Compressor foundation assessment and repairs key to reducing vibrations

Costly problems can be mitigated by optimizing multiple facets related to the foundation. By **Michael Golla**, Structural Technologies

Compressors are critical to many processes, and the foundations that support compressors need to be designed, assessed and repaired properly to minimize vibration and increase compressor reliability. Although machine bearings, misalignment or other mechanical issues can cause vibration, most vibration problems stem from the foundation. The foundation may have been designed improperly or deteriorated over time or damaged. Perhaps the compressor changed without determining if the existing foundation is suitable for the new weight and dynamic forces.

Many old foundations were not designed properly for vibration and have exceeded their design life. Vibration may also occur due to improper design and age. Sources of vibration can be identified with various techniques, and foundations can be repaired to reduce vibration from 50 to 100% in many cases.

This article will focus on reinforced concrete foundations that are commonly used to support compressors and absorb vibration and will discuss design, assessment and repair to reduce vibration.

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Foundation design

For compressors, a reinforced concrete foundation typically consists of grout, concrete, anchor bolts, jack bolts and soil (see Figure 1). The compressor frame is typically bolted to a baseplate or soleplate attached to the grout and concrete foundation. Jack bolts, chocks or shims might be used at the anchor bolt locations to assist with alignment.

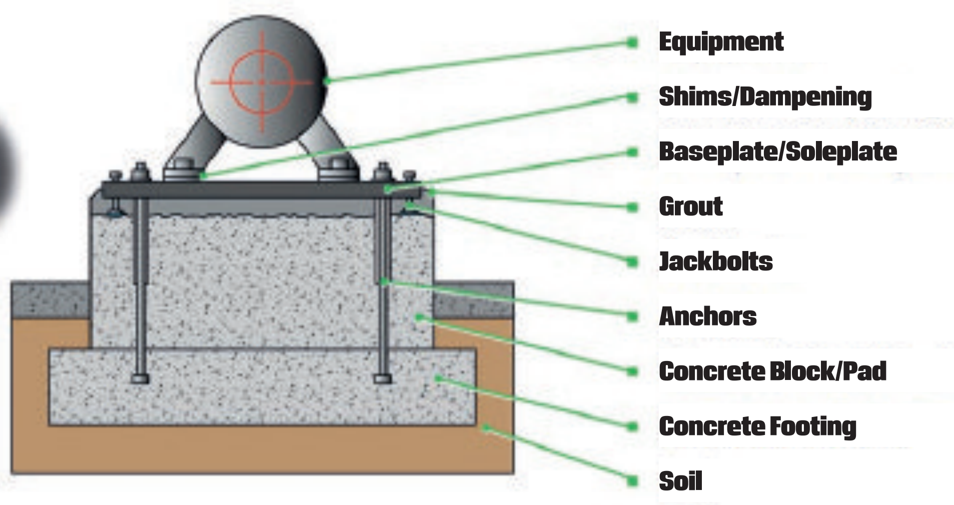
Old foundations built more than 40 years ago might not feature designs that can properly handle vibration based on today's standards. Without considering vibration, they might have been designed for static conditions using rules of thumb, such as foundation weight at three to five times compressor weight, with improper rebar design and spacing to minimize vibration forces. Additionally, grout, soil and anchor bolt material and designs have improved over the years to reduce vibration.

API 686 and ACI 351 provide good guidelines for foundation design (and repair) using modern standards and best practices. API uses the phrase "system" often to reinforce the importance of a unified foundation where all parts work together to minimize vibration.

Grout design/installation

Precision grouts (for applied loads) are a combination of hydraulic cement, fine aggregate and other ingredients. These grouts are designed to uniformly transfer

FIGURE 1 Reinforced concrete foundation for compressors



Grout cracking and edge lifting due to excessive grout placement, lack of expansion

Grout installation with expansion joints and anchor bolt sleeves.

machine load and forces to the foundation. They help resist applied forces as concrete cannot do this alone. The grout also helps to minimize vibration by filling voids due to irregularities between the compressor frame or soleplates and the concrete. Grout is critical for compressor alignment too, and many vibration issues have been resolved by simply replacing grout and re-installing the compressor on the new grout for re-alignment. Grout-induced misalignment is a common cause of excessive vibration.

Grout technology has improved significantly over the years and there are many factors to consider when choosing a precision grout from the various manufacturers. Compression strength affects maximum support load. Creep resistance helps avoid misalignment and loss of bolt torque. Modulus of elasticity is a measure of stiffness and deflection of under load. The coefficient of thermal expansion is important for temperature change effects. Flowability and bearing area are critical for the baseplate contact to evenly distribute the load. The coefficient of thermal expansion and flowability is most important for rotating equipment.

In addition to choosing the proper grout, the grout installation process is also important. There are good guidelines and best practices for formwork, mixing, placement, expansion joints and others. Grout failures are common in the field and include design and installation issues. From a design perspective, point load cracking can occur due to sharp or square edges in the grout design, and grout can separate from the concrete if large grout shoulders are used, causing grout "edge lifting" (see photo #1). Additionally, grout can crack if expansion joints are not used or are not spaced properly. Poor installation can lead to a lack of bonding and voids. Grout should touch the steel above and the concrete below. Steel and concrete surfaces must be prepared properly per guidelines, and grout placement techniques by an experienced contractor must be used to ensure a good bond.

Anchor bolt design/installation

Anchor bolts are another critical part of the foundation to resist forces and minimize vibration, and they are just as important as the grout. The grout prevents downward movement and the anchor bolts prevent upward movement. Concrete is strong in compression but weak in tension. Anchor bolts provide the tensile strength. Key considerations include the bolt material and fabrication, the type of termination, tension/torque relationships, allowed stretch, and adequate concrete cover. Many foundations designed prior to the 1980s do not follow today's standards for anchor bolts, potentially causing vibration issues (see Figure 2).

The importance of anchor bolts and termination design has been thoroughly researched in recent years, resulting in new standards for anchor bolt material, thread design and lengths that can also help minimize foundation cracking under stress. For example, "J" and "L" bolt designs, square plates and thin washers used in the past

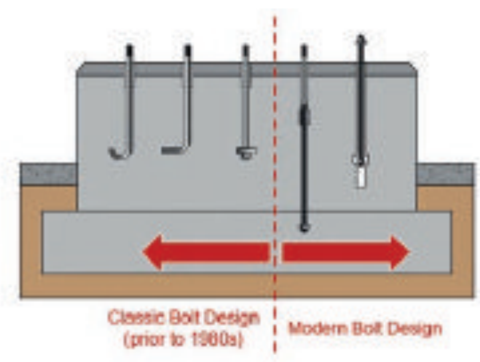


FIGURE 2 Anchor bolt design evolution

were not strong enough, resulting in concrete cracking and increased vibration. New designs are much improved. Round plates and plain nuts, instead of square plates and thin washers, help reduce tensile stresses caused by anchor bolts in the concrete. Extra rebar can be installed at the termination point of anchor bolts to provide extra strength and prevent cracking. Additionally, the metallurgy, number, diameter and length of anchor bolts are critical. Undersized anchor bolts were common on older machines. Bolts should now be as long as possible to provide more stretch to increase the clamping force.

Foundation assessment

If the foundation is causing vibration or if machine vibration or other factors are causing deterioration of the grout and concrete, there are numerous methods for assessing the situation, especially for finding the source of vibration and designing the proper repair.

The foundation may need to be assessed and repaired for several reasons:

- Process-driven changes (change of equipment, etc.)
- Defects (design, materials, construction, past repairs, etc.)
- Deterioration (dynamic load effects or vibration, thermal effects, chemical attack, foundation settlement)
- Damage (equipment failure, impact, spills, etc.)

Assessment methods include a review of drawings and past repair methods; a site inspection of the foundation (concrete block, grout, alignment, anchor bolts, soil, crack patterns); and numerous non-destructive, semi-destructive and laboratory testing techniques.

Different techniques can be used to determine sources of vibration; rebar design (if drawings don't exist), crack depth in concrete; voids in concrete or grout; and the condition, composition and strength of concrete.

Vibration

As mentioned earlier, the foundation is a frequent cause of vibration, due to foundation design or degradation over time. The foundation serves as a unified system with all parts working together to move vibration from the compressor down to the soil. If one part is not working properly, then vibration can occur.

Sources of vibration from the foundation can include:

- Inadequate rebar in upper part of concrete block
- Loose or wrong size/type anchor bolts
- Cracks due to anchor bolt terminations
- Cracks due to square internal corners
- Failed grout (voids, etc.) or improper installation
- Grout induced misalignment
- Failed bond between grout and skid (baseplate/frame) or between grout and concrete
- Improper attachment of concrete block to concrete mat (floor)
- Poor oil (or chemical) containment
- Inadequate soil
- Past failed repairs
- Oil can attack the grout, skid or the concrete and cause vibration. Cracks in the concrete can increase in size if oil enters them.

Vibration analysis

Various methods can be used to determine if the foundation is contributing to machine vibration. For example, resonance can occur if the operating frequency of the machine equals the natural frequency of the system, resulting in excessive vibration. Modal analysis can be used to confirm resonance, and the foundation can be modified to change the natural frequency and solve the problem.

Three other common vibration analysis methods, especially for compressor foundations, are operation deflection shape (ODS), motion amplification video (MAV) and finite element analysis (FEA).

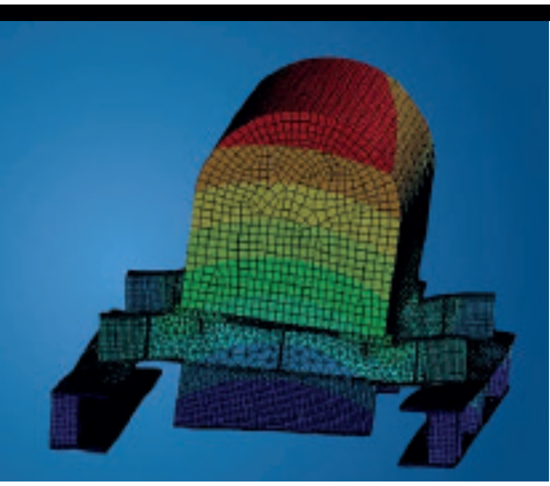


FIGURE 3 ODS example of compressor motor vibration (without animation)

ODS uses sensors to measure vibration at different locations on the foundation system at the compressor operating speed and frequency on a given day. Software is used to provide a 3D animation of the foundation movement (see Figure 3). It might be able to determine if a particular part of the foundation is vibrating excessively, such as a cylinder support pedestal, due to resonance, inadequate design, or deteriorated concrete. It is a proven method for identifying certain types of vibration problems and has been used for many years.

MAV is a relatively new technology and uses a special camera and software to amplify and measure vibrations not visible to the human eye. Each camera view pixel becomes a vibration measurement sensor. MAV can sometimes identify loose anchor bolts, oil weeping from cracks, frame movement on grout (due to poor bonding) or other sources of vibration. It might also find low-frequency vibration missed by conventional vibration analysis methods.

MAV is much faster than ODS, and the resolution is more intuitive without the animated, cartoon-like image of ODS. In summary, MAV can be a cost-effective and quick method for finding sources of vibration, especially for reciprocating compressors that operate at lower frequencies than types of turbomachinery.

In general, ODS can be used for complex machinery issues requiring 3D views and trending, while MAV can be used for specific areas requiring high-spatial resolution.

FEA uses foundation drawings, compressor operating frequencies and dynamic forces, and concrete and soil condition data (if available) to create a theoretical 3D model of the foundation and then determine how the foundation reacts to various frequencies and forces. It doesn't require sensors or cameras and offers several unique benefits over other methods. For example, in addition to finding the source of the vibration without site work, FEA can be used to redesign the foundation/supports that are vibrating excessively.

Many compressors are routinely re-grouted without reducing vibration, and FEA might confirm that parts of the foundation need to be redesigned or repaired to reduce vibration, increase bearing life, reduce maintenance costs and increase the reliability of the machine.

Case study

Here is an example of using a licensed, specialized contractor to provide high-quality assessment, repair design and repair methods to fix a compressor foundation and reduce vibration.

A four-throw, reciprocating compressor – built in 1970 with a conventionally reinforced concrete foundation and below-grade mat – experienced excessive vibration that caused frame movement at the grout interface and localized cracking in foundation components. Bearing life was reduced, causing unexpected shutdowns and increased maintenance costs.

ODS confirmed that two cylinders (one side of compressor concrete block) were moving too much and FEA confirmed that two separate cylinder support piers (not attached to the block) were resonating at compressor operating frequency (see Figure 4) and also contributing to vibration. FEA was then used to redesign the supports to eliminate the resonance. The solution included strengthening and enlarging the pier foundations, connecting them together with traditional rebar and post-tensioned bolts. The foundation block was also rebuilt to remove cracks and restore strength.

Vibration dropped substantially, which improved bearing life and decreased maintenance costs.

Summary

Compressor foundations can be very complex and inadequate foundations can suffer from vibration and decreased compressor reliability. All parts of the foundation are critical to performance. Assessment, design and repair quality are essential, and vibration reduction can be significant after using trained and experienced inspectors, licensed and specialized design engineers with equipment foundation experience, and knowledgeable repair contractors. **CT2**

FIGURE 4 FEA results to determine source of foundation vibration