# EFRC Training Workshop

## Foundation design for reciprocating compressors

Excitation Loads

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# Introduction

- Reciprocating compressors impose heavy dynamic forces on the foundation These forces are of two types
- Global forces apply due to net unbalance inertia forces from the rotating and reciprocating parts plus unbalance pulsation forces in the pulsation bottles and in the cylinder nozzles. These are typically the only forces reported and act on the entire foundation
- Local forces are internally balanced within the compressor and so local forces on foundation result from the differential elastic stretch of the compressor

# Unbalance rotating and reciprocating mass

Unbalance Inertia forces are the vector addition of the rotating and reciprocating mass of all throws.

For vertical force

$F=m_{rot}.r.w^2$ sinw.t  Where $m_{rot}$ is the rotating mass, r is crank radius, w is angular velocity in radians/sec, w.t is the crank angle (0=outer dead center)

For horizontal force (axis of piston rod)

$F=(m_{rot}+m_{rec}).r.w^2 \cos.w.t+m_{rec}.r.w^2\ r/L \cos 2w.t$ where L is the connecting rod length.

For the reciprocating mass there are a 1x and a 2x component.  Ratio r/L is typically about 20%.

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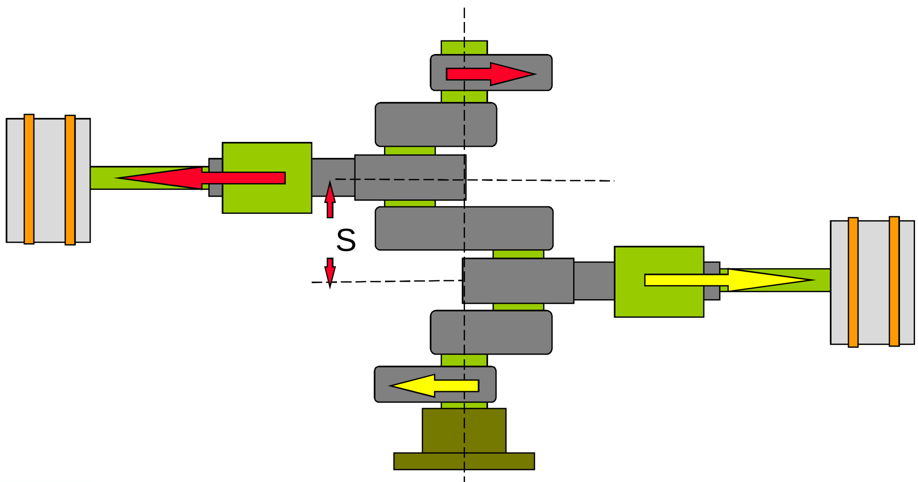
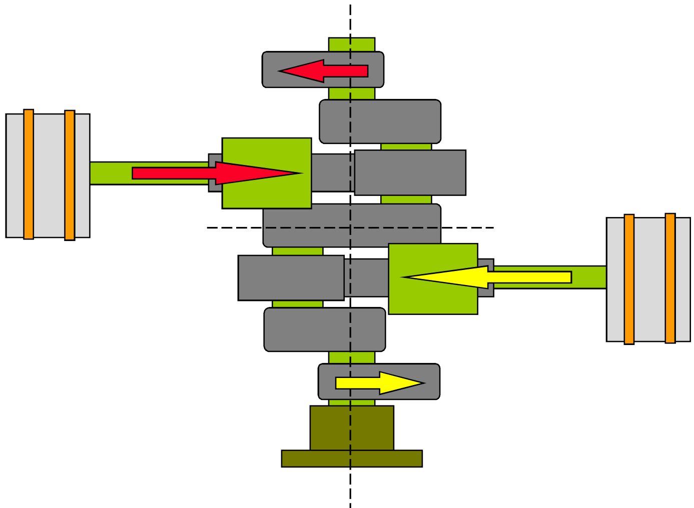
## *Forces and Moments*




At the outer position the reciprocating weight gives a tension accelerating force, this is balanced by the opposing throw, but the throws are offset resulting in a moment.  Counterweights are added to reduce moments

## *Forces and Moments*



180 degrees later the reciprocating weight gives a compression accelerating force, this is balanced by the opposing throw, but the throws are offset resulting in a moment.

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# Inherent unbalanced forces & moments for opposed recips

| No of crank throws | Crank Angle | Unb force 1x | Unb force 2x | Unb moment 1x | Unb moment 2x |
|---|---|---|---|---|---|
| 2 | 180 | 0 | 0 | F'xS | F"xS |
| 4 | 90 | 0 | 0 | 1.414F'xS | 0 |
| 4 | 0 (flat) | 0 | 0 | 0 | 0 |
| 6 | 60 | 0 | 0 | 0 | 0 |
| 8 | 90 | 0 | 0 | 0 | 0 |

Note the 1x unbalance moment can be reduced using counterweights

F' inertia force of 1 throw, F" 2x inertia force of 1 throw S is axial spacing between opposing throws.

Assumes all recip weights are equal.

A counterweight pair is usually provided to reduce the 1x moment.

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# Allowable Unbalance Forces

- Some unbalance is inevitable.
- Slow speed process compressors mounted on massive concrete foundations will accept large unbalance forces. Balancing opposing throws so the (1x + 2x) unbalance force is less than 5% of the machine rod load rating is typical and usually adequate to achieve acceptable vibration
- Skid mounted and compressors mounted on poor foundations require closer balancing.
- Compressors mounted on offshore platforms require close balancing.

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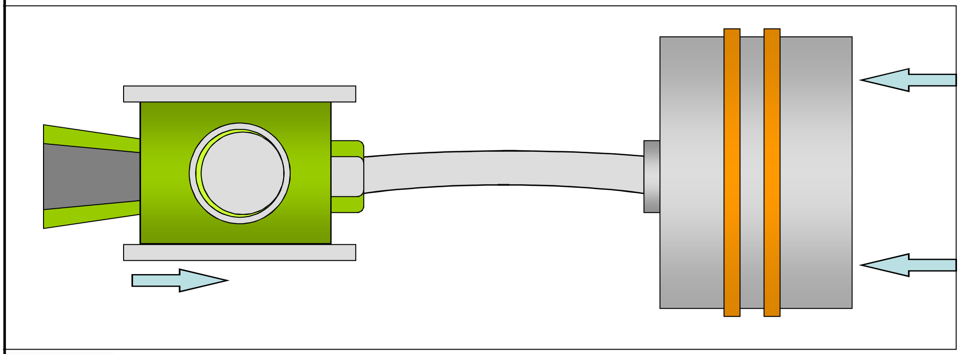
## *Gas Load (compression)*



This shows the gas force acting on the piston Compressive on the outboard stroke This is balanced by an equal and opposite force on the cylinder DP frame

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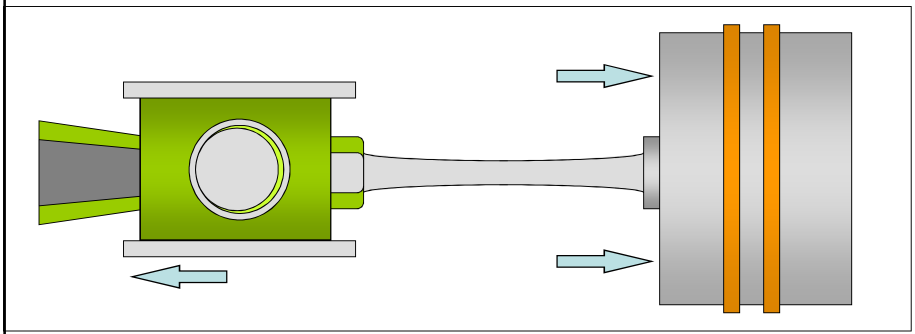
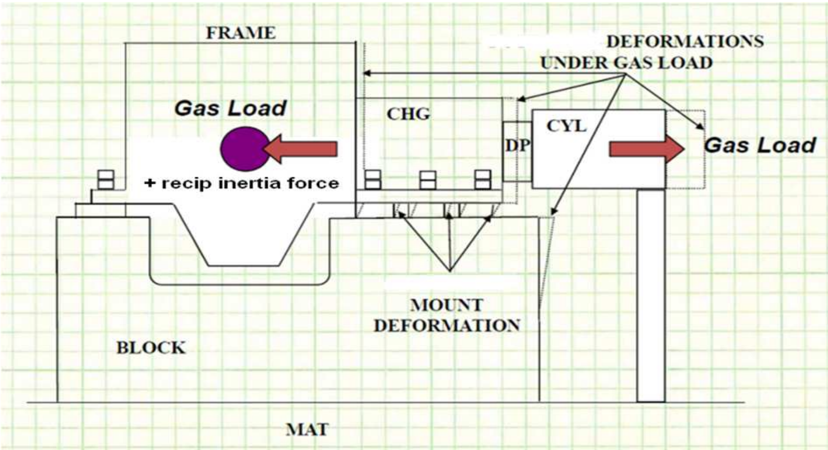
# Gas load (tension)



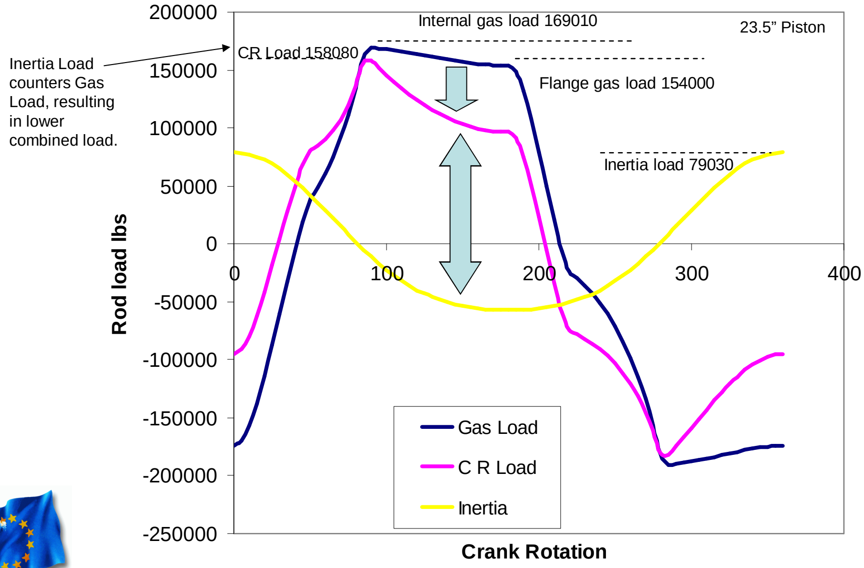
180 degree later the gas force acting on the piston is compressing on the inboard stroke This is balanced by an equal and opposite force on the cylinder DP frame



# Elastic Stretch due to gas load



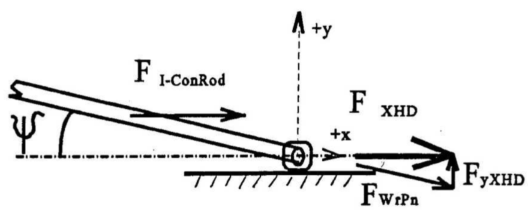
# *Rod Load – Combined Load*





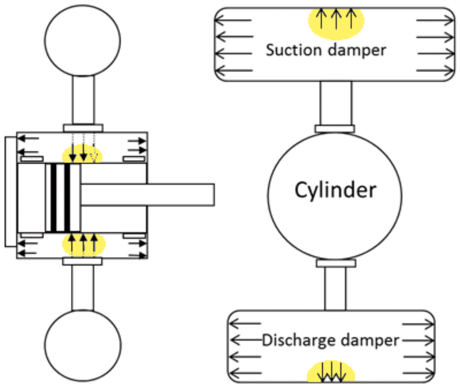

# Vertical rod load force at the crosshead (local)

- The combined rod load acts on the connecting rod wrist pin. The connecting rod oscillates as the crankshaft rotates. This imposes a vertical component force on the crosshead guide which is restrained by the guide foundation.




- This a local force because there is an equal and opposite force at the big end of the connecting rod and acts at the main bearings into the frame.

# Gas Unbalance forces at the cylinder flange (global)




The pressure pulsation at the cylinder flange results from the intermittent flow into the cylinder

This cause a vertical unbalance force (global)

Restrained by cylinder supports

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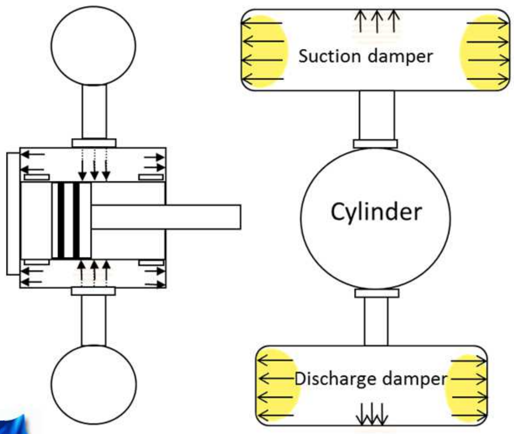
# Gas unbalance forces in the pulsation bottle (Global)




- Pulsation in bottle may cause unbalance force in the bottle
- Force restrained by cylinder and bottle supports

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# Gas Forces acting on the piping (global)

- Gas pulsations in the piping result in shaking forces at elbows and changes in area.
- To the extent that the gas force on opposing elbows are out of phase there is a resultant unbalance.
- The permissible shaking force is per API618 and is equal to 45 x NPS  Where the force is in Newtons and NPS is nominal pipe size in mm.



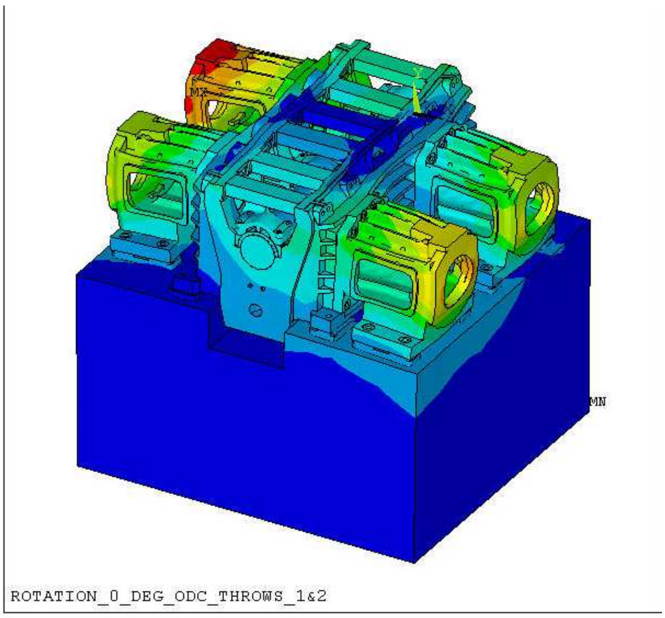
# Foundation Analysis

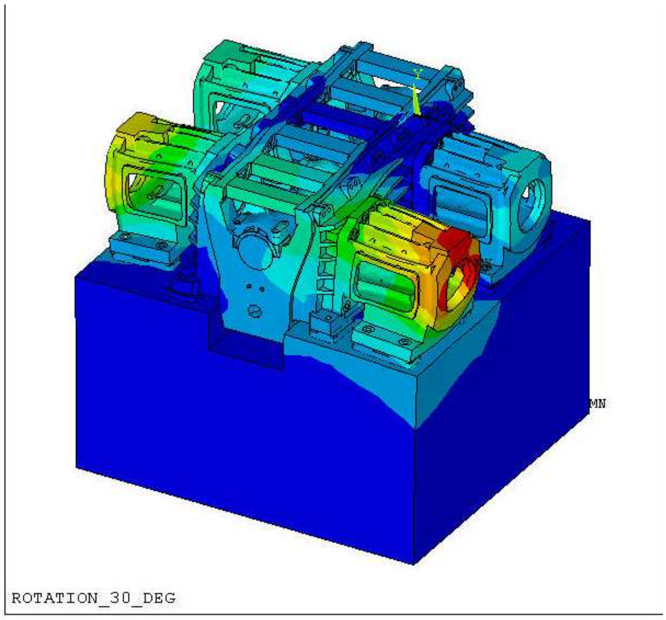
- Most foundation analysis only considers the global forces – Unbalance forces and moments from the compressor moving parts plus the pulsation forces at the pulsation bottle and cylinder.
- This is reasonable because it covers the deep foundation and is the information required by the geotechnical civil engineer.
- The local forces need to be considered for the design of the anchor bolts and upper part of the foundation.
- The anchor bolt size and design preload and also design side load is specified by the compressor OEM

# Flexible frame analysis

- The local loads on the foundation are obtained using a flexible frame FEA which considers all the forces and the flexure of the frame and distance piece including the cylinder and pulsation bottles.
- This analysis is done by the compressor OEM during the original compressor design.  It is not done on each order for foundation block mounted machines.
- The compressor OEM determines the maximum load on the foundation at each anchor bolt with the compressor operating at max load and speed.  The loads are used to select the anchor bolt size and required preload.





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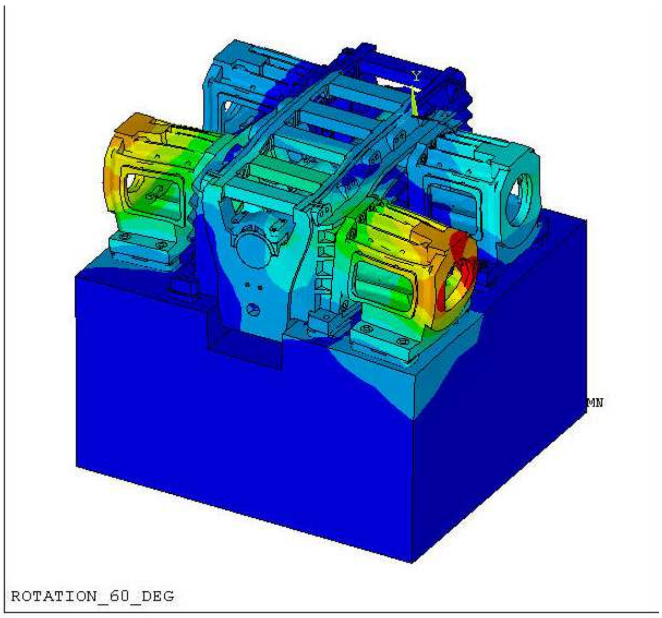


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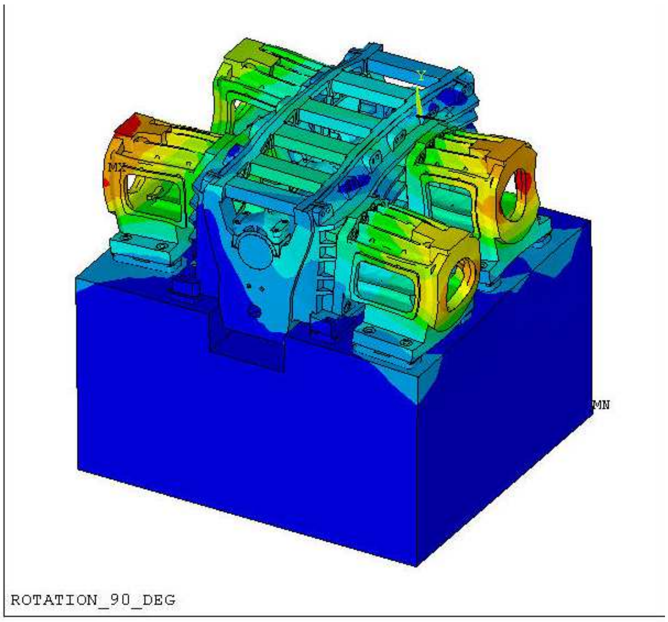


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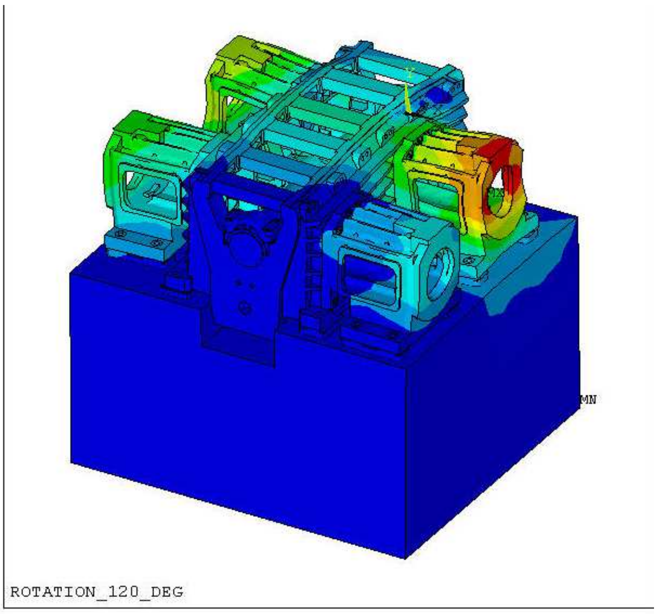


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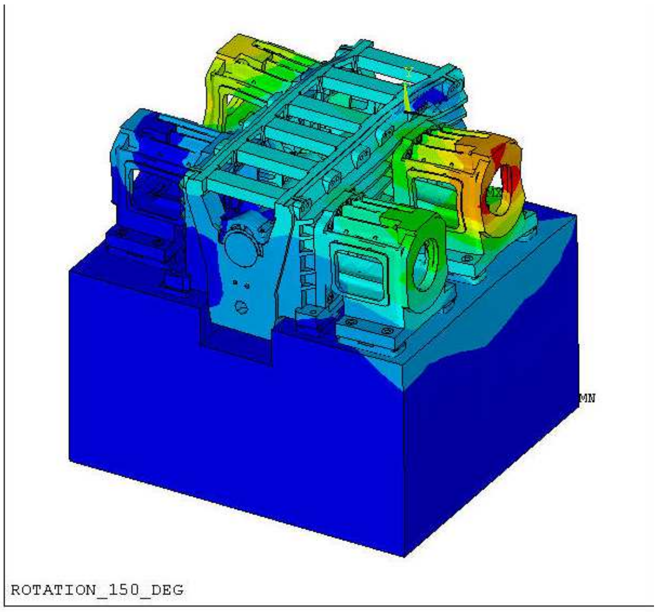
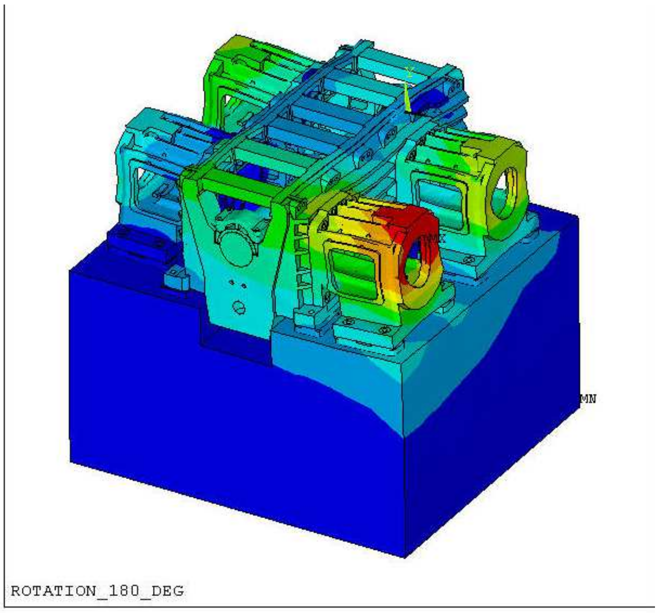
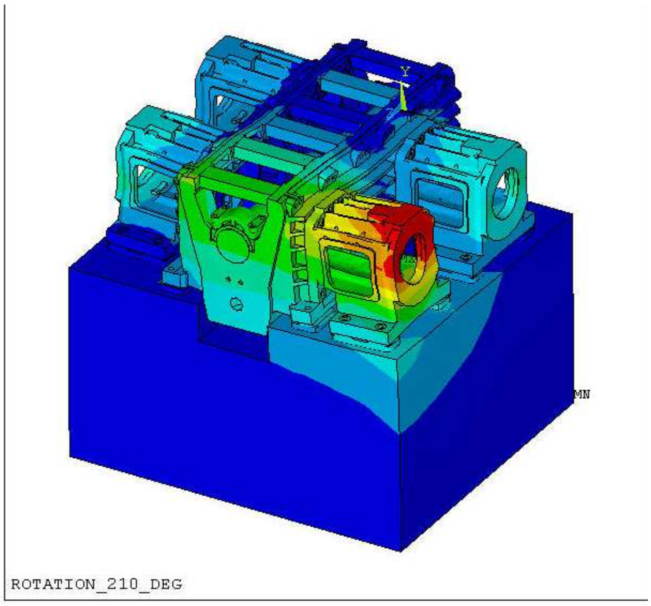

MN
ROTATION_150_DEG


MN
ROTATION_180_DEG

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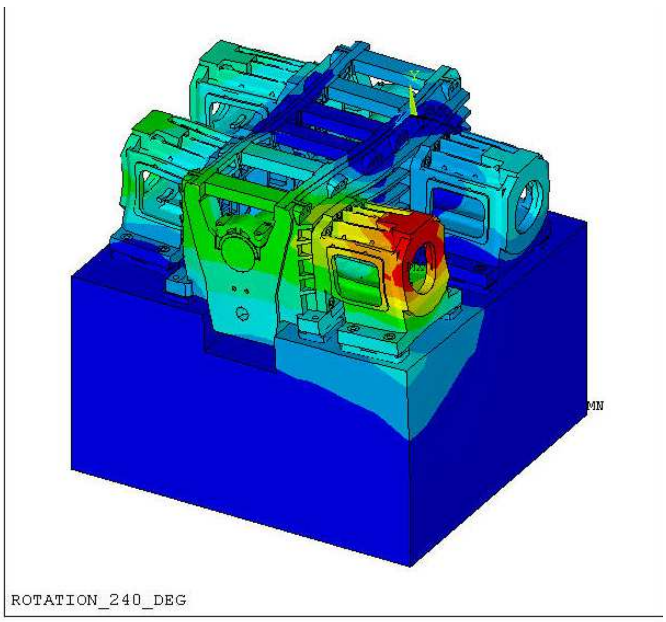


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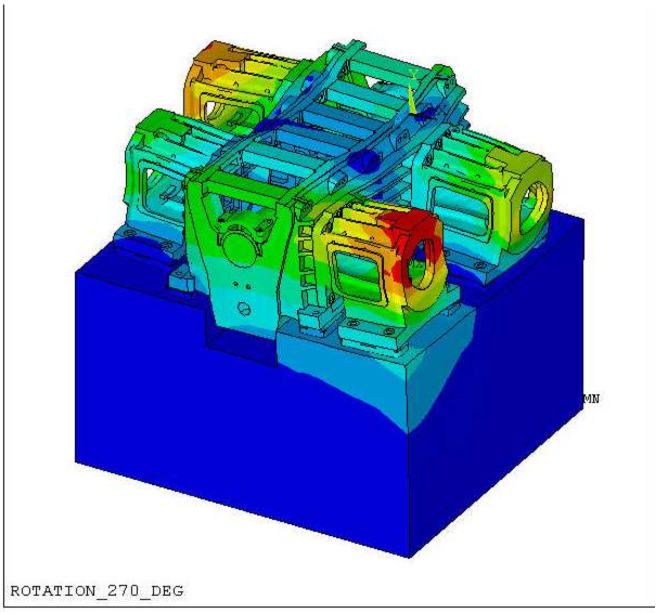


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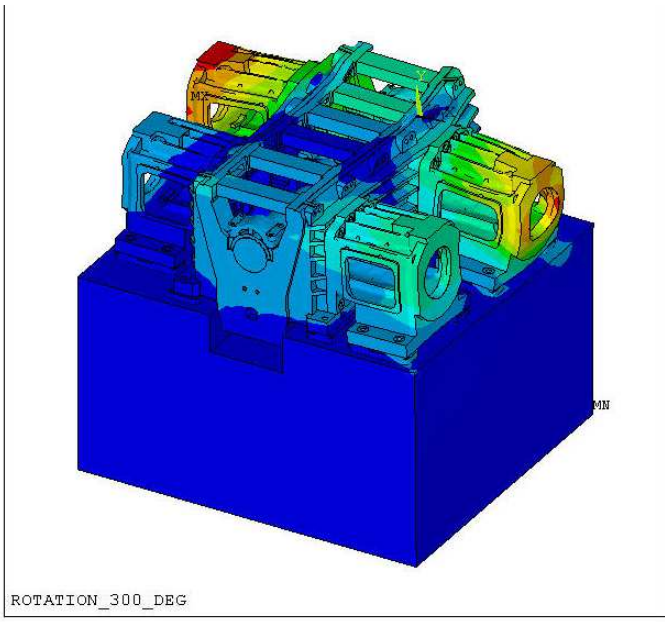


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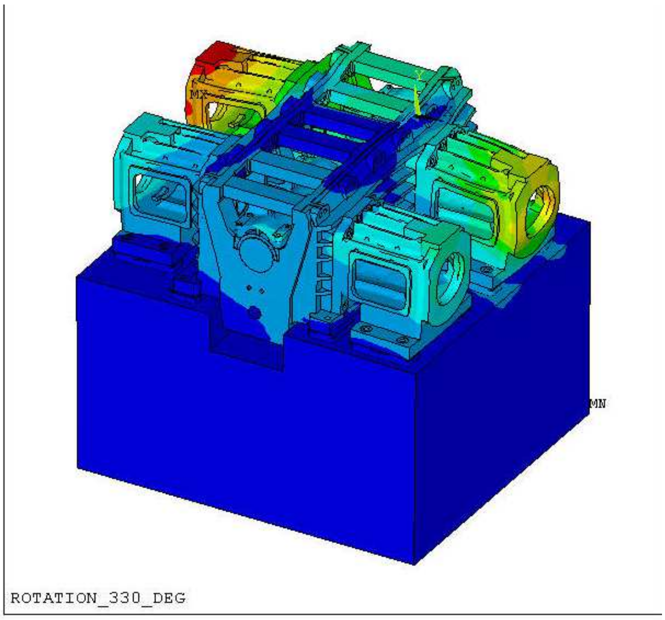


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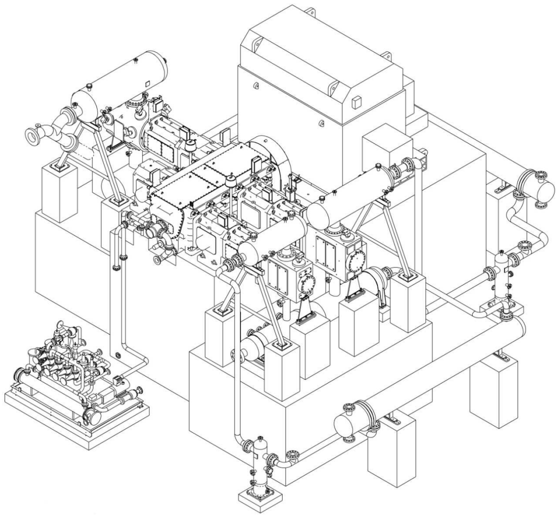
# Skid analysis

- Packaged compressor on a skid.
- A flexible frame analysis should be done on all new or unique design packages unless prior experience of similar designs shows this to be unecessary.
- This FEA will include the skid, compressor frame, distance piece, cylinder and pulsation bottles, modeling all global and local forces.
- Forces and deflections at the skid to compressor interface as well as stresses within skid are determined.
- Loads on the skid to foundation are determined.

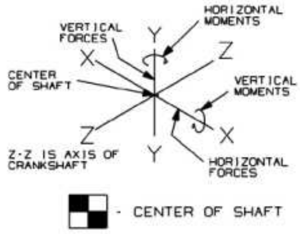
# Large Process Compressor GA





# Typical Unbalance Forces & Moments for a 1.5 MN machine

| | |
|---|---|
| **Max Horizontal primary force** | **29134 N** |
| **Max Horizontal secondary force** | 4510 N |
| **Max vertical primary force** | 0 N |
| **Max vertical secondary force** | 0 N |
| **Max horizontal primary moment about y axis** | 428,833 N-m |
| **Max horizontal secondary moment** | 11,259 N-m |
| **Max vertical primary moment about x-x axis** | 106,780 N-m |
| **Max vertical secondary moment** | 0 N-m |



# Design Requirement

- OEM Foundation drawings shows anchor bolt size, location, basic design type, strength level and preload.
- Foundation is designed for the UBF&M global forces
- Foundation will accept anchor bolt preload plus dynamic side load from each anchor share of the global forces plus side load due to elastic horizontal stretch of 0.1 mm per meter Pk-Pk resulting from the local forces.
- The foundation-grout-chock (or skid) needs to have some compliance to accept the elastic compressor stretch without causing slip at each anchor bolt
- The major part of the compressor vibration is usually due to local forces (primarily gas rod load force).



*Questions and Answers*

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