our Wish that your Holiday Season is Joyful and that 2005 is Healthy and Prosperous for us All.

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