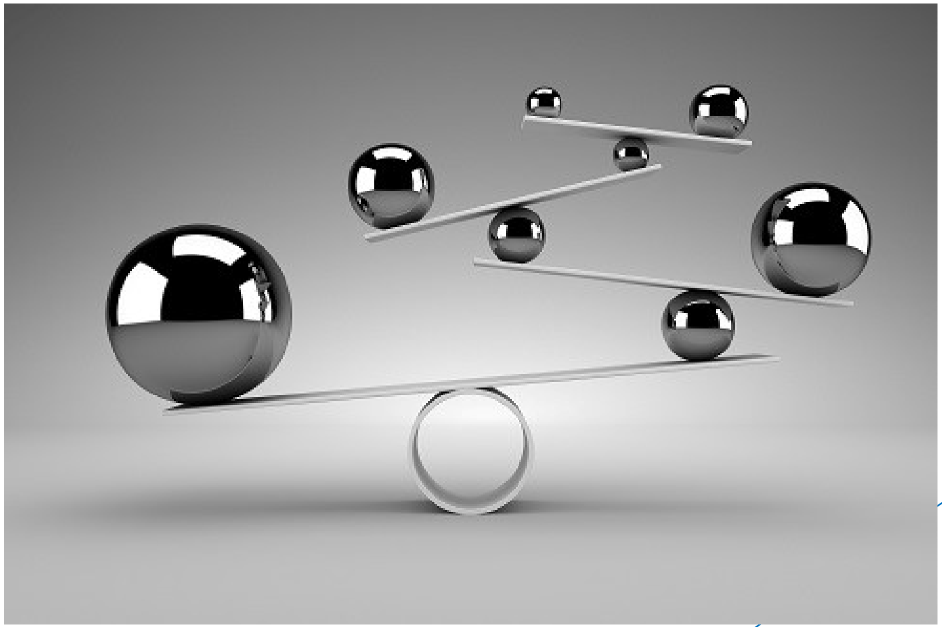
Balancing Theory and Tips

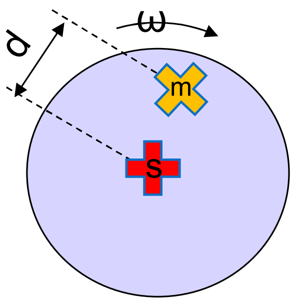
Presented By Colin Pickett

What is balancing?

- To the average person, rotor balancing is often thought of as a "black art".
- Most people's knowledge of balancing is limited to car wheels that must be balanced before fitting to cars; otherwise, they will experience steering wheel judder, uneven wear and so on.
- This training will give you an insight into the world of balancing and help to unveil the "black art".

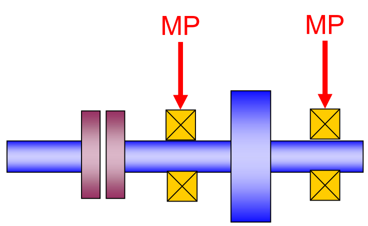


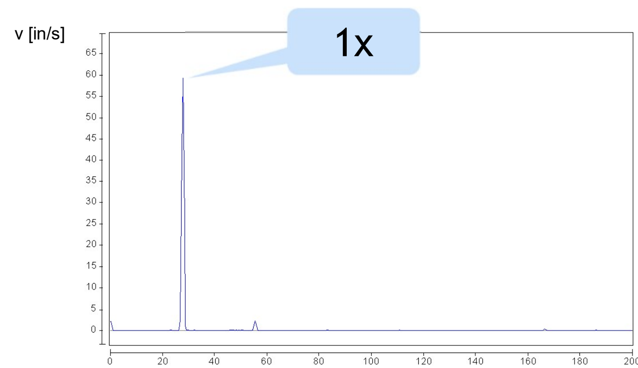
What is balancing?



Unbalance is the condition when the geometric centerline of a rotation axis doesn’t coincide with the mass centerline.

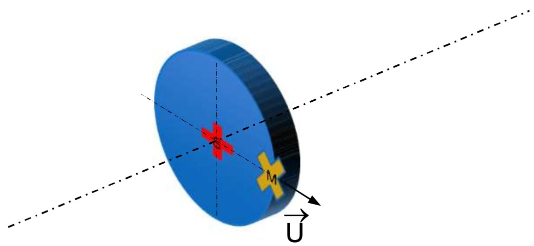
$F_{unbalance} = m\ d\ \omega^2$

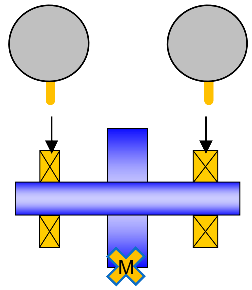




A pure unbalance will generate a signal at the rotation speed 1X vibration signal predominant at the radial direction.

What is balancing?
Static unbalance – common



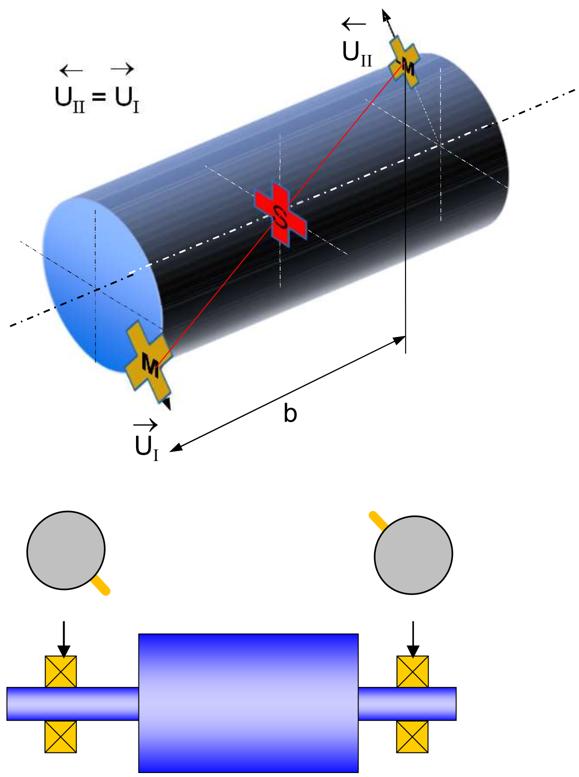


Static unbalance is caused by an unbalance mass out of the Geometric centerline.

The static unbalance can be seen when the machine is not in operation, the rotor will roll so the unbalance mass is at the lowest position. This can be easily corrected by adding weight to the “light” spot until the roll stops.

The static unbalance produces a vibration signal at 1X, radial direction dominant, and matching phase signals at each end of the shaft.

What is balancing?
Couple or Moment unbalance - rare

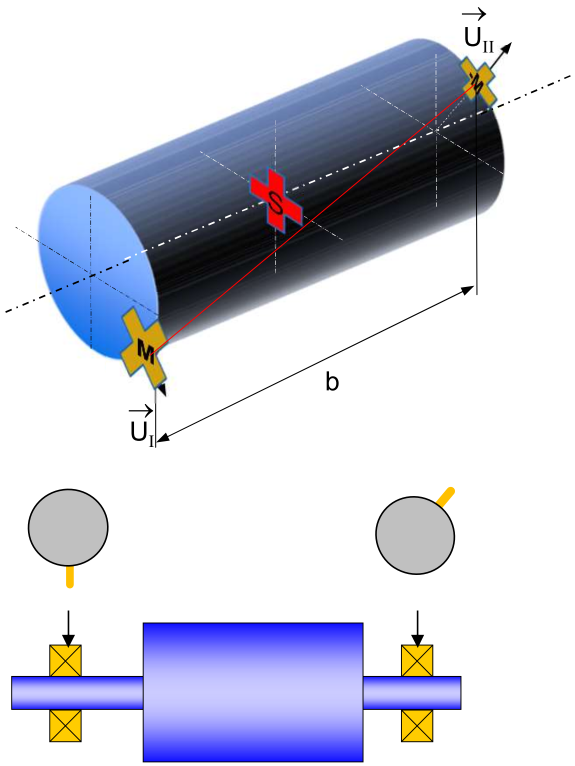


Moment or Couple unbalance is caused by two identical unbalance masses located 180° apart in the transverse area of the shaft.

Moment / Couple unbalance can be statically balanced.

When rotating Couple unbalance produces a vibration signal at 1X, radial predominant and in opposite phase signals in both shaft extremes.

What is balancing?
Dynamic unbalance – most common

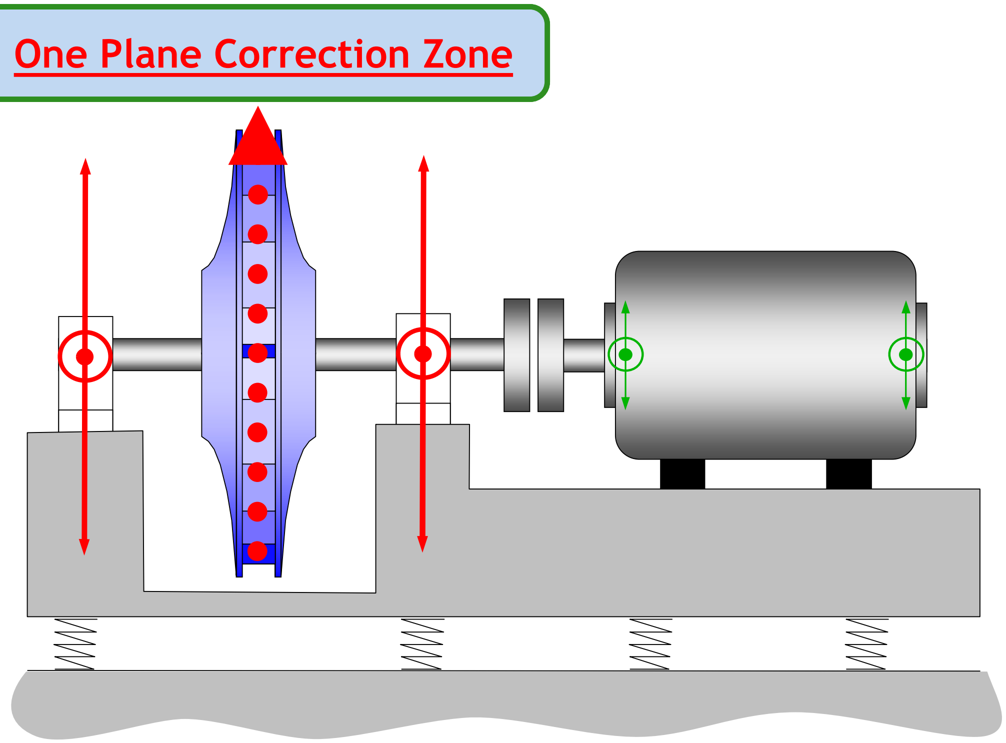


Dynamic unbalance is static and moment (couple) unbalance at the same time.

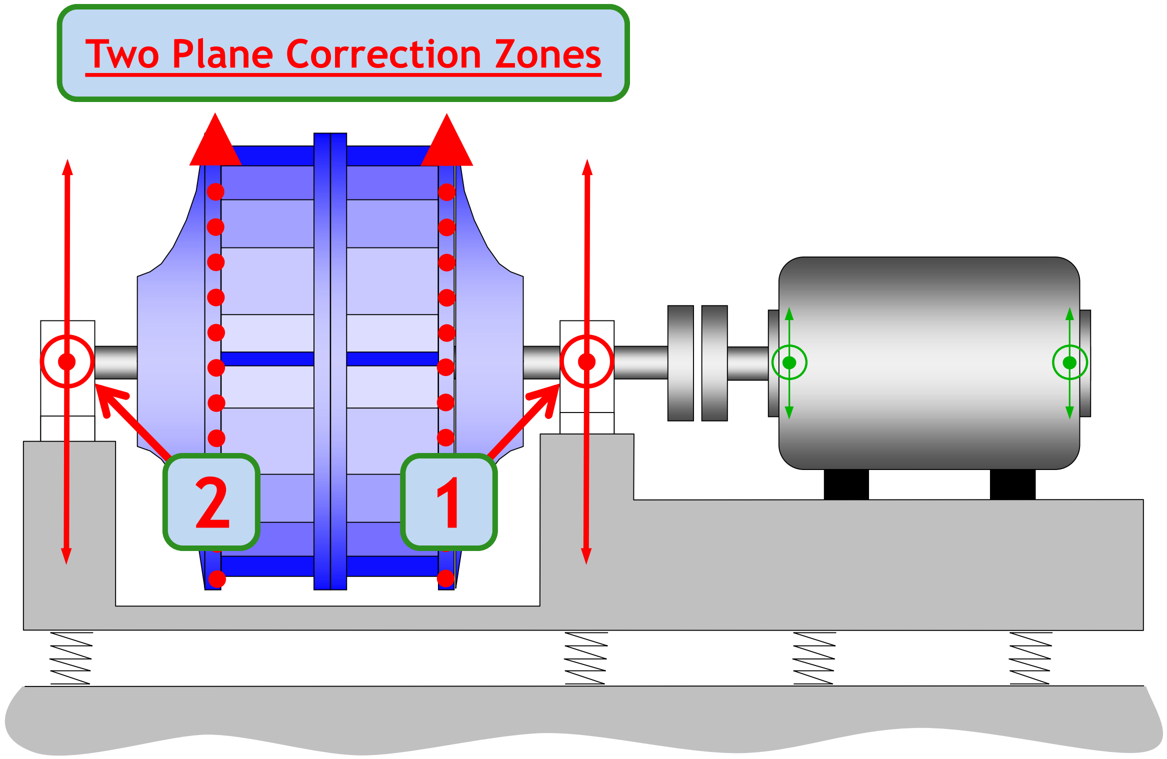
In practice, dynamic unbalance is the most common form of unbalance found.

When rotating the dynamic unbalance produces a vibration signal at 1X, radial predominant and the phase will depend on the mass distribution along the axis.

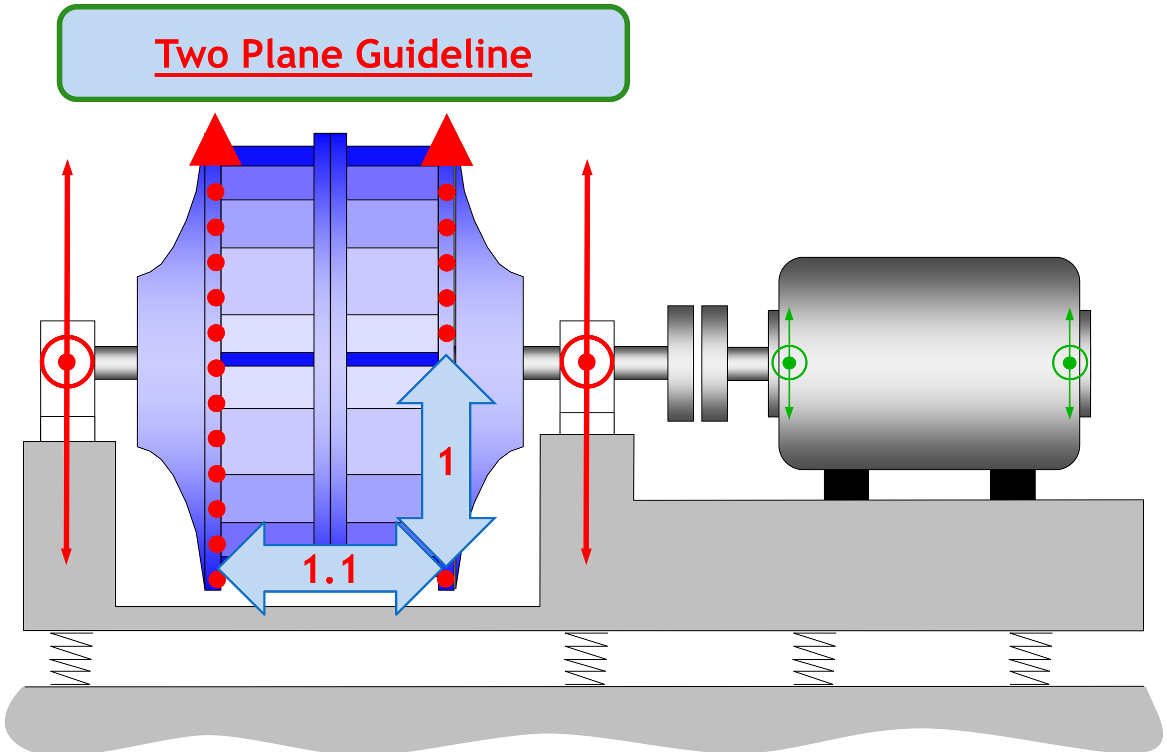
What is balancing?
One Plane balance



What is balancing?
Two Plane balance

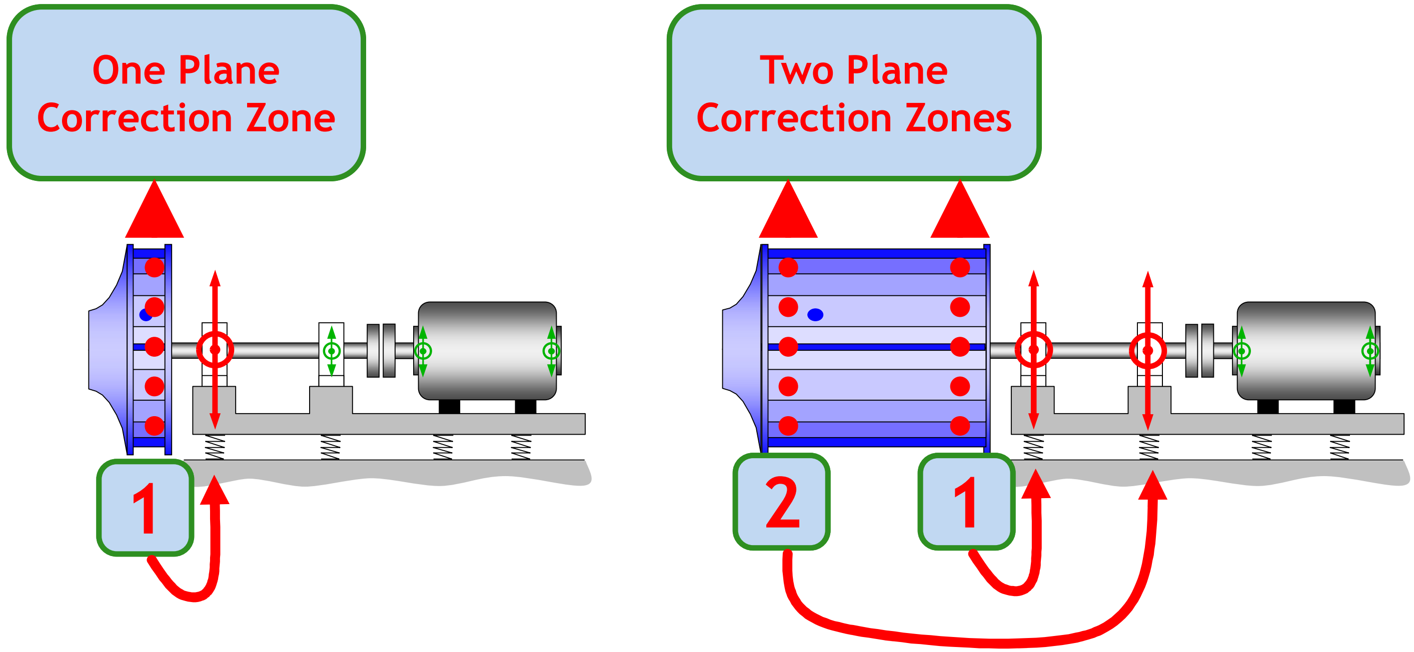


What is balancing?
When to do a Two Plane balance?



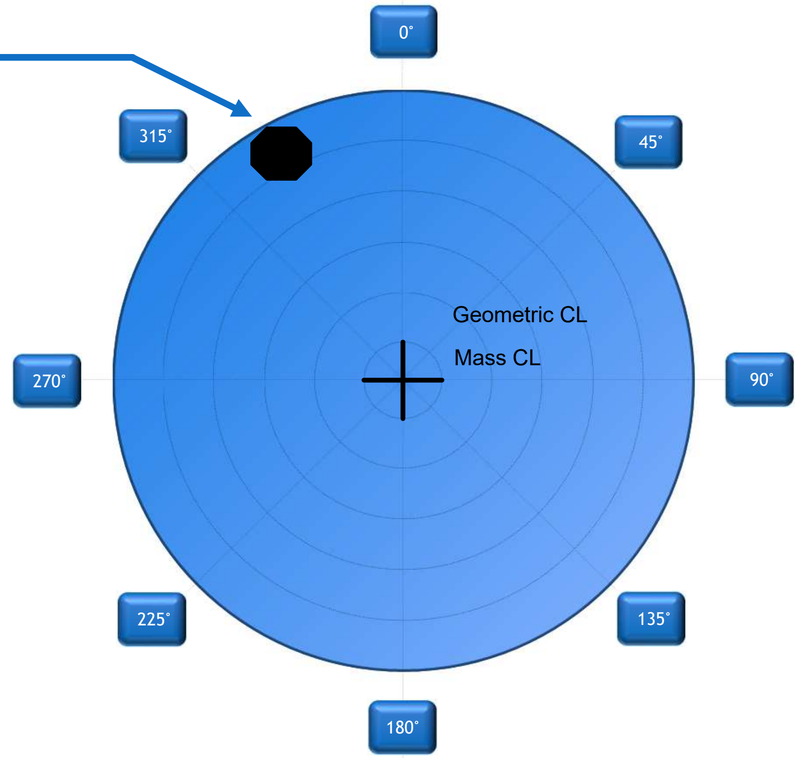
2 Plane Balance
When Balance Plane Separation is Equal to or Greater than the Rotor Radius

What is balancing?
Correction zones



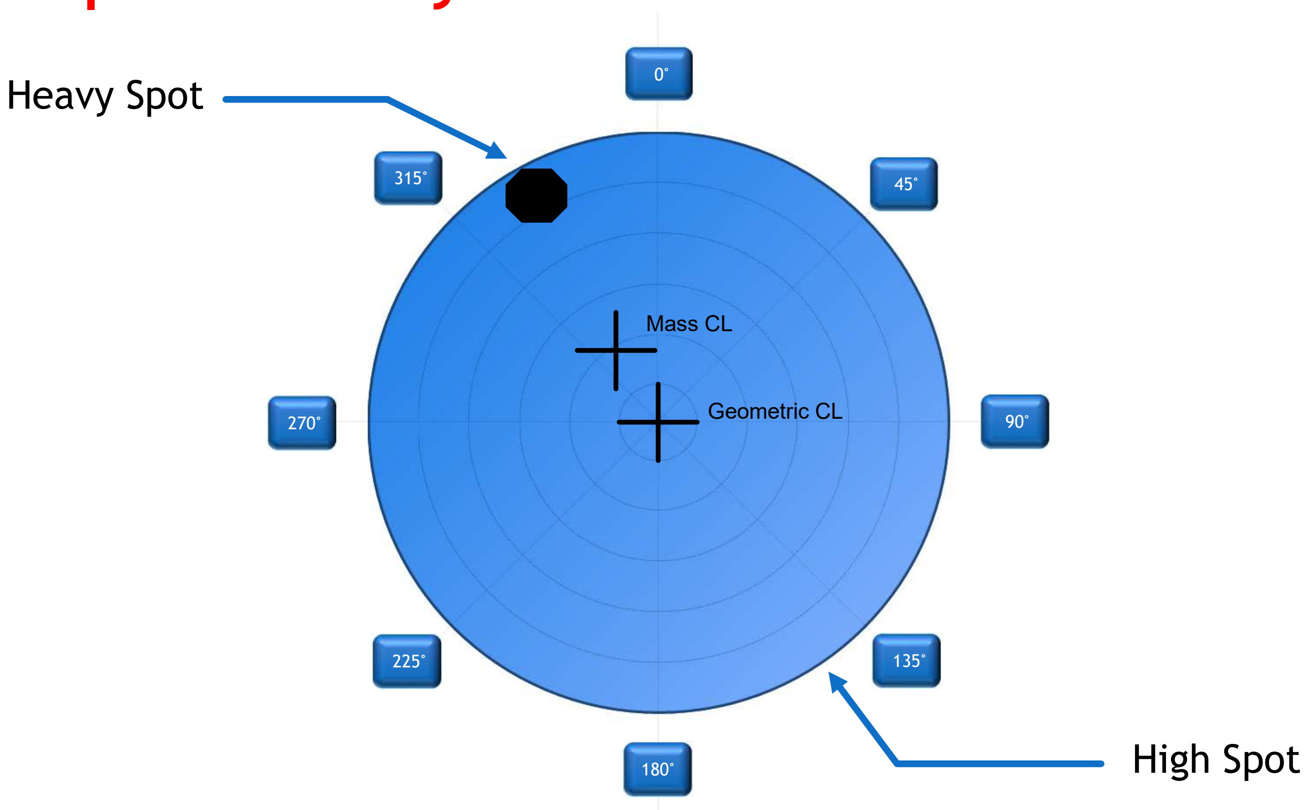
What is Balancing?
High Spot Theory

High Spot =
Heavy Spot



Below 1st Critical shaft tries to rotate around Geometric Centerline

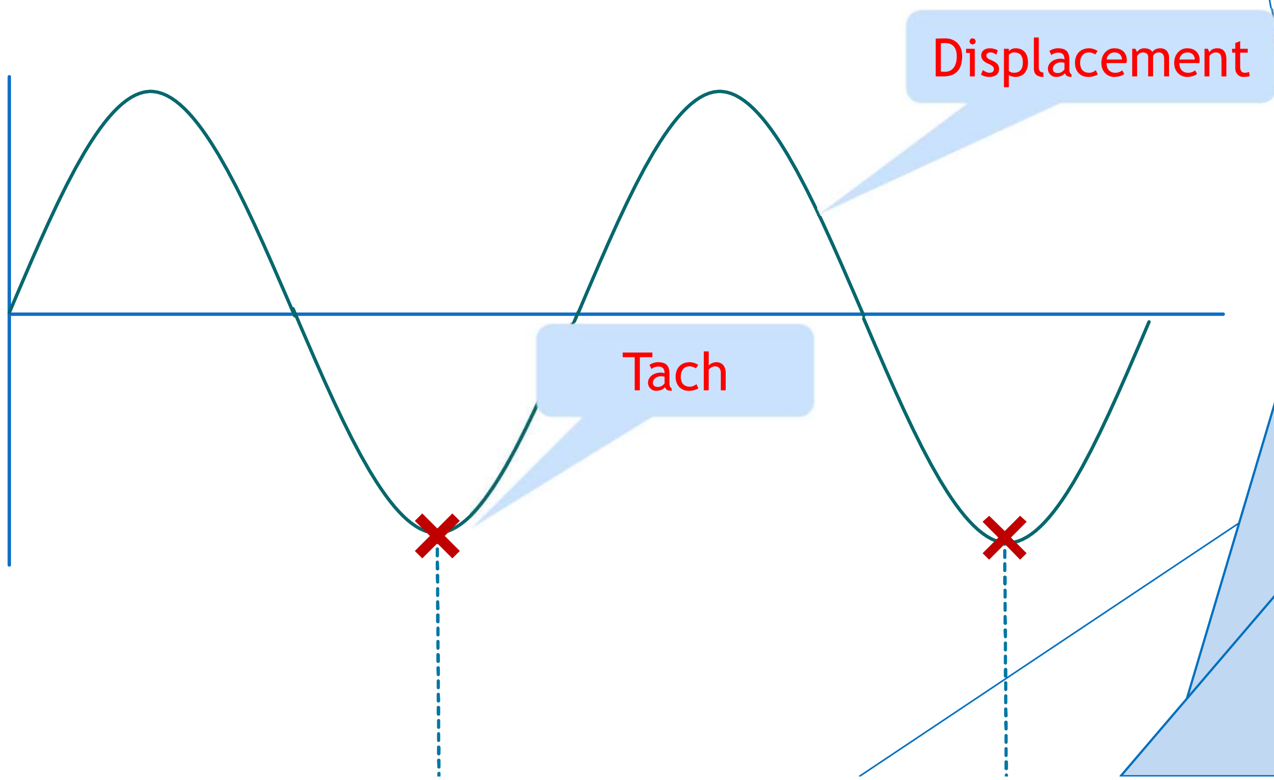
What is Balancing?
High Spot Theory



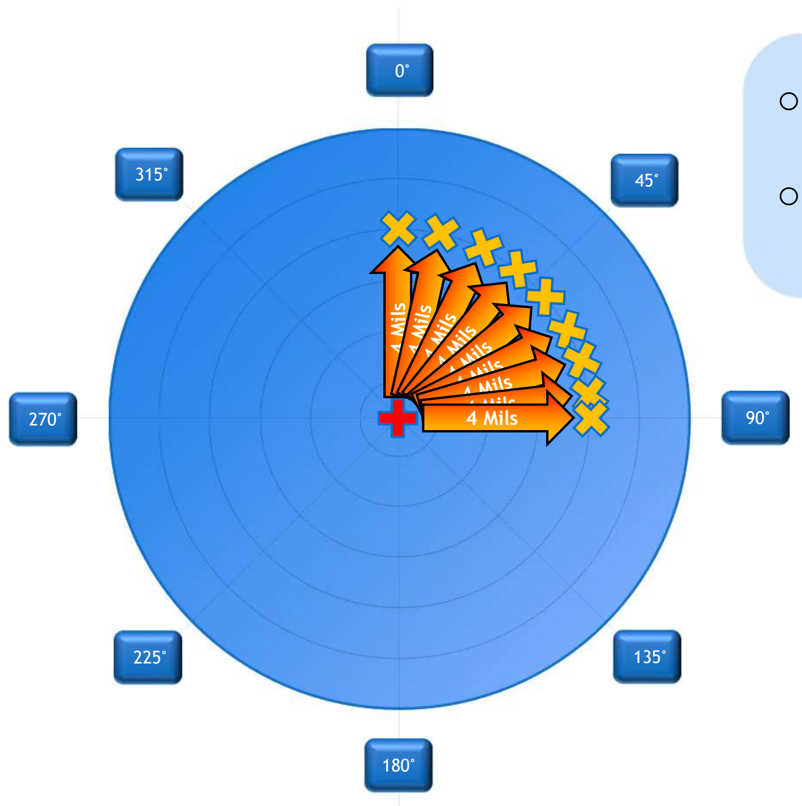
Above 1st Critical shaft tries to rotate around Mass Centerline

What is balancing?
Phase Angle

Phase Angle is the reflective tape passing under the laser-tach and its relationship to the vibration high spot

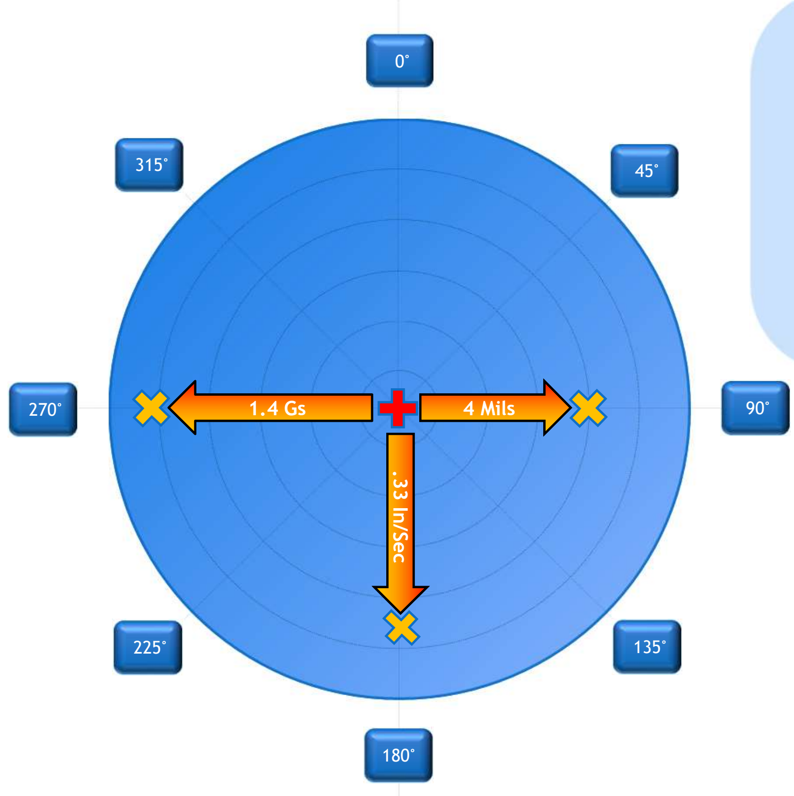


What is balancing?
Vectors



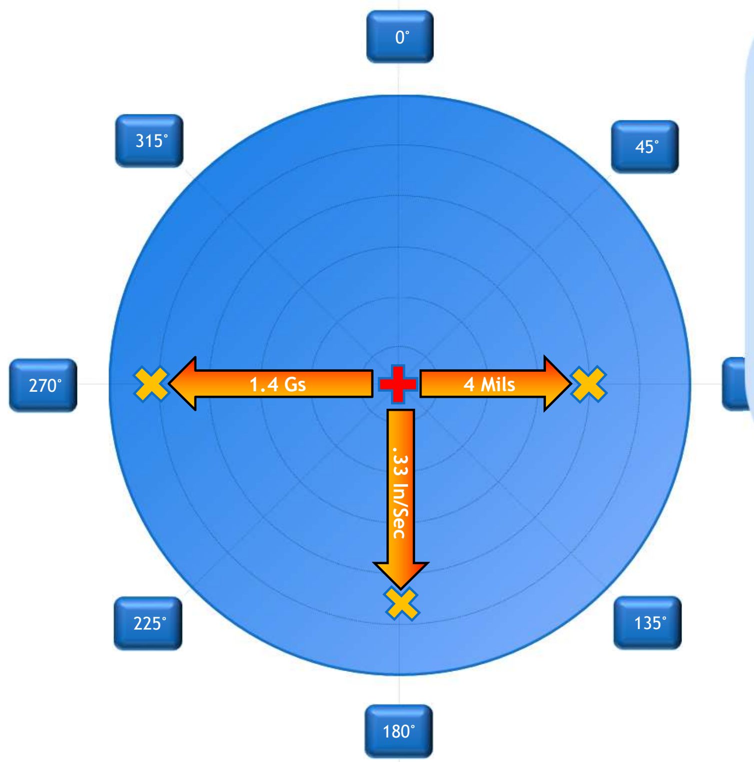
- Vectors consist of a value
- and an angular direction for that value

What is balancing?
Vectors



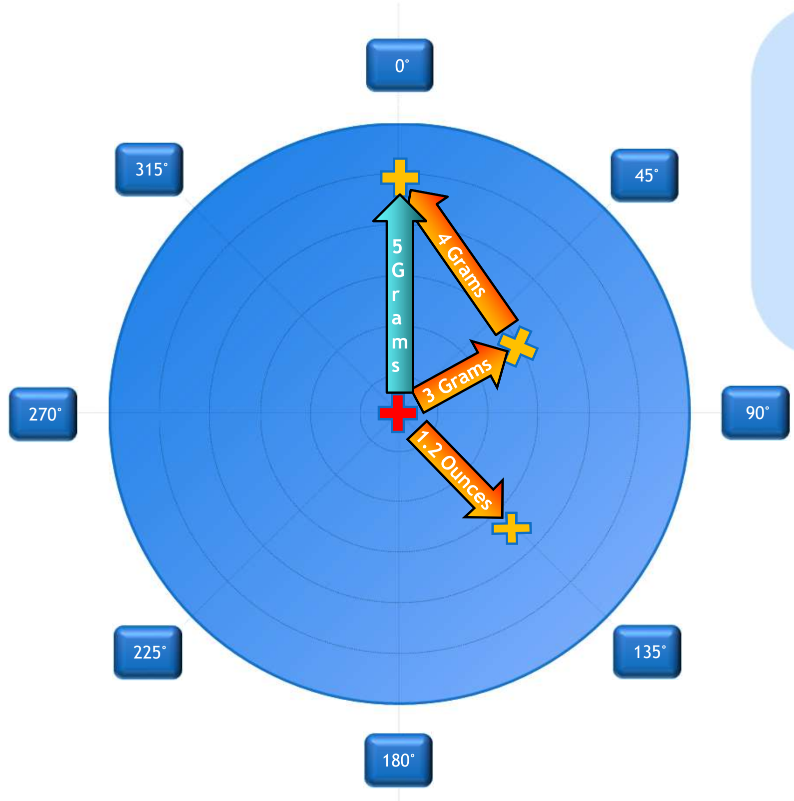
- Vectors can represent vibration amplitude such as:
- Mils or Microns of displacement
- Inches or mm per second of velocity
- Gs of acceleration

What is balancing? Vectors



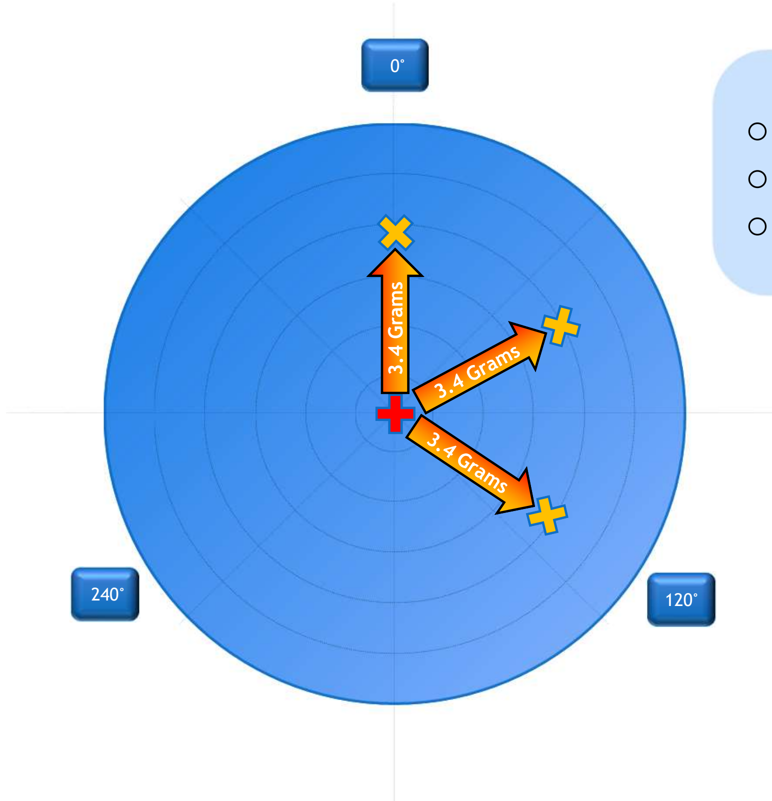
- Mils of displacement
  - In Thousandths
    - Distance
- Inches per second of velocity
  - Speed of change in distance
- Gs of acceleration
  - Force - rate of change of speed

What is balancing?
Vectors



- Vectors can represent a mass:
- Ounces
- Grams
- Vectors can be added and subtracted

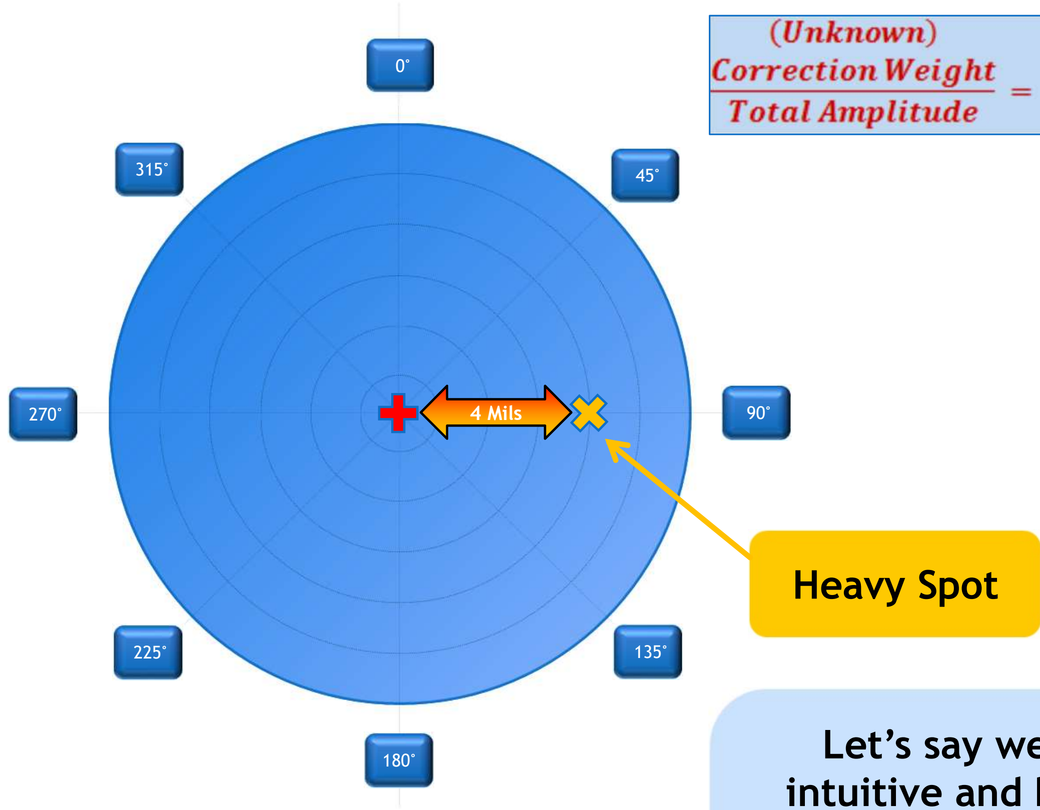
What is balancing?
Vectors - 120



- 3.4 Grams at 0 Degrees
- Plus 3.4 Grams at 120 Degrees
- Equals 3.4 Grams at 60 Degrees

What is balancing?
Ratios

$$\frac{(Unknown)\ Correction\ Weight}{Total\ Amplitude} = \frac{Trial\ Weight}{Change\ in\ Amplitude}$$

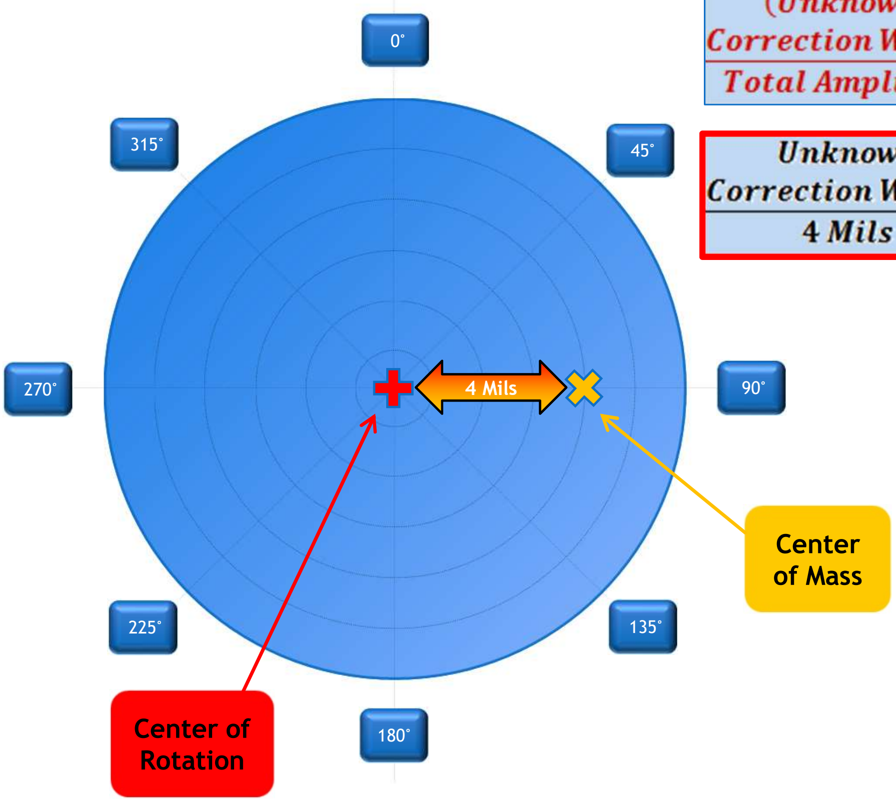


Let's say we are naturally intuitive and know where the heavy spot is on a rotor. We will take care of the angles later.

What is balancing?
Ratios

$$\frac{\text{(Unknown) Correction Weight}}{\text{Total Amplitude}} = \frac{\text{Trial Weight}}{\text{Change in Amplitude}}$$

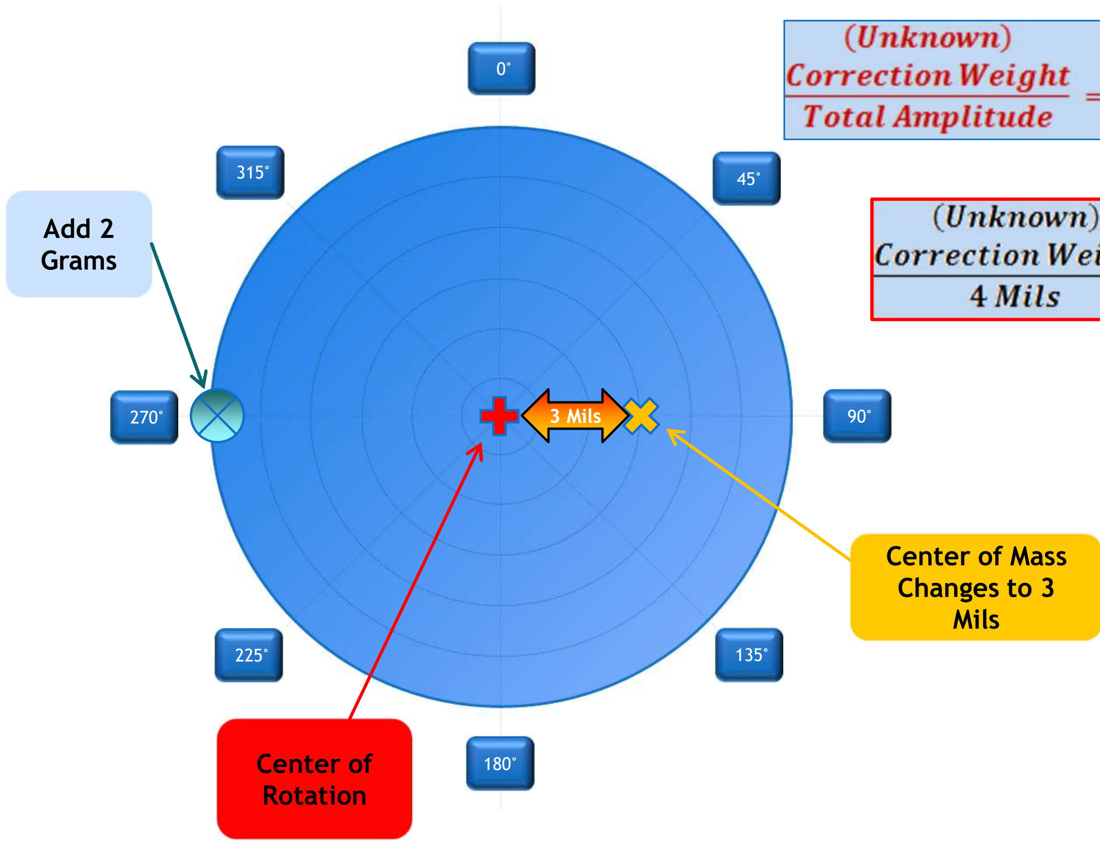
$$\frac{\text{Unknown Correction Weight}}{\text{4 Mils}} = \frac{\text{Trial Weight}}{\text{Change in Amplitude}}$$



What is balancing?
Ratios

$$\frac{\underset{Correction\ Weight}{(Unknown)}}{Total\ Amplitude} = \frac{Trial\ Weight}{Change\ in\ Amplitude}$$

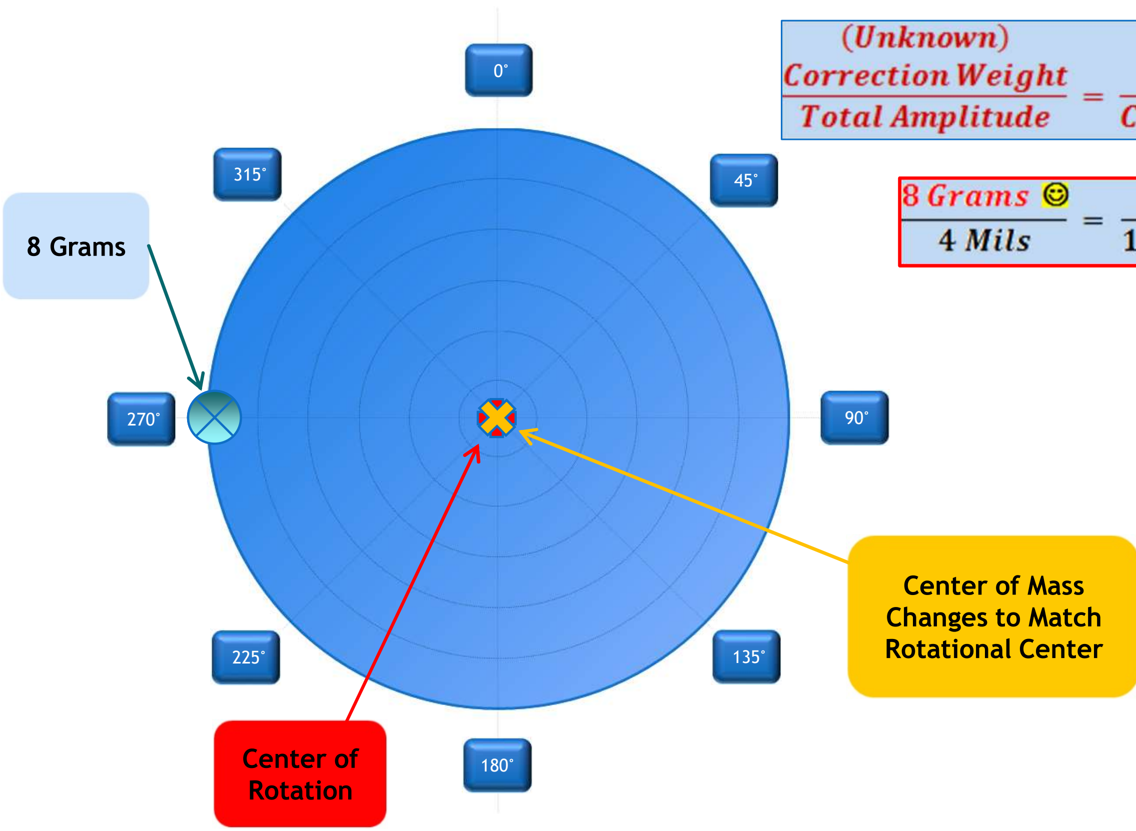
$$\frac{\underset{Correction\ Weight}{(Unknown)}}{4\ Mils} = \frac{2\ Grams}{1\ Mil\ (Change)}$$



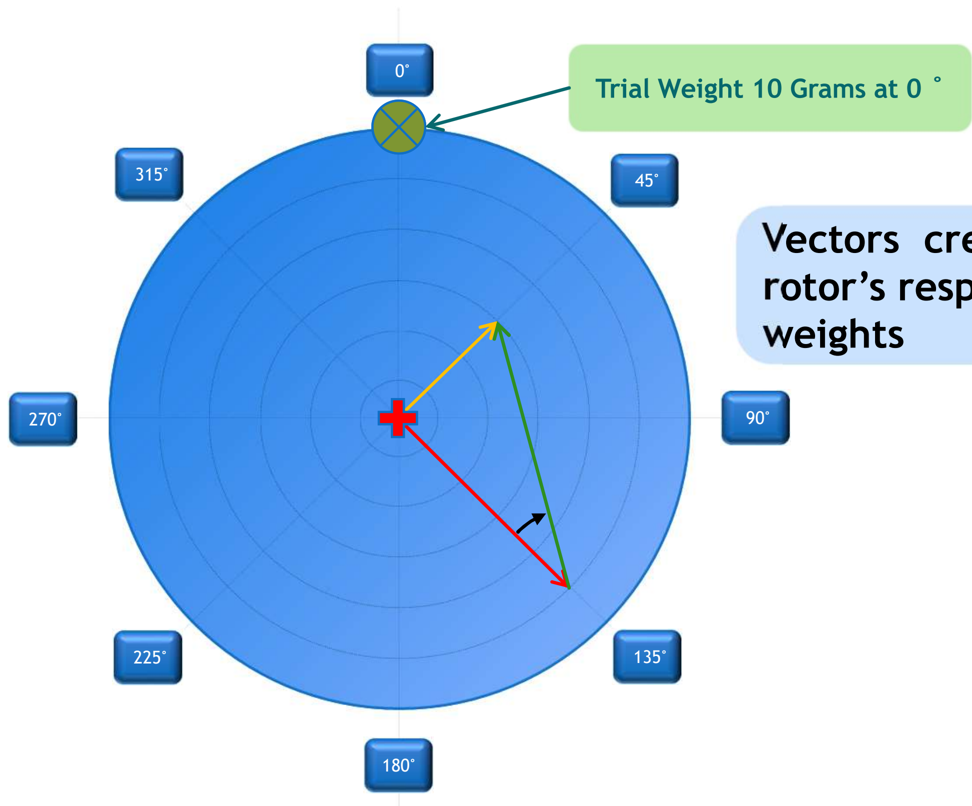
What is balancing?
Ratios

$$\frac{\text{(Unknown) Correction Weight}}{\text{Total Amplitude}} = \frac{\text{Trial Weight}}{\text{Change in Amplitude}}$$

$$\frac{\text{8 Grams ☺}}{\text{4 Mils}} = \frac{\text{2 Grams}}{\text{1 Mil (Change)}}$$

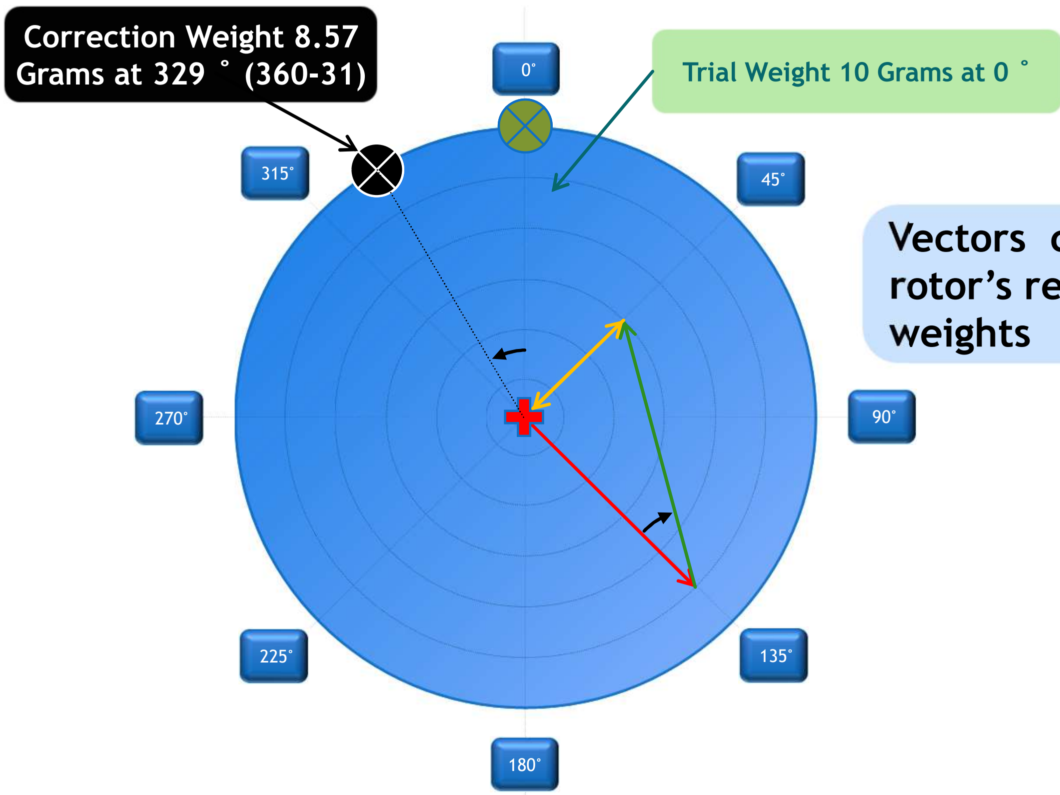


What is balancing?
Using Vectors



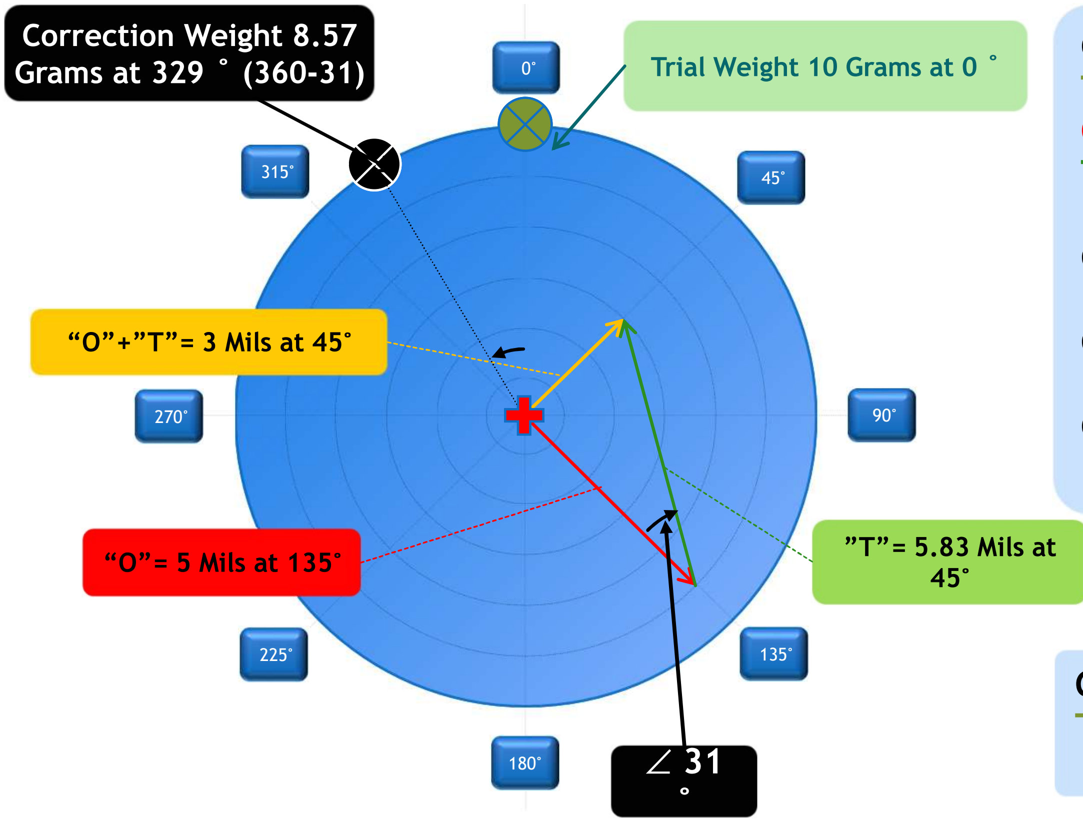
Vectors create a picture of a rotor's response to correction weights

What is balancing?
Using Vectors



Vectors create a picture of a rotor's response to correction weights

What is balancing?
Using Angles & Ratios



Correction Weight = CW
Trial Weight = TW
Original Unbalance = O
Trial Unbalance = T

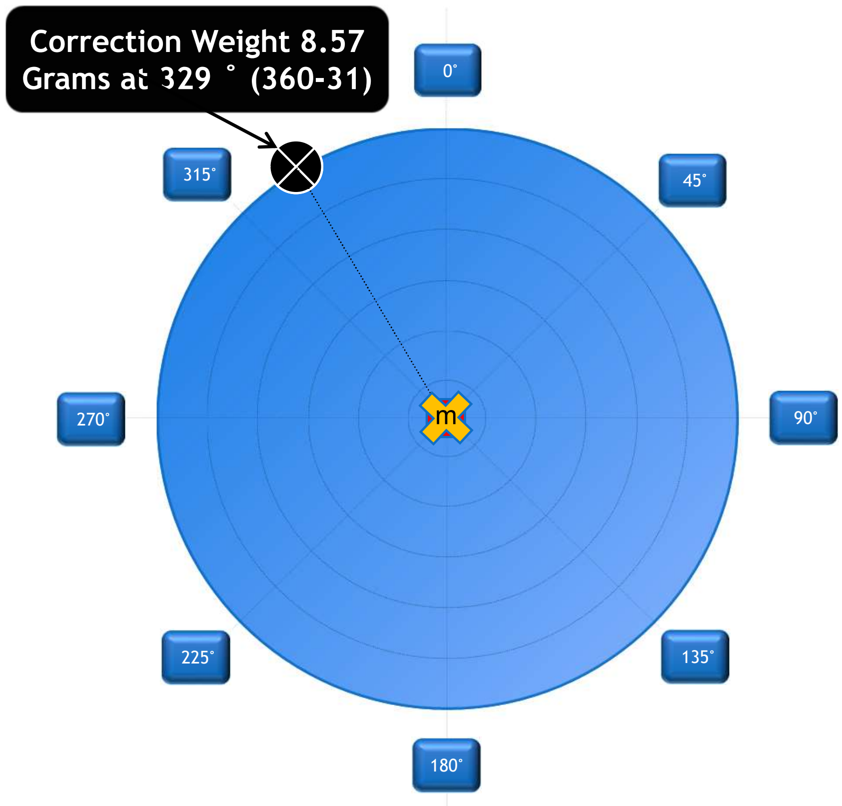
CW = TW x O / T

CW = 10 x 5 / 5.83

CW = 8.57

Correction Angle
TW Angle - O T Angle

What is balancing?
Ratios



Correction Weight = CW
Trial Weight = TW
Original Unbalance = O
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CW = TW x O / T

CW = 10 x 5 / 5.83

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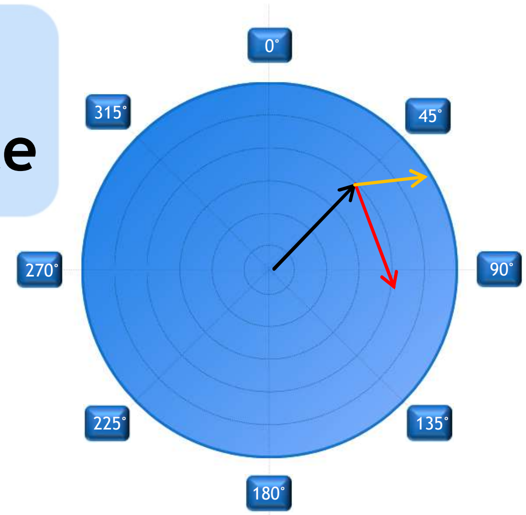
Correction Angle
TW Angle - O T Angle

What is balancing?
30 – 30 Rule

30 Degree Phase Change or 30% Amplitude Change

Initial Unbalance

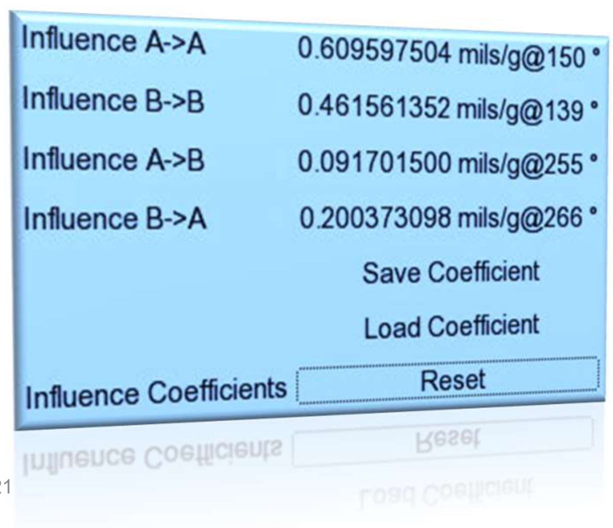


30% Amplitude Change

30° Angle Change

What is balancing?
Influence Coefficients

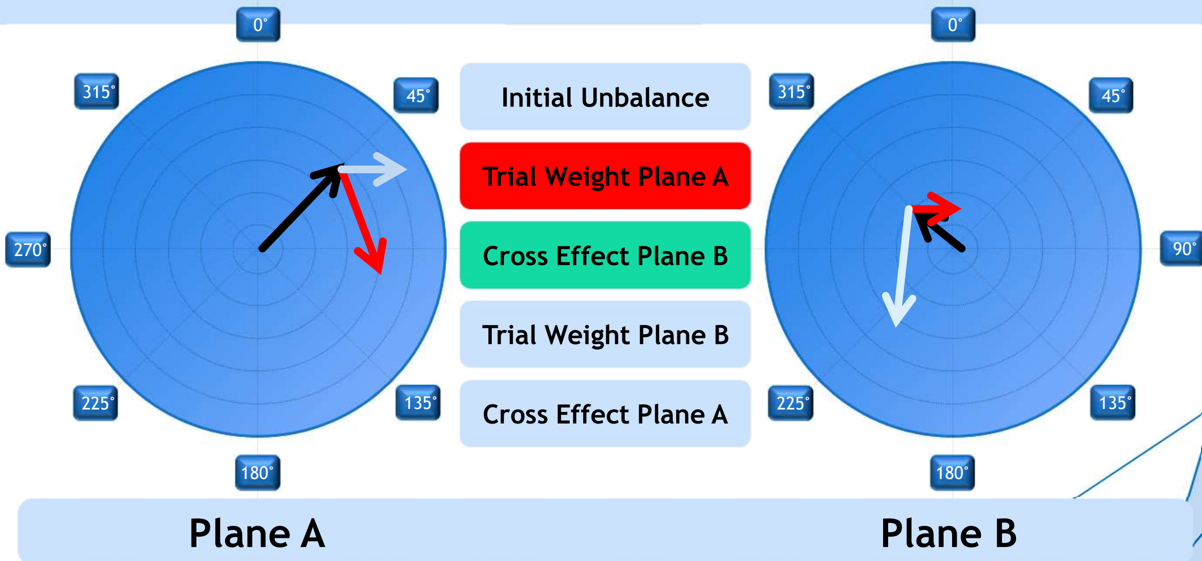
- Influence Coefficients are created when Single or Two Plane Vector Calculations are Performed.
- The Coefficients are a calculation of the response of your rotor to the trial weight.
- They can be stored and recalled for a specific rotor so that the trial weight process is not required a second time.
- This can be a significant time saver but requires some specific conditions to be successful.



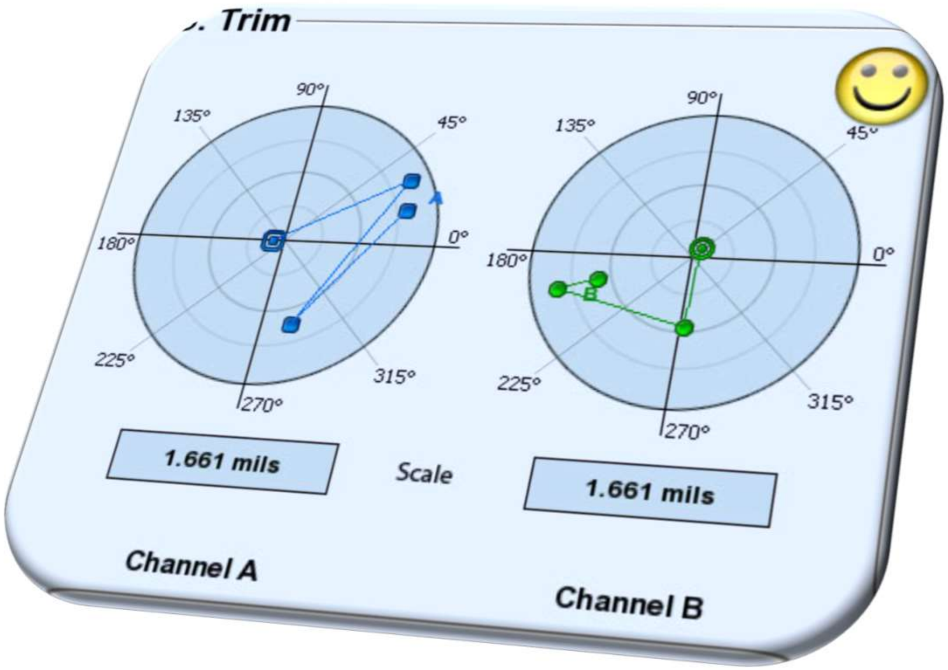
- The RPM must be the same
- The tachometer and phase mark must be in the same position
- The accelerometer must be in the same position
- The structure and rotor mass must be the same as when the original balance coefficients were calculated

What is balancing?
1 Plane V's 2 Plane

- Back when we plotted out the vectors on polar paper, 2 plane balancing was avoided at nearly all costs.
- People typically single planed the worst side first then single planed the other side seesawing back and forth until an acceptable result was achieved.
- The vector calculations are a complex process which require solving simultaneous polar plots. Accounting for "Cross Effect" is what makes this so complex.



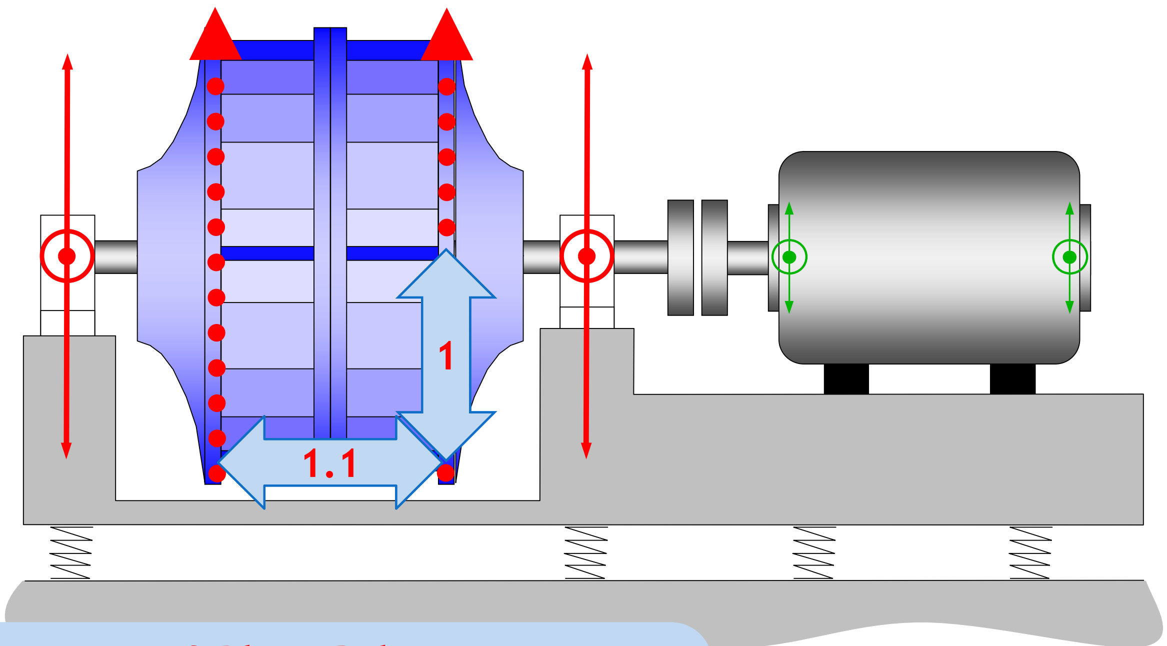
What is balancing?
When to do a 2 Plane Balance?



- Using today's modern computer-based analyzers, if there is a doubt, I recommend going two Plane.
- In the long run you will obtain a better result with less balancing shots or runs.

What is balancing?
When to do a 2 Plane Balance?

Two Plane Guideline

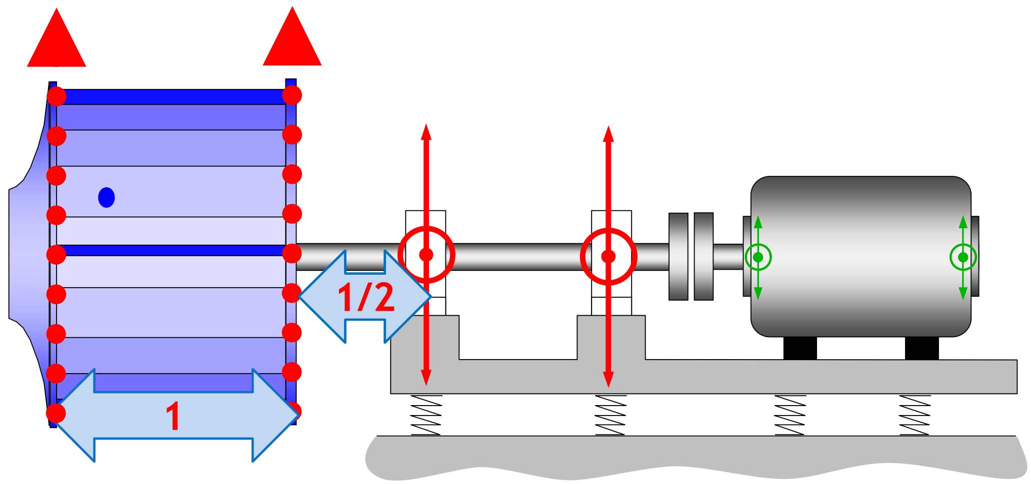


2 Plane Balance
When Balance Plane Separation is Equal to or Greater than the Rotor Radius

What is balancing?
When to do a 2 Plane Balance?

VCMR

Two Plane Guideline Overhung



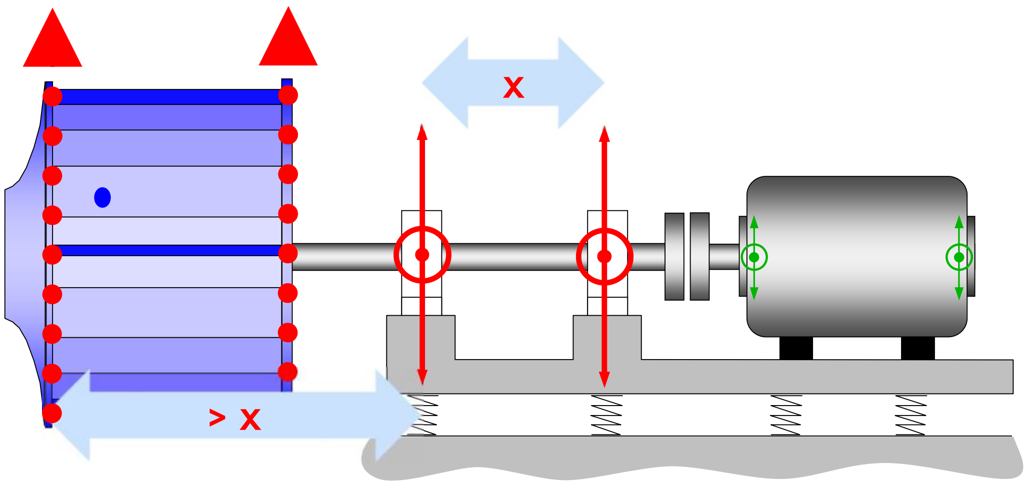
2 Plane Balance Overhung
When the Distance from the Adjoining Bearing is
Less than the ½ the Balance Plane Separation

What can go wrong?

Balancing Caveats – “Gotcha’s”

What is balancing?
Issues? – look here:

Problemantic Balance



If the distance between the bearings (x) is smaller than the distance from the INBOARD bearing to the second plane(>x), the machine will be in a critical state and may NOT be balanceable.

What is balancing?
Balancing Caveats - Resonance

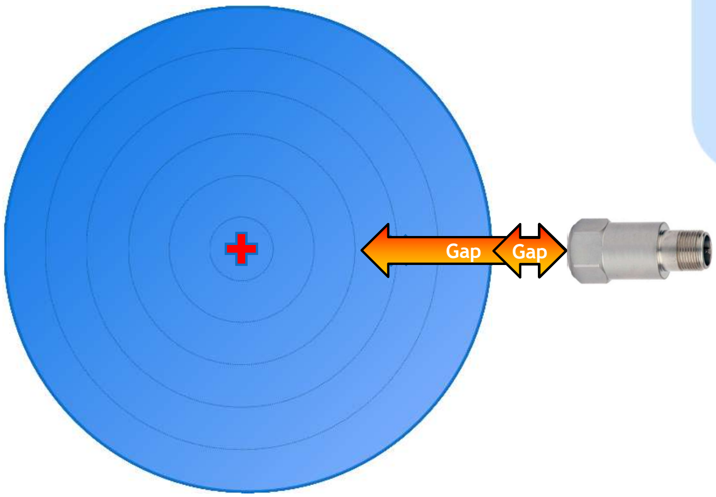
Symptoms of Resonance:

- Phase Shifts with Speed Changes
- Amplitude Changes with Speed Changes
- Phase and Amplitude are difficult to Stabilize
- Resonance can be in the Shaft or the Structure

What is balancing?
Balancing Caveats - Resonance

Below resonance the rotor wants to rotate around its machined center

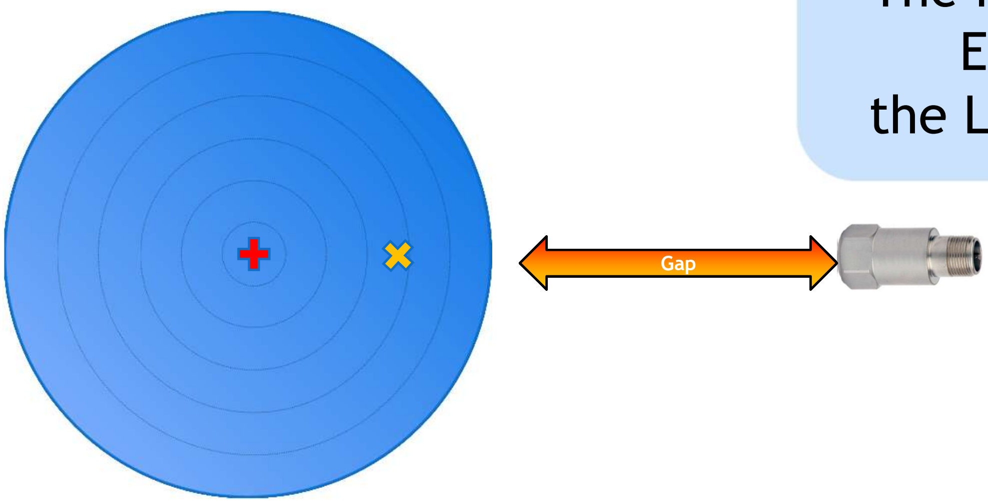
The High Spot
Equals
the Heavy Spot



What is balancing?
Balancing Caveats - Resonance

Above resonance the rotor wants to rotate around the center of mass

The High Spot
Equals
the Light Spot



What is balancing?
Balancing Caveats - Resonance

- Phase rolls 180˚ when passing through a resonance.
- Amplitude increases going into resonance and decreases as one passes out of resonance.
- At the peak of resonance phase has shifted 90˚ and amplitude is at a maximum.
- Trial weights and correction weights that effect amplitude will cause the phase to roll.

What is balancing?
Balancing Caveats - Resonance

- Try to balance at least 10% away from resonance.
- In resonance the addition of trial weights and correction weights will change the amplitude. This change in amplitude will cause the phase response to roll.
- Balancing in resonance:
  - Try one balance shot. This will typically reduce the vibration but not as much as normal.
  - Leave the correction weight but do not trim.
  - Restart the balance with new trial weights.
  - This will take several additional runs but repeating this process will get the rotor balanced to acceptable tolerances.

What is balancing?
Balancing Caveats – Other Issues?

- One can balance a machine all day but if unbalance is not the problem, the vibration will not be corrected.
- Before balancing always check for other problems.

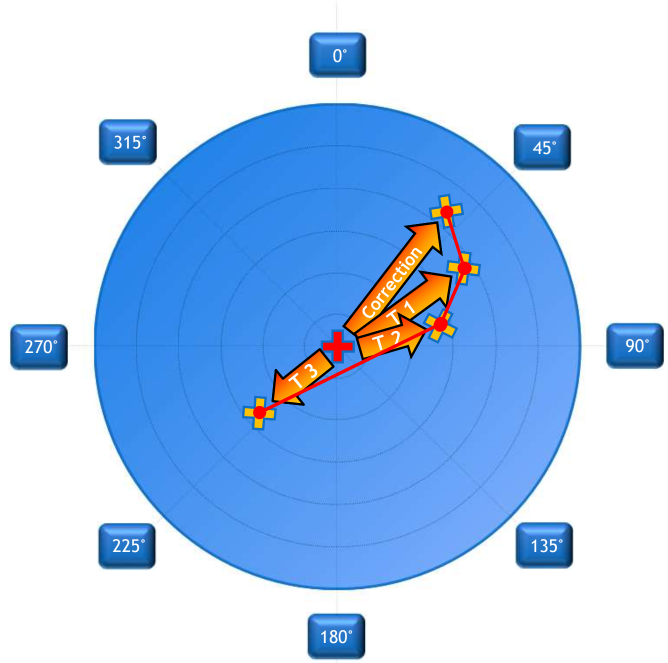
What is balancing?
Balancing Caveats – Other Issues?

Common Problems

- Resonance
- Misalignment
- Looseness
- Eccentric Belt Sheaves
- Bent Shaft
- Electric Motor Problems
- Mechanical Looseness
- Cavitation
- Drive Belts
- Couplings

What is balancing?
Balancing Caveats – Other Issues?

Non-Linear Response



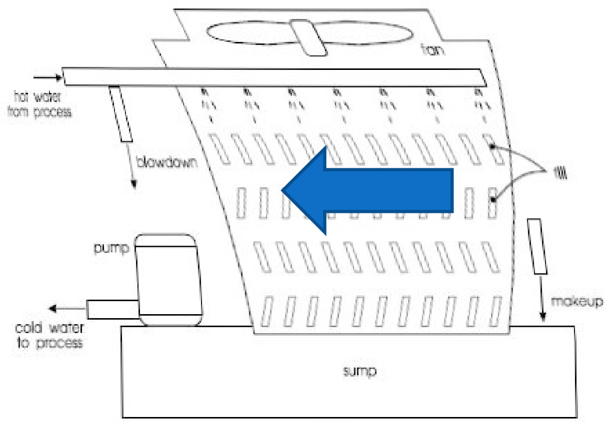
What is balancing?
Balancing Caveats – Other Issues?

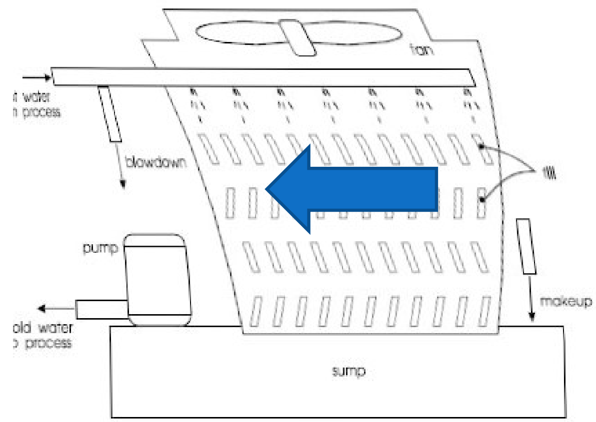
Interference from Other Machines

- Unstable Phase and Amplitude
- Beating Frequencies
- Time Synchronous Filtering

What is balancing?
Balancing Caveats – Other Issues?

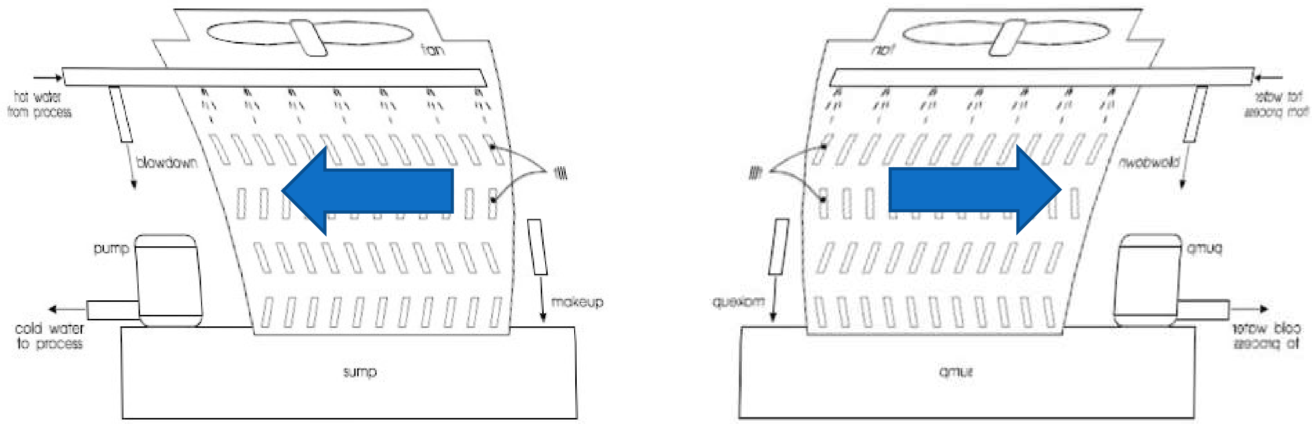
External Machine Interference
(In Phase Beat Frequency)





What is balancing?
Balancing Caveats – Other Issues?

External Machine Interference
(Out of Phase Beat Frequency)

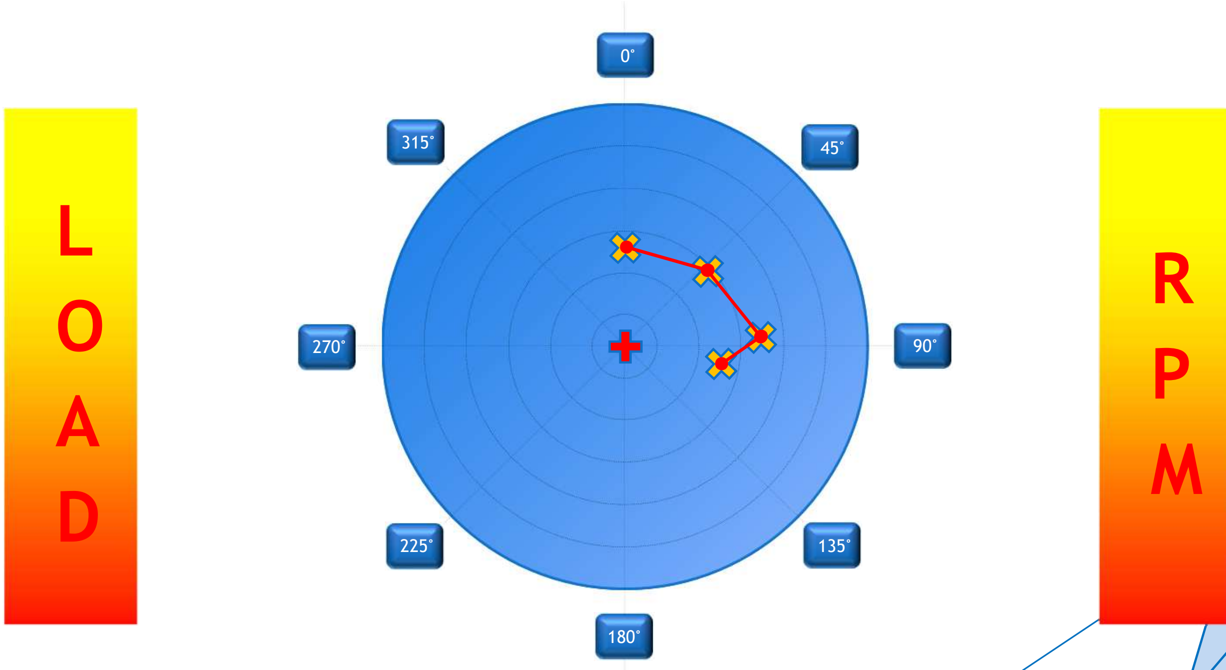


What is balancing?
Balancing Caveats – Other Issues?

Dirty Rotor

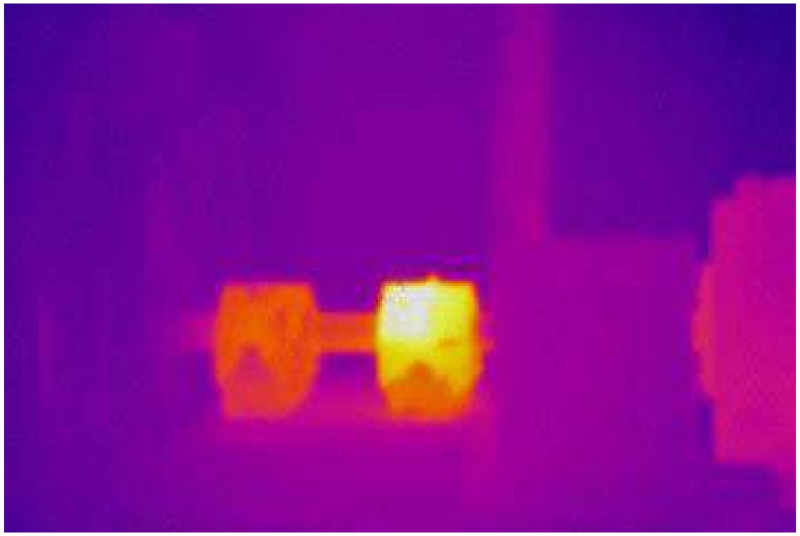
What is balancing?
Balancing Caveats – Other Issues?

Load / RPM Changes



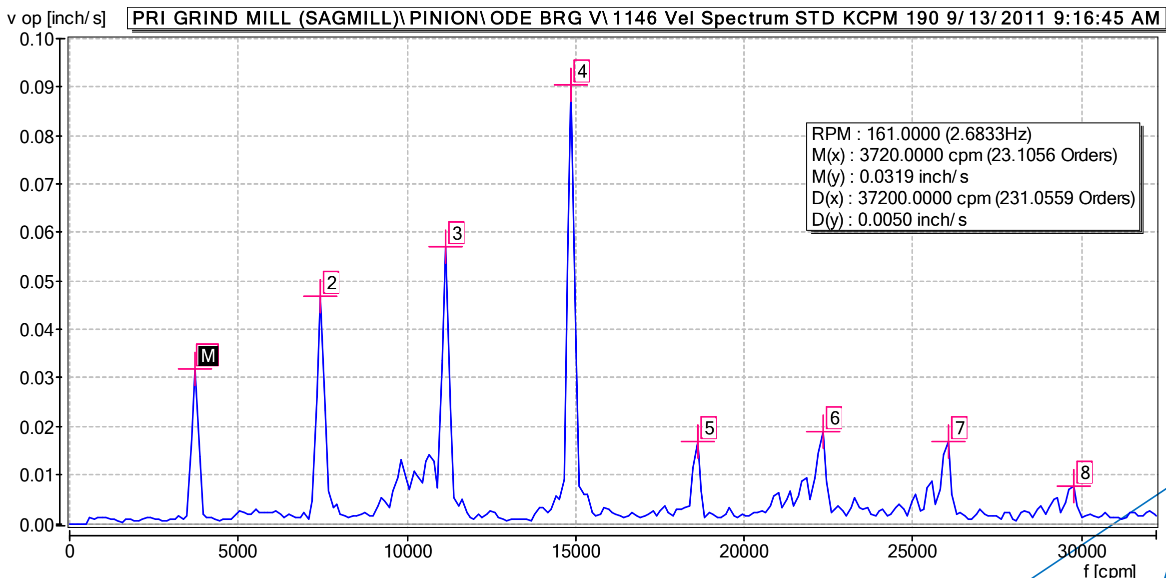
What is balancing?
Balancing Caveats – Other Issues?

Rotor Heating and Cooling



What is balancing?
Balancing Caveats – Other Issues?

Looseness



What is balancing?
Balancing Caveats – Other Issues?

Horizontal vs. Vertical

- Horizontal Amplitude more than 2X of Vertical
- Vertical Amplitude more than 2X of Horizontal

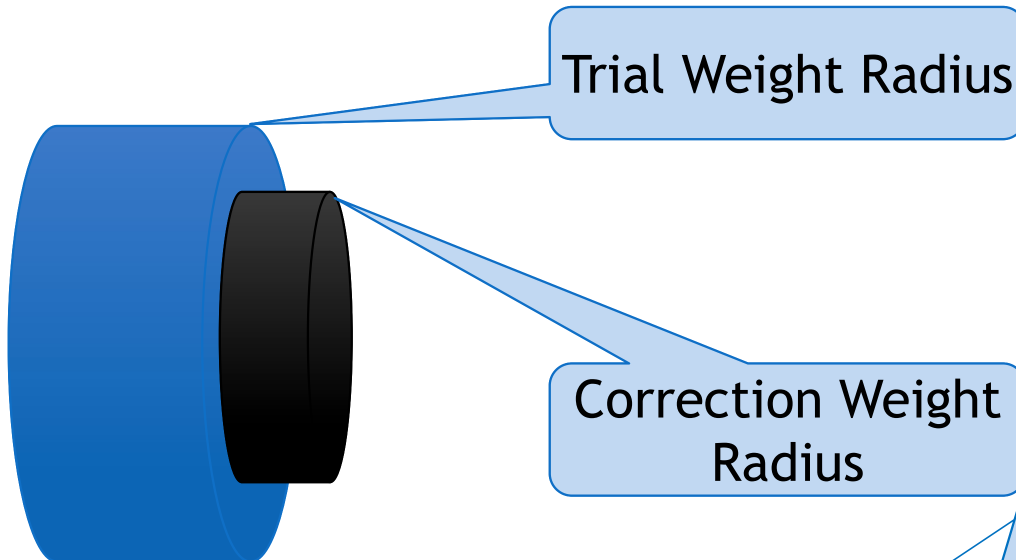
Probably Resonance

- Horizontal Plane Vector Does Not Shift 90° from Vertical Plane Vector

Something Else Contributing to Amplitude

What is balancing?
Balancing Caveats – Other Issues?

Final Correction Placed at Different Radius than Trial Weight



What is balancing?
Balancing Caveats – Other Issues?

The Scale Died

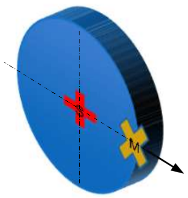
Keyway Stock Trial Weight

1.5 Inches

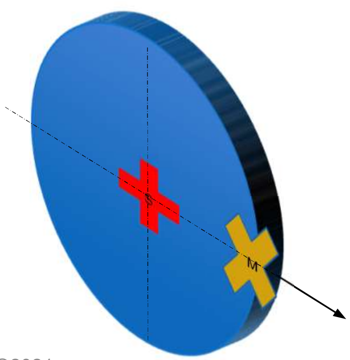
- Enter 1.5 as your trial weight.
- The correction callouts will be in inches rather than weight.

What is balancing?

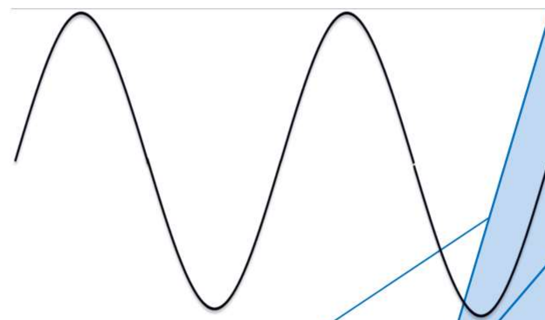
How Much Unbalance is to Much Unbalance?



100 lb
1800 RPM
15 oz-in



500 lb
3600 RPM
15 oz-in



What is balancing?
Balancing Standards

Balance Standards:

- ✓ ISO 1940/1
- ✓ API 684
- ✓ MIL-STD-167
- ✓ ANSI/HI Pump Standards

What is balancing?
Balancing Standards

ISO Balance Grade Consist Of:

1. The Type of Rotor
2. The Weight of the Rotor
3. The Operating Speed
4. The Amount of Residual Unbalance

What is balancing?
Balancing Standards

ISO Grade “G” 1940/1

Balance Quality Grade	Rotor Types - General Examples
G 4000	Crankshaft/drives(3) of rigidly mounted slow marine diesel engines with uneven number of cylinders(4)
G 1600	Crankshaft/drives of rigidly mounted large two-cycle engines
G 630	Crankshaft/drives of rigidly mounted large four-cycle engines Crankshaft/drives of elastically mounted marine diesel engines
G 250	Crankshaft/drives of rigidly mounted fast four-cylinder diesel engines(4)

What is balancing?
Balancing Standards

ISO Grade “G” 1940/1

Balance Quality Grade	Rotor Types - General Examples
G 100	Crankshaft/drives of fast diesel engines with six or more cylinders(4) Complete engines (gasoline or diesel) for cars, trucks and locomotives(5)
G 40	Crankshaft/drives of rigidly mounted fast four-cylinder diesel engines(4)
G 16	Crankshaft/drives of fast diesel engines with six or more cylinders(4) Complete engines (gasoline or diesel) for cars, trucks and locomotives(5)

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ISO Grade "G" 1940/1

Balance Quality Grade	Rotor Types - General Examples
G 6.3	Parts of process plant machines Marine main turbine gears (merchant service) Centrifuge drums Paper machinery rolls; print rolls Fans Assembled aircraft gas turbine rotors Flywheels Pump impellers Machine-tool and general machinery parts Medium and large electric armatures (of electric motors having at least 80 mm shaft height) without

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Balance Quality Grade	Rotor Types - General Examples
G 6.3	special requirements Small electric armatures, often mass produced, in vibration insensitive applications and/or with vibration-isolating mountings Individual components of engines under special requirements Gas and steam turbines, including marine main turbines (merchant service)
G 2.5	Gas and steam turbines, including marine main turbines (merchant service) Rigid turbo-generator rotors Computer memory drums and discs

What is balancing?
Balancing Standards

ISO Grade “G” 1940/1

Balance Quality Grade	Rotor Types - General Examples
G 2.5	Turbo-compressors Machine-tool drives Medium and large electric armatures with special requirements Small electric armatures not qualifying for one or both of the conditions specified for small electric armatures of balance quality grade G 6.3 Turbine-driven pumps

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Balancing Standards

ISO Grade “G” 1940/1

Balance Quality Grade	Rotor Types - General Examples
G 1	Tape recorder and phonograph (gramophone) drives Grinding-machine drives Small electric armatures with special requirements
G 0.4	Spindles, discs and armatures of precision grinders Gyroscopes

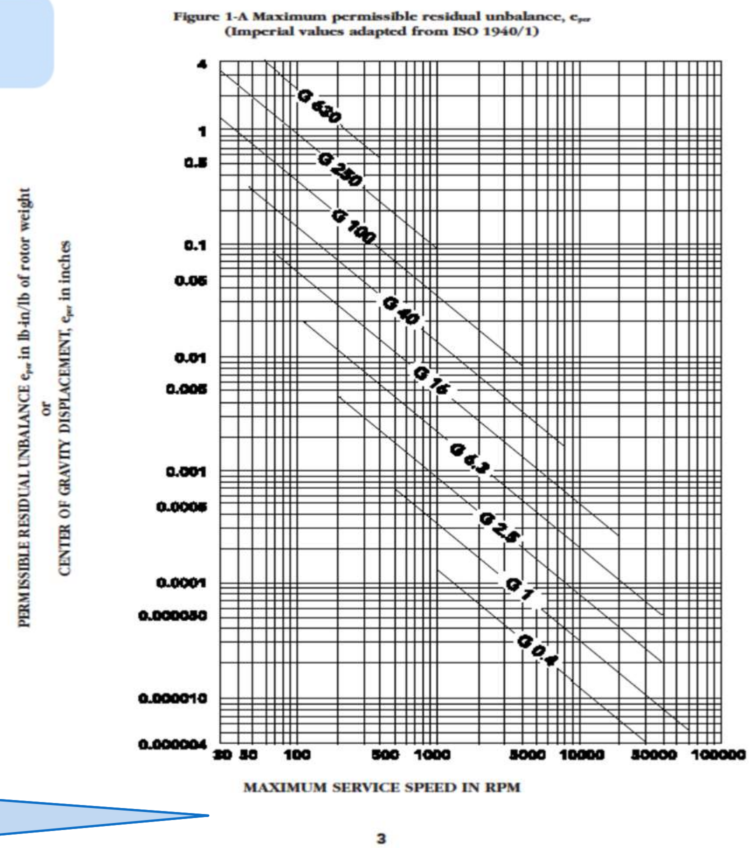
1) v = 2^{1}n/60 Å n/10, if n is measured in revolutions per minute and v in radians per second.
2) For allocating the permissible residual unbalance to correction planes, refer to "Allocation of Upper to correction planes."
3) A crankshaft/drive is an assembly which includes a crankshaft, flywheel, clutch, pulley, vibration damper, rotating portion of connecting rod, etc.
4) For the purposes of this part of ISO 1940/1, slow diesel engines are those with a piston velocity of less than 9 m/s; fast diesel engines are those
with a piston velocity of greater than 9 m/s.
5) In complete engines, the rotor mass comprises the sum of all masses belonging to the crankshaft/drive described in note 3 above.

What is balancing?
Balancing Standards

ISO Residual Unbalance

Permissible Residual Unbalance
E_{per} in-in/lb of Rotor Weight
Or
Center of Gravity Displacement
E_{per} in-inches

Maximum Service Speed



What is balancing?
Balancing Standards

Permissible Residual Unbalance

Constant

Balance Grade

$$\text{Total Residual Unbalance (oz-in)} = \frac{6 \times \text{Rotor Weight (lb)} \times G}{\text{RPM}}$$

Example:

Speed = 2000 RPM
Rotor = 100 lb
G = 2.5

$$\frac{6 \times 100 \text{ lb} \times 2.5}{2000 \text{ RPM}} = 1.89 \text{ oz-in } (U_{per} \text{ total for rotor})$$

What is balancing?
Balancing Standards

Permissible Residual Unbalance
Metric Units

$$\text{Total Residual Unbalance (oz-in)} = \frac{6 \times \text{Rotor Weight (lb)} \times G}{\text{RPM}}$$

$$\text{Total Residual Unbalance (gram-mm)} = \frac{9549 \times \text{Rotor Weight (kg)} \times G}{\text{RPM}}$$

What is balancing?
Balancing Standards

Calculate G Number from Residual Unbalance

$$G = \frac{\text{RPM x Total Residual Unbalance (oz-in)}}{\text{6 x Rotor Weight (lb)}}$$

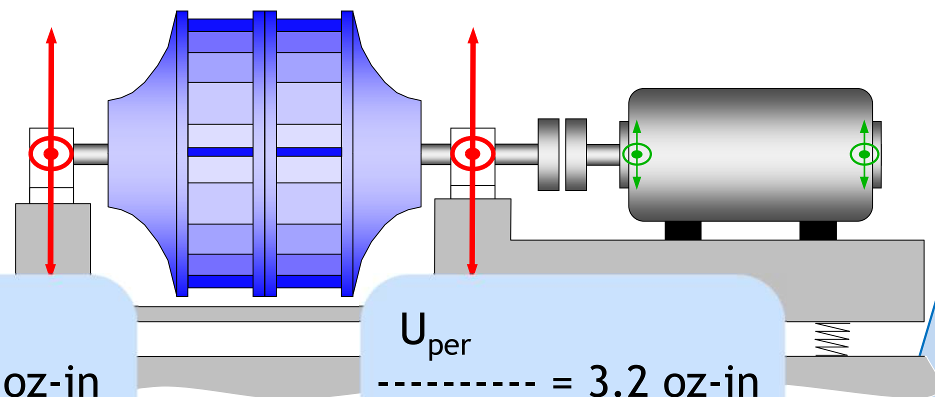
$$\text{Example: } \frac{\text{2000 RPM x 1.89 oz-in } (U_{per} \text{ Total for Rotor})}{\text{6 x 100 lb}} = G\ 6.3$$

What is balancing?
Balancing Standards

VCMR

Permissible Residual Unbalance
Two Plane

Total U_{per} = 6.4 oz-in



$\frac{U_{per}}{2}$ = 3.2 oz-in

$\frac{U_{per}}{2}$ = 3.2 oz-in

VCMR

Vibration Condition Monitoring & Reliability

Thank you