Studies and Analyses

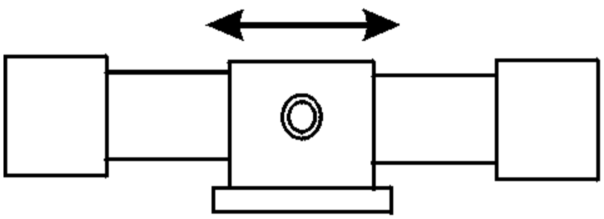
Unbalanced Forces and Couples

Reciprocating compressors develop unbalanced forces and couples due to tolerances in the reciprocating weights at the offset of the compressor throws. The unbalance comes in the form of horizontal and vertical forces and horizontal and vertical couples.

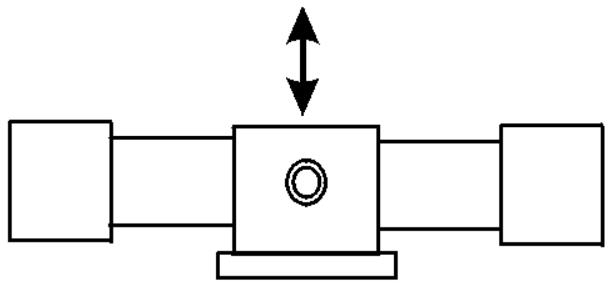
The compressor skid and foundation must be designed to dampen and transfer these forces.

All Forces and Couples act about the center of the crankshaft.

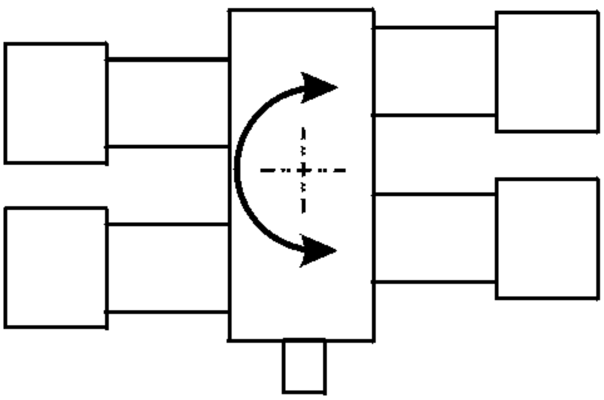
Related topic: Balanced Opposed Design



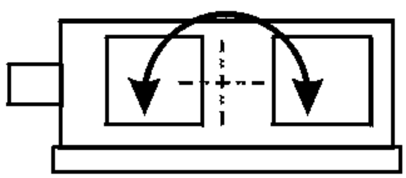
HORIZONTAL FORCE



VERTICAL FORCE



HORIZONTAL COUPLE



VERTICAL COUPLE

Starting Torque

Start up torque is used to determine if an engine starter, or electric motor driver has enough torque to start a compressor.

Start up torque is characterized by two main components, break away torque and speed up torque. The break away torque is the static friction and gas load on the piston rod area at zero rpm. The speed up torque is the dynamic friction and the pressure load on the cylinders as the unit speeds up toward full speed.

Ariel provides start up torque data within the Ariel Performance Program. All start up torque calculations provided assume that a bypass or gas recirculation line is installed and open, sized to bypass 100% of the compressor flow.

The break away torque is dependent on the pressure on the unit when the start button is pushed. Higher start up pressures will result in higher break away torque. If the break away torque must be reduced for starting, the pressure on the unit must be reduced. Six throw units are mostly exempt from this as the phasing of the six throws offers a cancellation of the individual throw torques from the pressure on the piston rod.

The speed up torque can be impacted by both the starting pressure, as well as the bypass line pressure loss. Smaller bypass lines will have higher pressure losses, resulting in higher torques as the unit approaches full speed.

Start Up Torque Calculations:

- Use the highest suction pressure that the unit will see when the start button is pushed. This may be a normal (max) suction pressure, or a settle out pressure.
- Load all manual capacity devices (close VVCP's, remove spacers, double act cylinders if valves are removed manually for single acting cases).
- Unload all panel controlled capacity devices (open FVCP's, single act if SVU's are provided)
- Consider and calculate the bypass line pressure losses for a more accurate torque curve.
- Apply the final flywheel inertia from the torsional analysis and current pulsation analysis for the final start up torque calculation

Bypass Line Pressure Losses:

- Ariel provides an entry for the bypass line pressure loss. This is a value multiplied by the number of stages, for a total pressure loss.
- The default value is 25 psi times the number of stages. This is only a rough value for a beginning assumption.
- The start up torque calculation will include a "flow at Start up". Apply this value when calculating the bypass line pressure loss. At the lower ratios of start up (bypass line open) the flow can be much higher than the compressor design flow.

For electric motor drives, please also refer to Driver Power Rating topic.

Typical Starting Torque Data and Curves provided within the Ariel Performance Software:

Disch Press equals Suction Press

Breakaway Torque

Speed RPM	Srv 1 Disch psig	Power BHP	Mean Torque ft-lbs
0	350.00	0.00	3207.5
90	350.250	5	299.4
180	351.000	16	472.6
270	352.250	39	760.8
360	354.000	80	1163.5
450	356.250	144	1679.7
540	359.000	237	2308.4
630	362.250	366	3048.6
720	366.000	534	3898.7
810	370.250	749	4857.6
900	375.000	1015	5923.7

Starting Torque (Pull-up Torque)

Disch Press increases as speed increases flow

Friction Breakaway Torque: 1400.00 ft-lbs

Total Running Gear Inertia: 82838.289 lb·in2
Expected Startup Flow at full speed: 115.644 MMSCFD

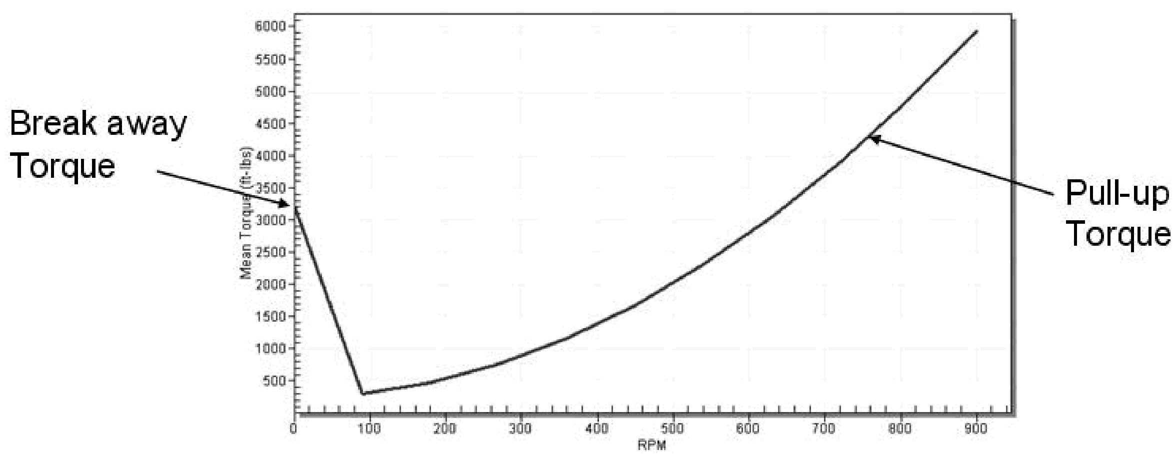
Compressor Inertia

Break away torque

- Static friction
- Equalized gas pressure
- Gas pressure on piston rod area

Pull-up torque

- Dynamic friction
- Gas compression due to increased discharge pressure as flow increases on bypass



Torsional Vibration Analysis

Torsional Vibration Analysis is the analysis of the torsional dynamic behavior of a rotating shaft system as a result of forced vibration. Torsional vibration, or twisting, is different from lateral vibration, or shaking. A torsional system, compressor, driver, and coupling, are modeled as a mass-elastic system (inertia and stiffness) to predict stresses in each component. Mass-elastic properties of the system can be changed by adding a flywheel (additional inertia), using a soft coupling (change in stiffness), or by viscous damping (absorb natural frequency stimulation). Not all systems require any modification to the mass-elastic properties to achieve a torsionally sound system.

Ariel Corporation can provide the data for the compressor necessary to perform a torsional vibration analysis. This includes the torque effort curves (torque versus crank angle), mass elastic data and fourier coefficients representing the torsional driving forces. The torsional analysis is the responsibility of the Packager.

Care must be taken to represent the operating conditionsthe unit will see, including any partial load conditions. Any single acting cylinder operation is important to include as these cases can represent the more dynamic torque effort curves.

When applying variations in speed and single acting cylinder configurations the torsional and acoustical response analysis will be much simplified by applying single acting configuration only at one given speed. In order to eliminate over complicating the torsional and acoustical systems, specific capacity control methods may be more attractive than others. For a discussion on these methods, and recommendations on capacity control methods, refer to the Capacity and Load Control topic.

Capacity control sequencing can be very important when considering single acting operating cases. Sequencing of cylinders for unloading can be very important to both the torsional analysis as well as the acoustical analysis. Single acting provides a much more aggressive forcing function for the torsional analysis. There is no absolute rule on which cylinders to single act at a time, but a recommendation is to **unload adjacent cylinders before unloading opposing cylinders** (unloading opposing cylinders is much more aggressive on the torsional forcing function than unloading adjacent cylinders). The opposite is true for acoustical analyses when considering single stage compressors with symmetrical pulsation vessels. These are recommendations for a more polite torsional solution, but not the only sequence that will work. A more aggressive load sequence, may just end up with a more aggressive solution to the torsional (black out speeds, torsionally soft coupling, larger flywheel...).

Once a load sequence is chosen, this needs to be applied to the torsional analysis, acoustical analysis, and the control panel logic sequence. If the unloading is to be by manual methods, such as removing valves, it is recommended to review load sequences for any possible variation single acting location.

When applying an electric motor driver, whether fixed speed or variable speed, specific attention must be made to the motor shaft design. The motor stub shaft and the section through the drive end bearing should equal or exceed the compressor drive stub diameter. JGE:K:T/6 and KBB:V frames have flanged drive end connections on the crankshaft, use the crankshaft journal diameter for the minimum motor shaft diameter.

ER-83 provides torsional analysis limitations and guidelines. Ariel provides Vibratory Torque Limits rather than allowable stress limits. Appropriate safety factor and fatigue method has been applied within these vibratory torque limits. Auxiliary end limits and guidelines are defined. Flywheel overhung weight limits are defined along with the proper calculation method.

The torsional analysis should be scheduled as early in the process as practical. Changes to the system design may be required to satisfy the torsional analysis. This may include a different coupling type or model, the addition of a flywheel, or on rare occasion a change to the compressor or driver design.

Below is a list of data necessary for the different phases of a project:

Quotation:

- System definition (compressor type / size, driver type / size)
- If electric motor, define if fixed speed or variable speed

- Include 4 to 7 operating points for review to characterize the full operational map (conditions and load steps) of the compressor

Purchase:

- Full system layout defining compressor, driver, coupling, speed control

Compressor Load Data:

- Define the full range of operating conditions
- Suction pressure range
- Discharge pressure range
- Load step sequence, including pockets and single acting
- Speed range
- Be sure to define load steps consistently throughout the case manager
- Be sure to provide the same load step sequence for the acoustical analysis and (if pneumatic capacity control devices) control panel logic

Compressor Data necessary for Torsional:

- Performance run file for the compressor defining the full operating map
- Mass elastic data
- Torsional supporting documents
- Performance report for each peak condition
- Gas analysis for each peak condition
- Crank effort curve for each peak condition
- Fourier coefficients for each peak condition

To Generate Data:

- Define the full operational map for the compressor in the Case Manager
- Define the Summary Field Configuration to include Peak-to-Peak/2 and Vector Sum 1 through 9 from the torsional section
- Run the Performance Summary and select the cases with the highest Peak-to-Peak/2 and Vector Sum 1 through 9

Run the Report Manager selecting the following reports:

- Configuration
- Mass Elastic Data
- Torsional Supporting Docs
- Performance
- Gas analysis
- Torque Demand Graph
- Fourier Coefficients

Confirmation:

Confirm Torsional recommendations against equipment on order or shipped. This includes confirmation of:

- Flywheel size
- Coupling model
- Internal flywheel size
- Detuner quantity and location
- Driver dampener

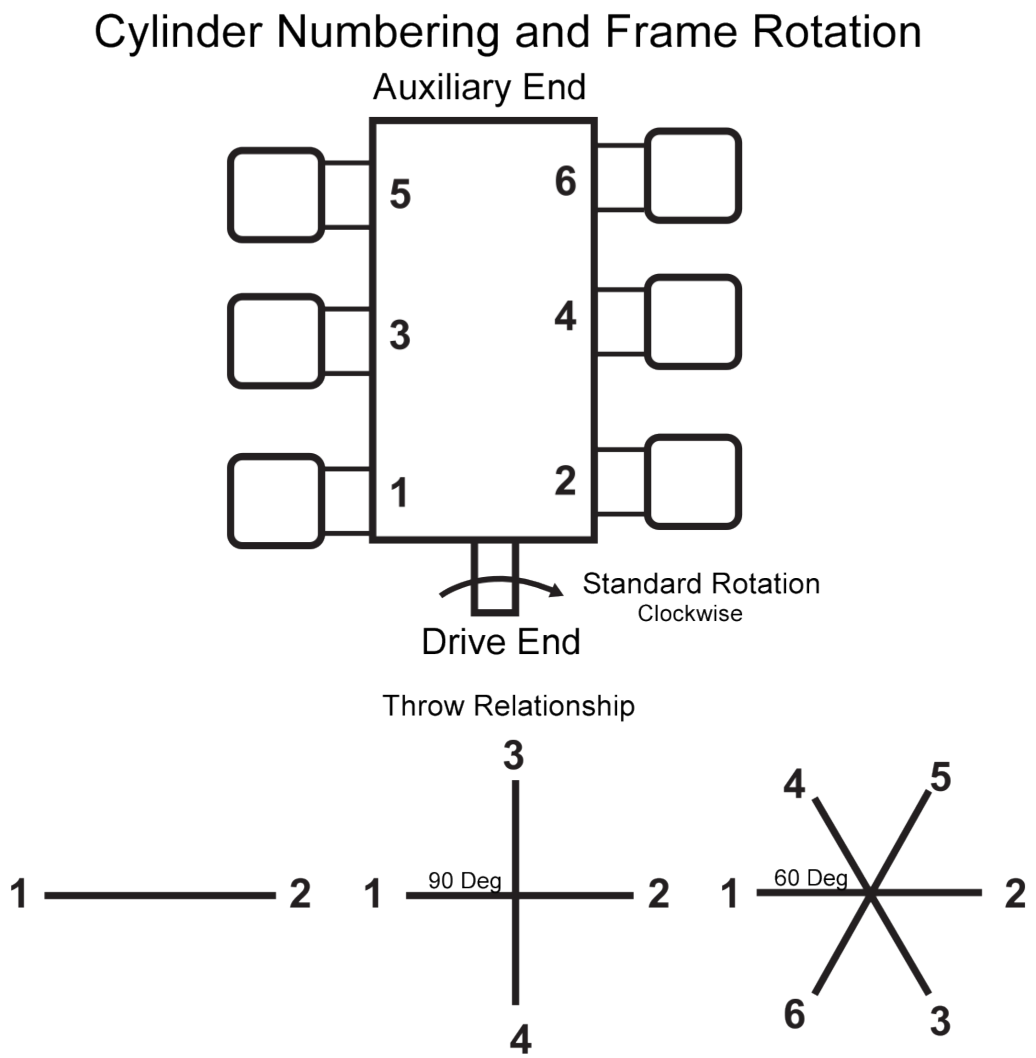
Confirm Torsional solution through field verification at start up for larger, more complicated and new driver compressor combinations, including

- Large Electric Motor Drives
- Variable Frequency Drives
- New Combinations of Driver / Compressor
- Complex Torsional Designs (black out speeds, torsionally soft couplings, black out load steps)

Documentation:

- Recommend including the Torsional Study report in the unit records book for the end user and jobsite

Cylinder Numbering and Phasing



Throw Phase Angles
(viewed from drive end toward aux end)

2 Throw	4 Throw	6 Throw
Lagging	Lagging	Lagging
Throw 1&2 0 Degrees	Throw 1&2 0 Degrees	Throw 1&2 0 Degrees
	Throw 3&4 270 Degrees	Throw 3&4 120 Degrees
		Throw 5&6t 240 Degrees
Leading	Leading	Leading
Throw 1&2 0 Degrees	Throw 1&2 0 Degrees	Throw 1&2 0 Degrees
	Throw 3&4 90 Degrees	Throw 3&4 240 Degrees
		Throw 5&6 120 Degrees

* Standard Rotation for the JGI frame is counter-clockwise

Inadequate Surge Volume

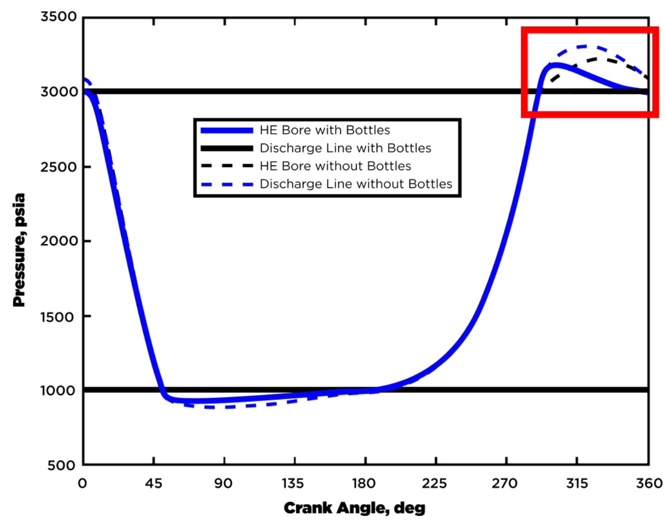
Pulsation vessels are required for both reducing pressure pulsations in the gas piping system and providing a surge volume of gas to allow the cylinders to breath well during suction and discharge events. Refer to API-618 for pulsation vessel sizing criteria.

If the suction or discharge system is too restrictive, ratio inside the cylinder will be increased— the suction pressure inside the cylinder will be lower, and the discharge pressure will be higher. This higher internal ratio can result in less flow when compared to predicted flow. This can also result in higher temperatures, higher gas rod loads, and higher power consumption. Significant impacts have been seen due to restrictive inlet and discharge gas piping systems.

Restrictive gas piping systems can be from additional equipment in the pulsation vessel, such as orifices, or from the use of piping without a surge volume. Though pulsation vessels are required, some smaller power units are built without pulsation vessels. Piping in and out of a cylinder can create these higher internal ratios. If applying piping rather than pulsation vessels, we have seen a reduction of the restrictive piping effects through the use of expanded pipe sections at the cylinder inlet and discharge.

API-618 includes an initial sizing recommendation for pulsation vessels.

Figure: PT Card with Comparison of Volumes



	With Bottles	Without Bottles
Power (HP)	211	221
Flow (MMSCFD)	4.55	4.41
Discharge Temp (°F)	231	240
Specific Power (HP/MM)	46.37	50.11