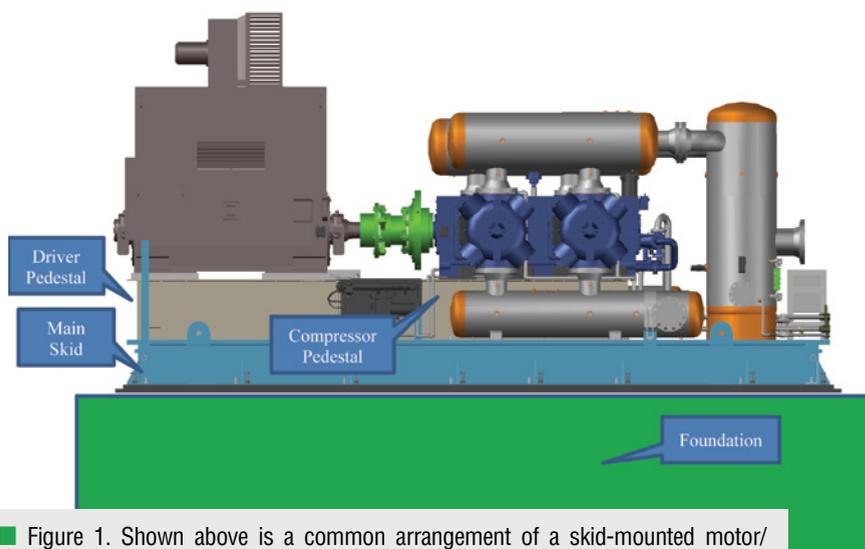


Foundation And Skid Design Considerations For Large, High-Speed Reciprocating Compressors >

New GMRC Guideline will draw on industry best practices

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■ Figure 1. Shown above is a common arrangement of a skid-mounted motor/compressor package.

In the past decade, high-speed (700 rpm and above) reciprocating compressors have become common for gas transmission and storage applications.

Driven by gas engines or electric motors, these compressor packages are generally 1491 to 5966 kW. Foundations and skids support the compressor and driver, ensuring frame and coupling alignment and providing energy paths for dissipation of equipment unbalance and other time-variant forces.

Proper foundation and skid design is a critical success factor when applying high-speed reciprocating compressors in this size range. The soon-to-be-completed Gas Machinery Research Council (GMRC) Design Guideline for High-Speed Reciprocating

Compressor Packages for Natural Gas Transmission and Storage Applications is the product of a two-year investigation of industry experience and best practices. This article provides a preview of some of the GMRC guideline's recommendations for skid and foundation design.

Many types of foundations are used for reciprocating compressors: block foundation (equipment mounted directly on a concrete block), skid on block foundation (equipment mounted on a fabricated steel skid that is mounted on a concrete block), block on mat foundation (equipment mounted on a concrete block supported on a mat), block on concrete piers (equipment mounted on a concrete block supported by deep reinforced concrete piers), block on driven steel

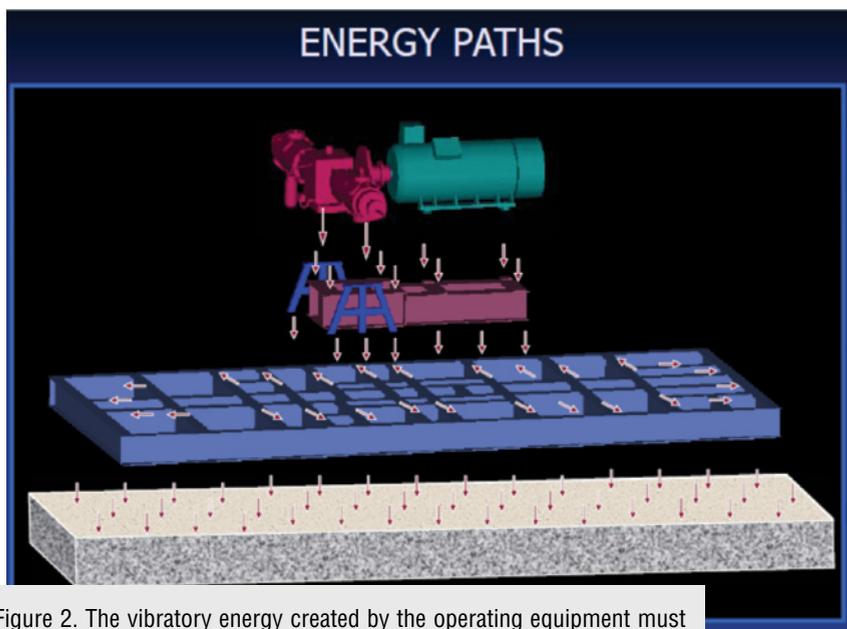
piers (equipment mounted on a concrete block supported by deep driven steel piers), block and skid on driven steel pilings (equipment mounted on a fabricated steel skid mounted on a concrete block supported by driven steel pilings), and skid on driven steel pilings (equipment mounted on a fabricated steel skid mounted on driven steel pilings).

High-speed reciprocating compressors are much more likely to be installed on a skid than classic slow-speed models. The skid is the fabricated steel structure that supports the compressor and driver and often the vessels, piping and other equipment required for the compressor system.

Figure 1 shows a typical arrangement of a skid-mounted motor/compressor package. The skid is often composed of two main structures: a main skid and one or more pedestals. The pedestal structure supports the compressor and the driver. It may be integral with the main skid. The main skid supports the pedestal as well as the other components of the compressor package.

The foundation is the structure that supports the skid. The foundation and the skid must provide the compressor, driver and other equipment with a stable base for safe, long term operation.

Skids and foundations have to be designed to support the compressor and driver weights and resist the driver dynamic (roll) torque, frame unbalance forces and moments, vertical cross-head forces, time domain gas and in-



■ Figure 2. The vibratory energy created by the operating equipment must have a continuous path into an appropriate foundation.

ertia forces at each compressor throw, and the effects of frame flexibility.

Designing simply for unbalance forces is not adequate. Skids must be designed for compatibility with their foundations, and must also be suitable for compressor package lifting and transportation prior to and during installation. Preferably, the skid and foundation should be designed as a system by the same engineering entity.

Compressor and driver time variant forces are dissipated by trying to move a large foundation mass. The vibratory energy created by the operating equipment must have a continuous path into an appropriate foundation (Figure 2).

If a skid is isolated or not properly anchored to the foundation, there is no energy path into the foundation for dissipation. If the foundation is not large enough, it will not dissipate enough energy. Time variant forces that are not dissipated by the foundation can excite natural frequencies of package components and cause failures of instrumentation, small-bore piping and pressure vessel nozzles, as well as fastener loosening and other problems that result in unscheduled shutdowns and safety hazards.

Each driver and compressor combination has a fundamental frequen-

cy associated with the rated operating speed. In addition, there are harmonic frequencies (multiples of operating speed) that result from mechanical and gas pulsation forces. A constant speed driver (e.g., synchronous electric motor) has a discrete set of forcing frequencies.

Variable speed drivers (gas engines or variable frequency electric motors) create ranges or bands of forcing frequencies that must be dealt with, making the placement and control of natural frequencies much more challenging. Wide speed ranges make the task of natural frequency placement very difficult, and if the speed ranges are too wide, the harmonic bands overlap such that there are no safe zones for placement of the higher frequency modes.

Solely from a vibration standpoint, constant speed equipment is always preferable, and the wider the speed ranges, the higher the risk of serious vibration related problems. For optimal vibration avoidance, flexible unloading schemes (combinations of automatic clearance volume pockets and, if absolutely necessary, end deactivators) are almost always preferable to wide operating speed ranges.

Successful design and construction of a skid and foundation system requires effective planning, coordination

between the technical specialists as the design is developed, and attention to construction details throughout the construction process. Performance criteria, guidelines and design strategy have to be agreed upon prior to the start of the design.

Once the initial compressor and driver types and sizes are chosen, a rough sizing of the skid footprint can be made. Since the final design of the skid is strongly influenced by the foundation design, the foundation type must be the next decision. The foundation design is dictated by soil conditions and other factors, such as type of compressor, type of driver, and distance to neighbors.

Very early in the project, a site inspection is required to measure soil properties and understand environmental factors. A specialized geotechnical report will help determine the required type of foundation for the site, as well as provide basic soil properties that are necessary for the foundation design and vibration analysis.

Foundations are generally categorized as either shallow (concrete block designs) or deep (pile foundations that include a concrete block with piles or, alternately, a skid that is mounted directly to the piles). Economics associated with the availability of concrete, pile-driving equipment, etc. will influence the choice of foundation, as will the size and type of compressor and number of throws. Poor soil conditions usually force the decision toward deep foundations.

It is important to map out the entire area that must support the foundation. Clay and sand are common types of soils in most locations. Wet clay can expand and contract, causing settlement and uplift. Dry sand has no cohesion and low-to-moderate load-bearing capacity. Slightly moist mixtures of clay and sand have moderate-to-high bearing capacity, good stiffness, and are desirable. Rock, shale and limestone are extremely dense and form good bedrock support.

Layered soil is often encountered, and understanding the effects of layering is critical. Soil properties must be obtained for each layer. The depth

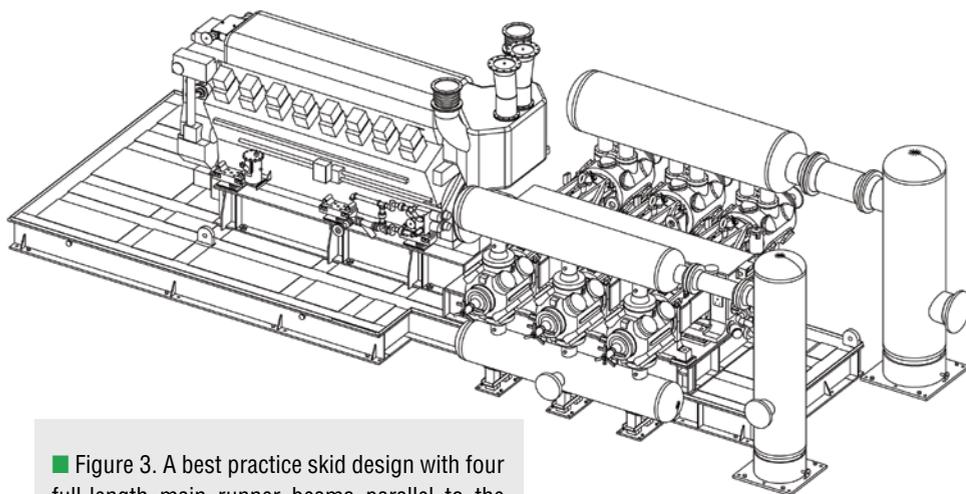
of the soil analysis is influenced by the type of foundation. Generally, a depth equal to four times the foundation equivalent radius is adequate for shallow foundations, but more depth should be assessed to determine that there is no undesirable layer present. Specialized geotechnical testing is required to measure the soil dynamic properties. It is advisable to select a local geotechnical consultant, since they can be expected to have specialized knowledge regarding the local soil and climatic conditions.

Vibration results from the structural flexibility of all components and time variant forces originating from the operating equipment. If the frequency of the forces is close to a foundation or skid natural frequency, the structure will resonate, and high vibration is likely to occur. It is important to keep foundation natural frequencies at least 20% away from the equipment operating speed range. Horizontal transverse, torsional and longitudinal natural frequencies are typically placed in the 300 to 500 cpm range, below the operating speed of most large, high-speed compressors used in natural gas pipeline and storage applications. Vertical, rocking and pedestal natural frequencies are typically placed in the 1250 to 1450 cpm range, above the operating speed.

Soil stiffness will change the foundation's natural frequencies and must be considered. Using dynamic analyses, the time variant forces are applied to the modeled equipment as forcing functions at their generated frequencies to find and eliminate potential resonances, evaluate predicted vibration levels, and determine mode shapes for the range of operation.

An appropriate foundation is an engineered design with high strength, low and even settlement, sufficient rebar (size and location — typically 2.5 to 4.5% rebar by weight), continuous energy paths and energy dissipation, adequate sole plates and grouting, suitable anchor bolts and center of gravity match with the mounted equipment.

Driven piles are a proven technology for compressor foundations. When



■ Figure 3. A best practice skid design with four full-length main runner beams parallel to the crankshaft, with additional width in the engine area for auxiliaries and maintenance platforms.

piles are required, it is important that they be installed below the compressor crankcase and under the crosshead guide supports. Pile spacing should be the same as the dimension from the top of skid to the compressor centerline. The typical number of piles required is equal to the number of compressor throws plus one.

In addition, two piles should be installed below each compressor cylinder head end for head end supports. Screw piles are an emerging technology for reciprocating compressor applications that may offer advantages on installation time and cost. However, they are more sensitive to soil conditions, can be more flexible, and at the current time have limited experience with large reciprocating compressors.

In addition to structural requirements, skid design factors such as equipment accessibility for operation and maintenance should be considered in the design. Unlike the majority of high-speed compressor skids, when coolers are required for large pipeline and gas storage applications, they are mounted off the main skid. Suction scrubbers may also be mounted off the skid for more rigidity and reduced vibration risk.

Figure 3 shows a skid design that has proven to be a best practice for this class of equipment, whether engine or electric motor driven. The skid has four full-length main run-

ner beams parallel to the crankshaft with additional width in the engine area for auxiliaries and maintenance platforms. Two runner beams are located below the compressor feet and two are located below the crosshead guide supports to provide energy paths to the foundation.

Full depth transverse beams with full-depth gussets are installed near the crosshead guide support anchor bolts and compressor frame anchor bolts. All beams have full coped connections. Keyed connections with webs cut out under the flanges are not acceptable. The beam flanges and web welds should have the same strength as the sections that they join, usually requiring full penetration welds on the flanges and fillet welds all around on the webs.

The skid beams must be designed to minimize the height of the compressor above the foundation, while still allowing for the proper discharge bottle size to be installed. Mounting the discharge pulsation bottles directly on the foundation (off the skid) usually reduces the required beam height.

The compressor sits on a pedestal that extends out under the crosshead supports. For added rotational stability, skid and pedestal are covered with a minimum 38 mm thick steel top plate, welded to the beams all around. The pedestal beams should match the main skid beams with the beam webs aligned vertically.

Compressor frame anchor bolts extend through the pedestal and main skid beams. Crosshead guide support anchor bolts are located as close to the web of the skid beams as possible, leaving enough space for accessing anchor bolt nuts for tightening. Two full-depth skid gussets are provided around each compressor frame and crosshead guide anchor bolt, located at a minimum distance from the anchor bolt, but with space for accessing nuts for tightening.

Access holes may be required in the skid top plate to check grouting and tightening the internal skid anchor bolts. Removable covers are required for access holes to avoid trip and fall hazards.

The compressor frame and crosshead supports should be leveled and supported with grout boxes and soleplates on top of the compressor pedestal. The engine is supported by a deep engine pedestal with external gussets for horizontal stiffness. The engine is supported and leveled with screw or incline plane adjustable devices on top of 25 mm thick support plates.

Perimeter anchor bolts are placed at the end of main skid beams, under the engine and compressor feet, at all skid corners and at the end of internal main runners. 10 mm thick diamond plate is recessed between beams and welded flush all around to provide a safe work surface for personnel. All components and their mountings should be welded to skid structural members, not to the deck plate.

Scrubbers and/or secondary volume vessels are mounted off skid and welded to 51 mm grouted foundation plates. This normally insures flexibility for the suction bottle inlet flange to enter horizontally into the vessel head. Vertical suction vessels should be located as close to the main skid as practical to minimize risk of spool piece resonance.

Discharge bottles are supported with bottle wedge supports inline with each compressor nozzle, and wedges with straps support extended bottle overhangs. The wedges should be mounted on grouted foundation sole

plates or skid beam outriggers that are grouted. Distance between the bottom of the discharge bottle and the bottom of the wedges should be 152 to 203 mm.

Adding concrete to the skid is beneficial for reducing vibration of the skid and skid-counted components. Concrete provides stiffness as well as damping, and is recommended in the skid below the compressor crankcase, crosshead guides and coupling area between the compressor and driver.

Concrete is also beneficial in the skid area below the driver, particularly for higher power units. If scrubbers are mounted on the skid, the areas underneath them should also be concrete filled. If the skid design includes a pedestal, it should be concrete filled in the same areas as the main skid. If the pedestal is not filled with concrete, provisions should be made to allow for concrete to be added on-site, if required.

Effective connection of the skid to the foundation is extremely important. Over time, temperature changes and creep in the foundation and epoxy grout will tend to cause anchor bolt loosening in vibratory service. Anchor bolts should be long and tightened to a high stress level to ensure that they stay tight. If they loosen, the path is lost for transferring vibratory energy into the foundation. Most sources agree compressor frame and crosshead guide support anchor bolts must have a free bolt length of at least 12 bolt diameters.

Commonly, perimeter and internal skid anchor bolts and anchor bolts for block mounted equipment are 914 mm minimum length and other anchor bolts are 457 mm minimum. Concrete strength and bolt stretch considerations dictate that anchor bolts extend to the lower third of the concrete block. Bolts should terminate with a lower disc supported in a three-dimensional rebar cage. To allow free bolt stretch and prevent bonding of concrete along the bolt length, best practice is to use a canister sleeve around each anchor bolt. Sleeves should not protrude above the concrete surface and

must be sealed to prevent water and concrete from entering.

Anchor bolts should be the largest diameter that the equipment mounting flanges permit, but no less than 28.6 mm diameter for equipment and skids in this size range. ASTM A193 Grade 7 bolts, made from AISI 4140 alloy steel with rolled threads, and ASTM A194 Grade 2H nuts are required.

Double spherical high-tensile washers are recommended under the nuts to minimize bending from misalignment. Engine and compressor manufacturers will often specify the required tightening procedures and tightening level for anchor bolts used to mount their machines.

Where the OEMs have no specifications for anchor bolt tightening, the best practice is to tighten them to 80% of the bolt proof stress or 55% of the bolt material ultimate tensile strength, whichever is higher. Before and after installation, preserve any fasteners that may be subject to corrosion.

Epoxy grout, soleplates and stainless steel shim packs are usually best practice for chocking the compressor to the skid. Maximum shim pack thickness should be 6 mm, with no more than three shims in a pack to prevent spongy (soft) pads. Adjustable chocks, in which the load is principally carried by a threaded member, are not recommended under compressors.

Epoxy grout is required for grouting the compressor skid to a concrete foundation. Thermal expansion joints are required in the grout and inspection ports in skids are recommended to verify grout flow under the skid. Most grout suppliers can provide assistance with grout specification, preparation, expansion joints, and installation procedures.

For compressor frames with 3729 kW and 24,014 kg rated rod load, block mounted foundations (i.e., no skid) are generally best practice. Options for mounting equipment directly to a concrete block include steel rail mounting, soleplates and shims, and soleplates and chocks. Skids and/or equipment should not be mounted on foundations with isolators or isolation pads. **CT2**