COMPRESSOR OPERATING CONDITIONS & LOADING: A TORSIONAL PERSPECTIVE

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Pipeline and Compressor Research Council Gas Machinery Conference, October, 1996
Canadian Machinery Vibration Association Annual Meeting, October, 1996

Abstract

A gas compression system's torsional response is very sensitive to a reciprocating compressor's configuration and operating conditions. Changing the shaft speed, unloading a cylinder, re-positioning a cylinder on the crankshaft, or accepting different gas conditions can significantly affect the system torsional response and corresponding shaft stresses.

If a reciprocating compressor system is subjected to a range of demand or field gas conditions and is operated in various loading configurations, the torsional response and shaft stresses at *each* compressor operating point must be acceptable. Since it is not generally feasible to calculate the torsional response at each operating point for all the potential modifications, appropriate "torsional design cases" must be determined.

Case studies and basic torsional vibration theory provide insight to the sensitivity of a system's torsional response to operating conditions and loading. Compressor performance simulations illustrate the relative influence which different operating conditions and loading have on the system's torsional response and shaft stresses. Guidelines for determining the "torsional design cases" are defined.

1. Shafts can fail due to changes in operating conditions or load steps.

Reciprocating compressors can operate over a relatively wide range of conditions and in various loading configurations, both by design and due to upset conditions such as valve failures. From a torsional point of view, such changes may cause changes in:

- compressor torque effort
- corresponding shaft stresses
- resonances

Therefore, it is critical to design the system for the range of potential conditions, not just the design condition.

If a compressor's operating conditions or loading vary, dynamic and mean shaft torque could change sufficiently to cause shaft failure in a system. Case 1 is one example, demonstrating the difference between double-acting and single-acting configurations.

Case 1 – Failure Imminent of Cylinders Changed From Double to Single-Acting

Unit:
- Four throw reciprocating compressor.
- 900 HP induction motor.
- Flexible disc coupling.

The primary mode of operation for this system has all four cylinders double-acting. In this configuration, the shaft and coupling stress design factors (i.e. safety factors) are appropriate, as shown in Figure 1.

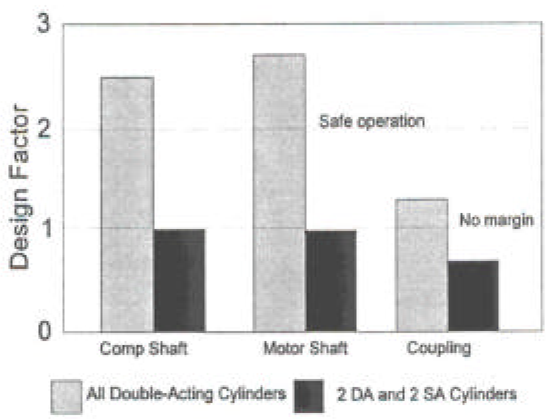

Figure 1. Design Factors are acceptable for the fully loaded case but are unacceptable for the single-acting case.

Other operating modes, however, are unsatisfactory. The most significant one for this system was two double- and two single-acting cylinders. This alternative configuration resulted in stress design factors of one or less. It should be noted that cylinders can also be made single-acting by valve failure; therefore, this condition could arise inadvertently.

"Torque effort" is the combination of mean and dynamic torque over one revolution. The driver must produce the torque effort demanded by the compressor. The different stresses result because single-acting cylinders have different torque effort curves than double-acting cylinders (Figure 2). These differences can have a dramatic effect on the overall system torsional response.

Design (Safety) Factors

Design factors are based on a calculation of shaft stress, which is a function of the applied system torque. Maximum allowable system torque is therefore determined by the maximum allowable shaft stress level. Generally the material endurance strength should be greater than the maximum shaft shear stress by a factor of at least two.

Usual Interpretation of Design F actors:

2	*--acceptable in all cases*
1.5 – 1.9	*--marginal*
1	*--no safety margin*
<1	*--failure is imminent*

In this instance, single-acting cylinder configurations produced high torque effort at five times shaft speed (5X), which corresponded to the system TNF, (i.e. resonance). To minimize the torsional response under single-acting cylinder configurations, a compressor side flywheel [1,2] was used to shift the system torsional natural frequency away from 5X shaft speed.

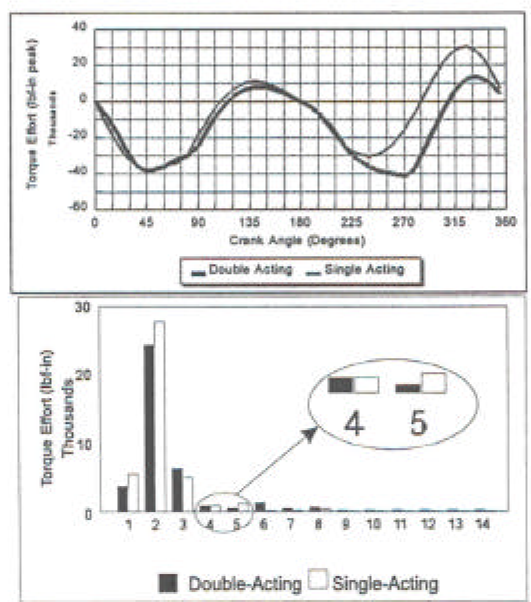

Figure 2. Cylinder torque effort at five times shaft speed for the single-acting case was more than double that of the double-acting case.

2. Design Guidelines (Torsional Viewpoint*)*

The following guidelines serve as a starting point for a torsional design. Early in the project, you should satisfy yourself about each point. Justification for the guidelines is provided in the following sections.

Torsional response and corresponding shaft stresses are so sensitive to compressor operating conditions and loading that, in most cases, the final analysis should normally encompass the entire range of operating conditions and load steps. However, if the preliminary analysis based on design case guidelines gives very high design factors and the compressor application is not critical, it may not be necessary to scrutinize the operating envelope further.

i) Analyze the extremes, in the preliminary stage of the analysis.

- high power double-acting case
- high power single-acting case
- maximum suction and discharge pressure
- minimum suction and discharge pressure
- pockets fully closed and wide open

ii) Analyze the speeds near the TNF.

Determine the torsional natural frequency (TNF) of the system components and check the system at those frequencies plus or minus 10%.

iii) Consider unusual conditions.

Operating the compressor on bypass may change the system torsional response significantly. Mechanical failures may result in a different operating mode, e.g. if a valve fails and creates a single-acting condition.
If the consequences of failure and the likelihood of an upset condition combine to generate an intolerable situation, analyze the effect of potential faults in the design stage.

iv) Place the cylinders appropriately.

Cylinders with the highest torque effort at orders of shaft speed near the system TNF should be positioned nearest the coupling. This approach will minimize the torsional response, since torque effort has less influence at the coupling (i.e. torsional modes tend to be nodal near the coupling).

Vectorial addition of the individual cylinder torque efforts provides an *indication* of the combined compressor torque effort. However, vectorial addition is not fully representative of the dynamic response. A detailed torsional analysis must treat each individual cylinder's torque effort at the appropriate position on the crank shaft. Lumping all the cylinders together is inappropriate.

3. Operating & Loading Conditions Influence Compressor Torque Effort

Operating and loading conditions strongly influence the shape and frequency content of each cylinder's torque effort curve. To understand how particular operating and loading conditions affect the compressor torque effort curve, it is necessary to understand how torque effort is determined.

3.1 Gas and Inertia Forces

Compressor torque effort as seen by the compressor shaft is a function of reciprocating inertia forces, cylinder gas forces, and geometry.
Reciprocating inertia forces are functions of crank angle, crank speed (Figure 3), geometry and reciprocating mass. They are most significant at one through four times shaft speed.
Cylinder gas forces are functions of crank angle, crank/rod geometry, cylinder loading (Figure 4), and operating conditions. They include all orders and are not significantly affected by shaft rational speed.

Torque effort for each cylinder is obtained by vectorially adding the reciprocating inertia and cylinder gas forces. These torques have a cancelling effect for much but not all of the crank cycle (Figure 5).

Torque effort curves of varying amplitude and frequency content result from different inertia and pressure curves. For example, inertia forces increase but the gas forces remain essentially unchanged for increased crank rotational speed; a different torque effort curve will result.

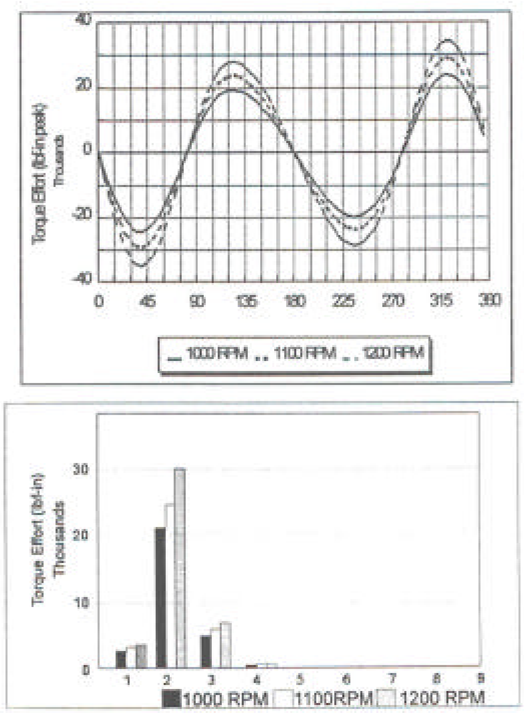

Figure 3. Reciprocating inertia torque (bore = 11.5", stroke = 4.5", rod length = 13.75").

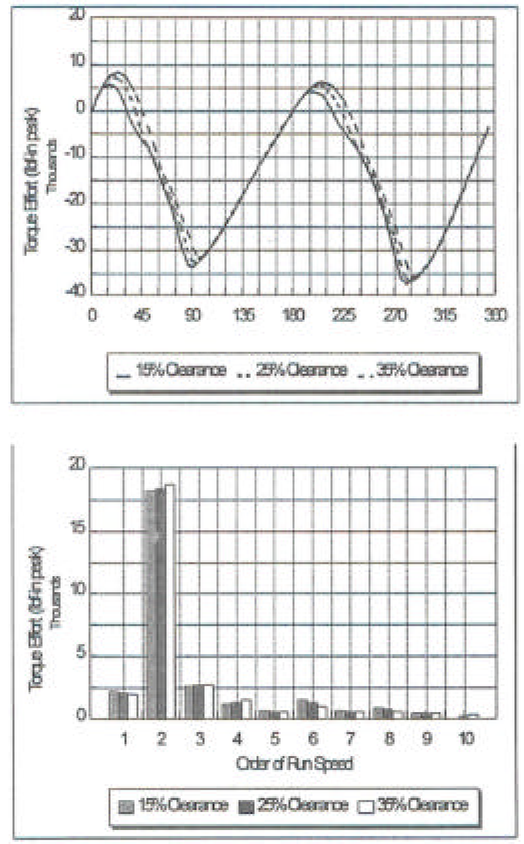

Figure 4. Cylinder pressure torque (bore = 11.5", stroke = 4.5", rod length = 13.75", Ps = 130 psia, Ts = 140F, Pd = 249 psia)

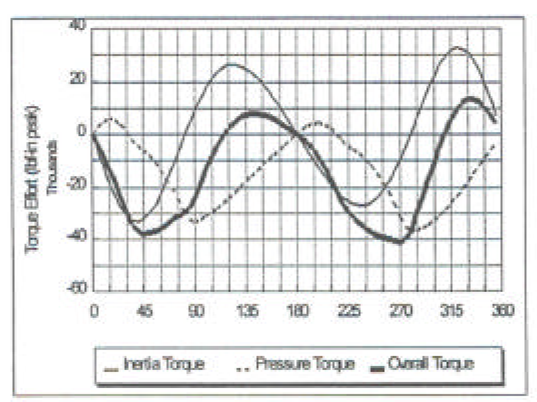

Figure 5. Torque effort of a double-acting cylinder.

3.2 *Cylinder Loading*

Compressor cylinder torque effort is influenced by single- or double-acting operation and by clearance volumes.

A double-acting cylinder typically has a higher mean torque but lower alternating torque than a single-acting one. An example is given in Figure 6, where the mean torque (shown as order zero) is greater for the double-acting case and the first through third order alternating torque efforts are greater for the single-acting case.

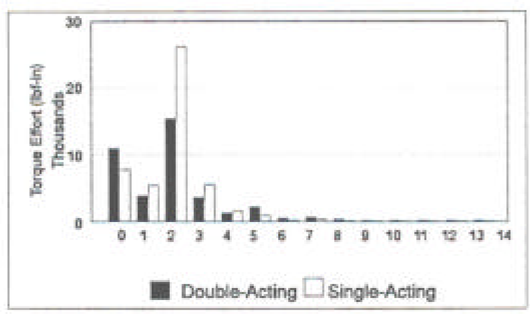

Figure 6. Cylinder torque effort (single-acting configuration has the head end valve removed).

Variable volume pockets also change the torque effort spectrum. Figure 7 shows one example for the fourth order and above, which is the concern because the TNF is usually in that range. Random variation is seen among the various configurations: single-acting and double-acting with different pocket openings. Therefore, it is important to test the final modification for all configurations.

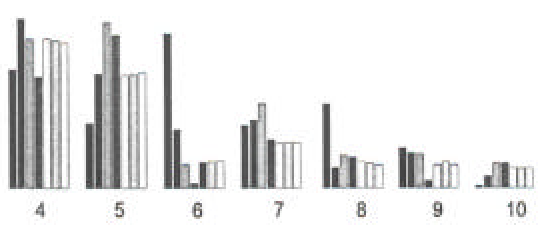

Figure 7. Each block shows the relative torque efforts for an order of runspeed for a cylinder loaded as follows: 15%, 50%, 75%, 100%, 150%, 200%, and single-acting. Amplitudes are low relative to torque at lower orders but the differences are often significant.

3.3 *Compressor Operating Conditions*

The reciprocating inertia component of cylinder torque effort is a function of the square of the shaft rotational speed. An increase in crank speed increases the torque effort at the first through fourth orders.

The system torsional response is most sensitive to speed changes when the torsional natural frequency is less than or equal to four times run speed. The ratio of torsional natural frequency to shaft speed indicates whether the system is torsionally resonant; if it is within 10% of an integer, the system is resonant for practical purposes.

Operating gas pressures and temperatures fluctuate over time. Any variation in gas composition results in different densities and specific heats. These variations in operating conditions influence the compressor gas torque effort.

One compressor operating condition is generally not representative of an actual operating system. There are many combinations of speed, pressure, temperature, flow, and gas composition which define the compressor operating envelope. The system torsional response and corresponding shaft stresses of every condition within this envelope must be acceptable.

Consider the following compressor operating envelope.

- constant discharge pressure
- *varying suction pressure*
- fixed clearances (volumes)
- fixed speed
- constant gas properties

As shown in Figure 8, a reduced suction pressure can reduce the alternating component of the compressor torque effort.

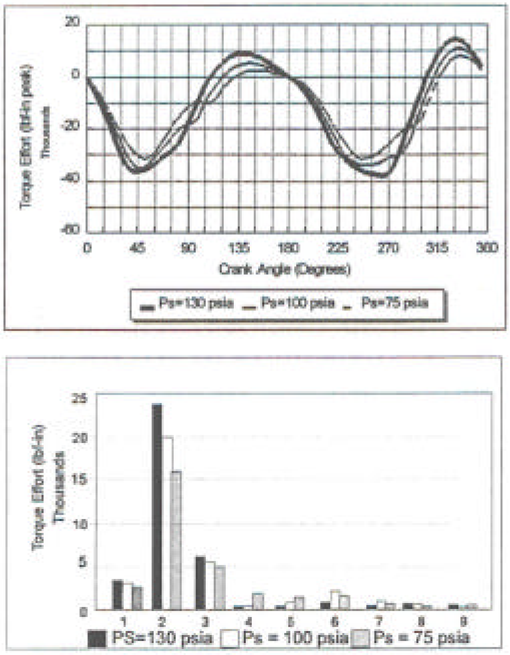

Figure 8. Suction pressure influences cylinder torque effort.

4. Position of Cylinder Throws on the Crankshaft is Critical

Another reason for excessive torsional response can be the position of the cylinders on the crankshaft. A given cylinder will produce a torque effort based on its geometry, load step, and operating conditions. To get the “system” torsional response, the combined effect of all cylinder is required.

Cylinder torque efforts do not act at one single-point on the crank shaft but are spaced along the shaft at the same positions as the crank throws. There is a finite shaft length between each throw which affects the dynamic “system” [1] response. Individual cylinder torque efforts *cannot* be simply added and lumped at one point on the shaft if accurate predictions are required.

Any one cylinder will have more or less influence on the overall torque effort curve depending on where it is positioned with respect to the mode shape of the system. A typical torsional mode shape of a motor driven reciprocating compressor is shown in Figure 9. It indicates that the dynamic torsional response is less sensitive to torsional excitation (i.e. cylinder torque effort) at throws nearest the coupling.

If, for example, the torque efforts at Throws 1 and 4 (as represented in Figure 9 by Nodes 10 and 6 respectively) were identical and of opposite phase they will not exactly cancel. The torque effort at Throw 4 has a higher dynamic amplification than at Throw 1.

Clearly, the objective is to place cylinders that produce maximum input at frequencies close to the TNF at positions of minimum influence. See Case II.

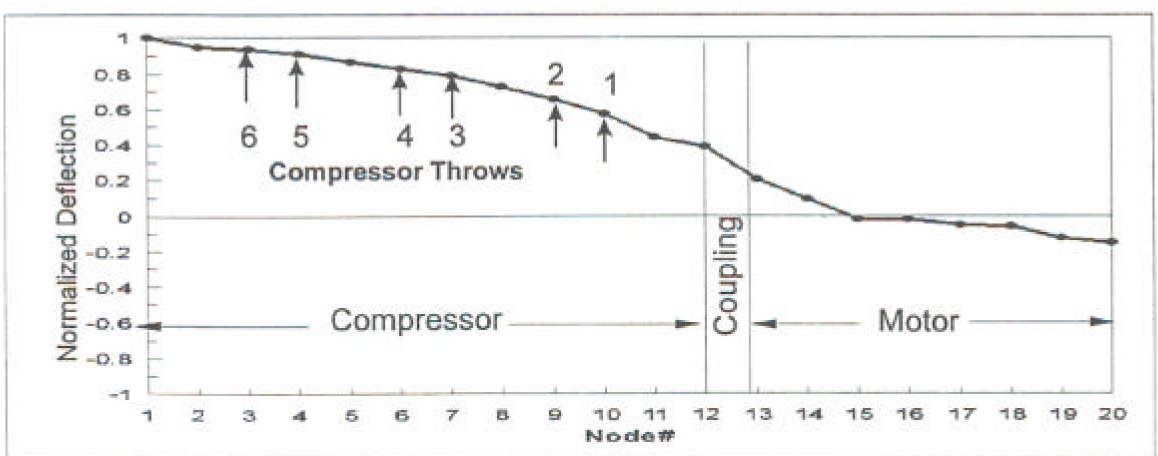

Figure 9. Torsional mode shape indicates that the system is nodal near the coupling.

Case II – Torsional Response is Sensitive to the Location of Compressor Throws on the Compressor Crankshaft.

Unit:
- Six throw reciprocating compressor.
- 4 throws active, 2 inactive
- 1200 kW induction motor.
- Flexible disc coupling

Four of the compressor throws drive double-acting cylinders. The other two throws drive inactive cylinders. Although the power requirement of the two inactive cylinders is negligible, torque effort due to their reciprocating inertia is significant (Figure 10). The mean torque of an inactive cylinder will be zero if friction is ignored but the alternating torque effort is large.

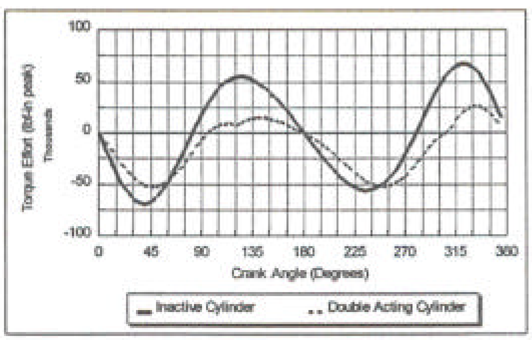

Figure 10. Torque effort for inactive cylinders is high, even though their consumption of horsepower is lower.

The original layout had the inactive cylinders positioned on the compressor outboard Throws 5 and 6, farthest from the coupling, (represented in Figure 9 by nodes 4 and 3). The mode shape is such that the system dynamic response is less sensitive to torque effort at the inboard throws (nodes 10 and 11).

Therefore, to minimize dynamic torsional response and corresponding shaft stresses, the inactive cylinders were re-located to the inboard throws. This modification increased the shaft stress and coupling torque design factors to acceptable values (Figure 11).

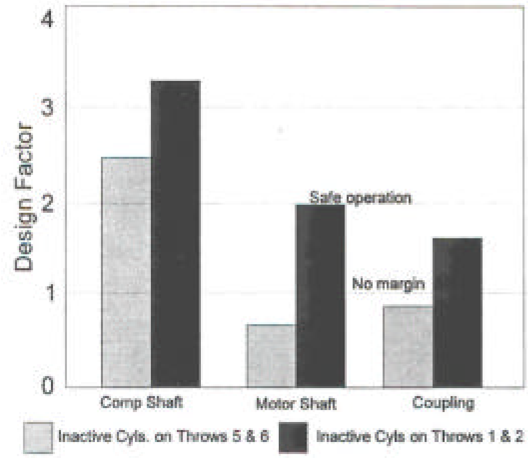

Figure 11. Design factors were much better when the cylinders with highest torque effort were positioned close to the coupling.

5. Conclusion: Torsional Analyses Must Consider the Full Operating/Loading Envelope.

1. Compressor operating conditions can change the torque effort characteristics significantly. Therefore, specify all operating conditions and ensure that analysts take them into account.

2. Compressor load steps, especially in conjunction with alternative choices of throws for unloaded or partially loaded cylinders can mean the difference between breakdown and reliable operation. Specify the entire range and make sure that they are all considered.

6. References

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[5] Zacharias, Val et al. *Torque Talk: Informed Decision-Making About Torsional Stress*. Calgary, Beta Machinery Analysis, 1996.

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