Unbalance

Single Plane Balancing – Procedure

1 - “as is” run

2 - trial weight run

3 - calculate and make permanent correction

4 - the final run

Single Plane Balancing

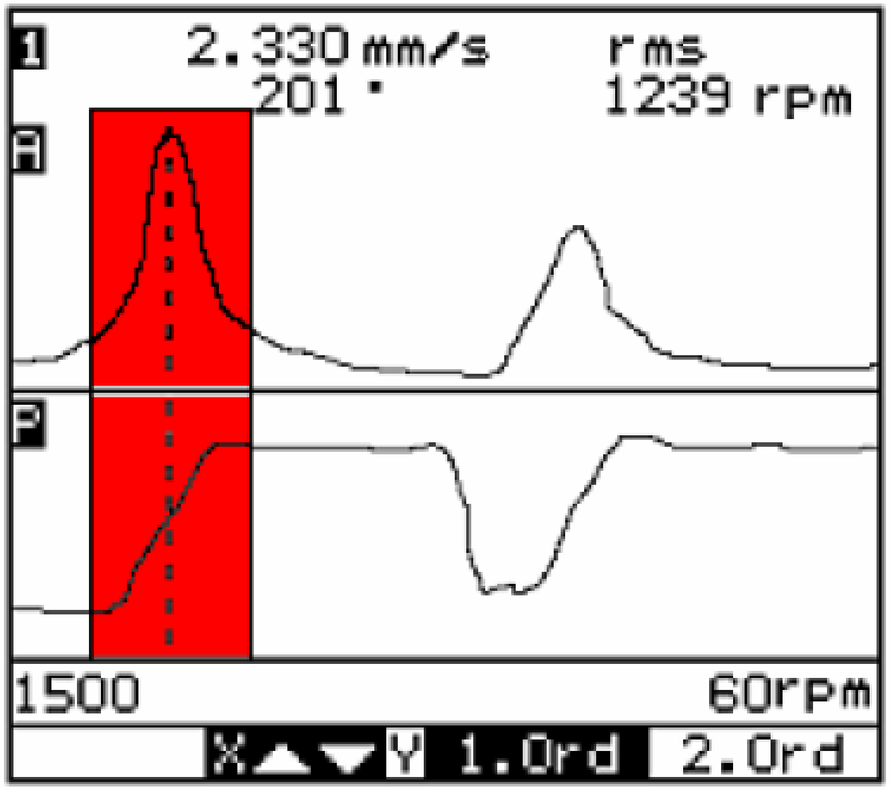


Figure 3.6: Run-up/coastdown curve of the machine to be balanced (see Vibration Analysis seminar). A balancing speed in the resonance range (shaded region) should be avoided if possible since small speed deviations lead to changes in the measurements.

Single Plane Balancing

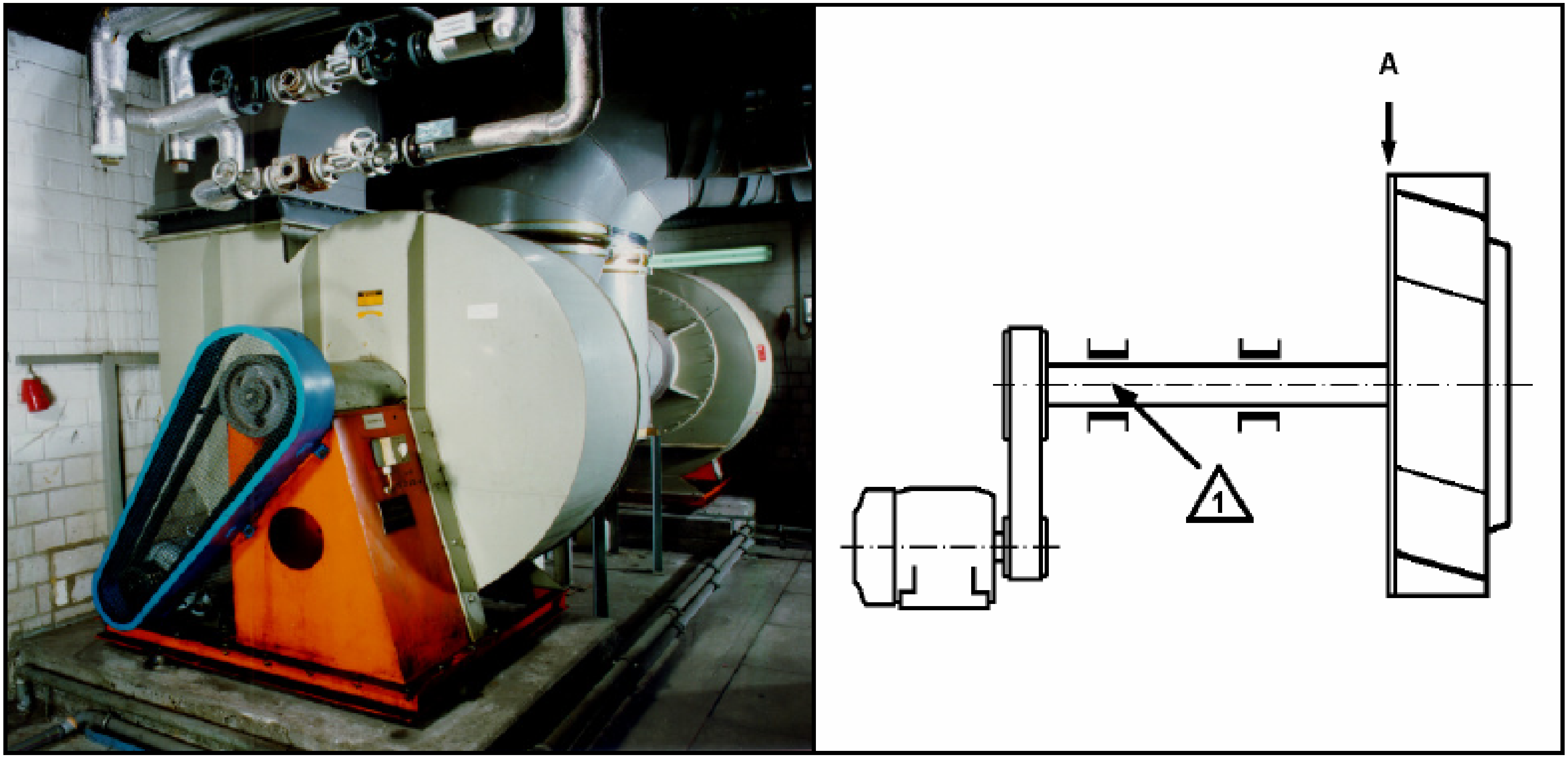


Figure 3.7: External view (left) and construction diagram (right) of the unbalanced fan. The measuring plane "1" and correction plane 'A" are indicated.

Single Plane Balancing

Figure 3.9: *The reference mark attached to the pulley and the photo-electric sensor mounted in the magnetic stand (left) in the example. The acceleration sensor was mounted by magnet on the bearing support structure.*

Single Plane Balancing

Single Plane Balancing – the "as is" run

- provides baseline data
- ensure repeatability
- record vibration amplitude and phase

Example: Vibration Amplitude = 10 at 30° (10 mils peak-to-peak at 30° phase relative to some reference)

We wish to know - location and weight of unbalance causing this vibration

Single Plane Balancing

Single Plane Balancing – the trial weight run

- this tells us how a known unbalance weight in a known location affects rotor dynamics
- how closely the machine is operating to a resonance is important (just below, just above, well above)
- watch phase change immediately after shut down & before coast down
- dramatic changes in phase mean operational speed is close to a resonance

Single Plane Balancing

- when calculating the unbalance weight include an extra 10% onto the weight of the rotor to account for vibrations absorbed into the bearings & supports
- the trial weight is equal to the unbalance weight divided by an amplification factor (determined from the location of the operating frequency on the system response curve)
- add trial weight opposite existing unbalance location
- collect trial weight run vibration data

Single Plane Balancing

Some general guidelines

- A trial weight should not yield a force of more than 10 % the static weight of the rotor
- Trial weight (W_T) calculation formula

$$W_T = 56{,}375.5\ (W/N^2 e)\ \text{(ounces)}$$

W - rotor weight (lb), N – rotor speed (RPM), e – eccentricity (in)

- If no vibration response is obtained, either the trial weight is too small or the problem is not mass unbalance

Single Plane Balancing

Single Plane Balancing – final calculation

The trial weight resultant vector

= (trial weight vector) + (initial unbalance vector)

Correction determined graphically or vector calculations

Single Plane Balancing

Single Plane Balancing – final run

- restart machine to check vibration levels
- if unacceptable treat as a new “as is” run
- do not tinker with weights already added.

Single Plane Balancing

Single-plane vector balancing procedure with trial weight (review)

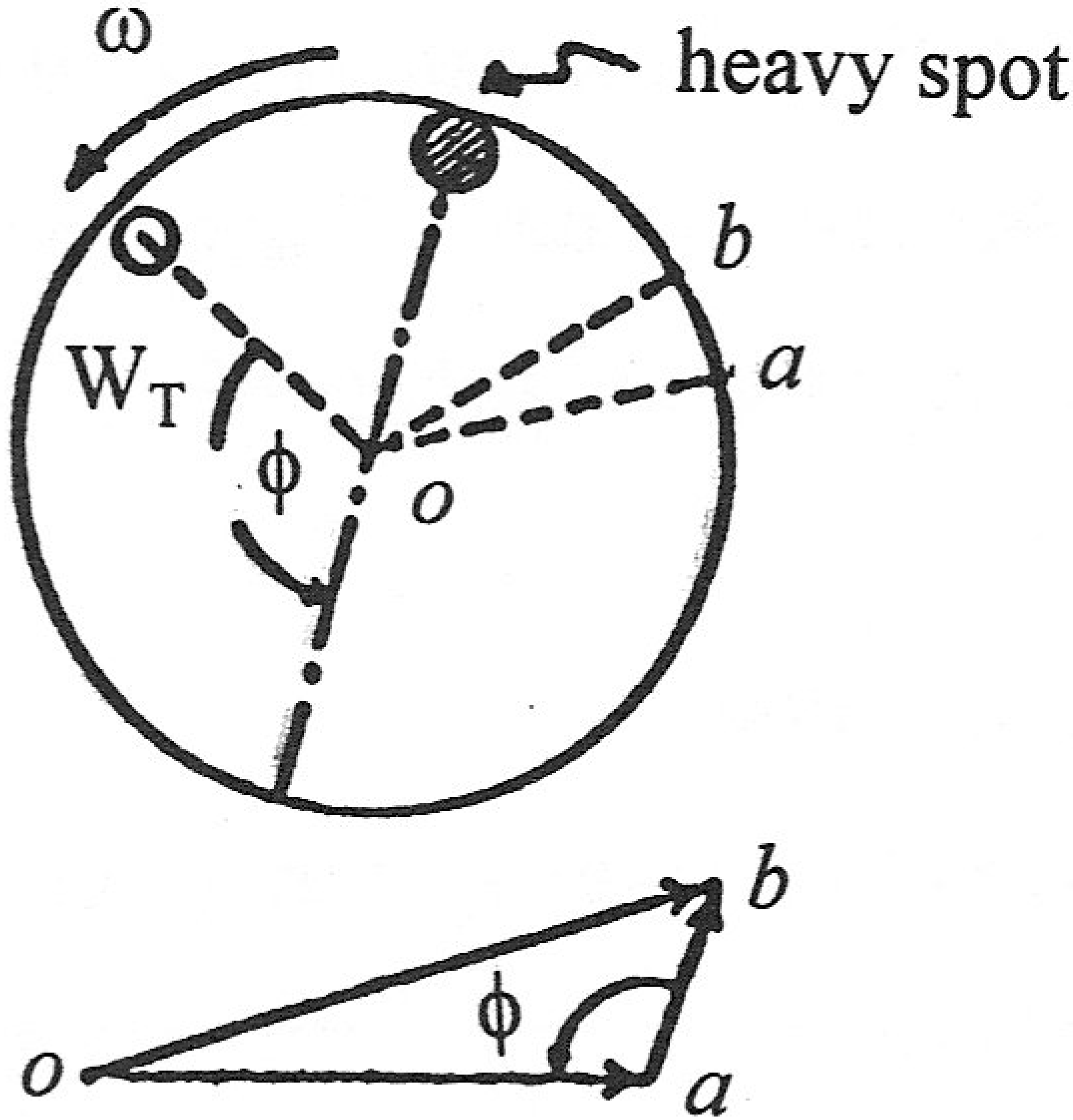
- Measure and record signal
- Install trial weight
- Measure and record trial run
- Calculate vectors
- Correct trial weight
- Measure and record trial run

Vector Method with Trial Weight

Single-plane balancing – a simple example

- Mark the high spot (***a***) and its amplitude (***oa***)
- Place trial weight $\mathbf{W_T}$ at selected direction and mark the new high spot (***b***) and its amplitude (***ob***)
- The vector difference ***ab = ob – oa*** is the effect of $\mathbf{W_T}$ alone
- Move the W_T in the same direction and angle ϕ to make (***ab)*** parallel to and opposite (***oa)***
- The trial weight is increased or decreased in the ratio (***oa/ab)*** equal to the original unbalance

Vector Method with Trial Weight



Vector Method with Trial Weight

Detailed procedures for constructing a vector diagram for single-plane balancing

1. Mark the direction of rotor rotation on the graph
2. Mark the direction of positive phase angle
3. Establish a scale of numbers of mils per division so the vectors are large but do not exceed the graph
4. The original vibration **O** (5 mils at 190º in Figure) is plotted on the graph

Vector Method with Trial Weight

5. The location of the trial weight (**W_T**) is plotted (30º) and its size (75 grams) are noted on the graph
6. Plot the vibration (**O+T**) obtained after the trial weight has been added to the rotor. The rotor must be operated at the same speed as when the original data (**O**) were acquired
7. The difference between **O** and (**O+T**) is the effect of the trial weight

Vector Method with Trial Weight

8. The effect of the trial weight is obtained by drawing a line between **O** and (**O+T**)
9. **O + T** must be equal to (**O+T**). The arrow on T must point to (**O+T**). Vectors add heads to tails and subtract heads to heads
10. T is now repositioned with its tail at the origin by moving it parallel and maintaining the same length
11. Draw a line opposite **O** from the origin

Vector Method with Trial Weight

12. The goal in balancing is to add a trial weight that will create a **T** vector directly opposite and equal to **O**

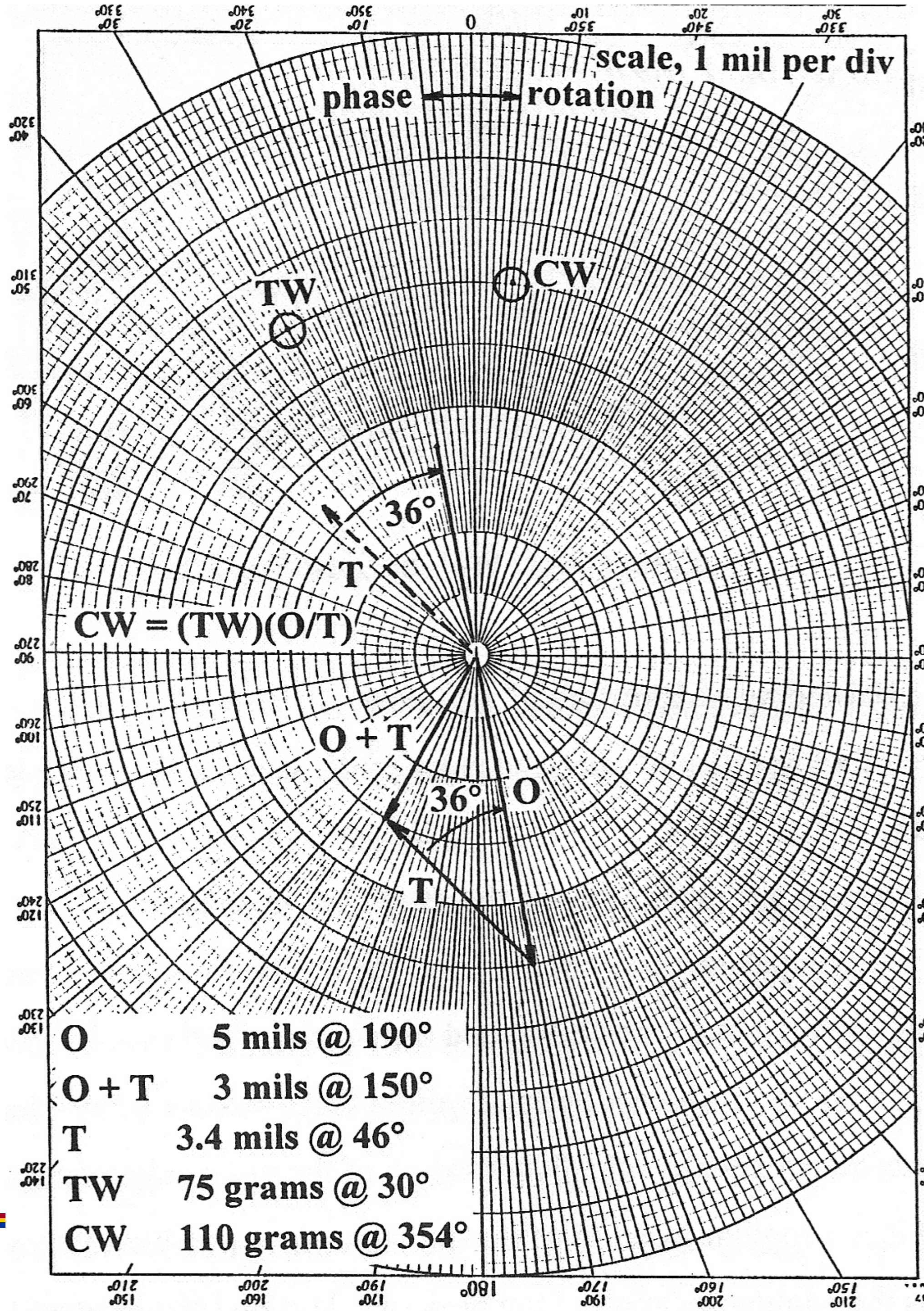
13. The angle between **T** and the line opposite **O** 36º determines how far and in what direction the trial weight must be moved

14. The trial weight is multiplied by the ratio of the original vibration to the effect of the trial weight (5/3.4)angle between **T** and the line to determine the balance weight

$$75 \text{ g } (5/3.4) = 110 \text{ g}$$

Vector Method

- Procedure of single-plane balancing

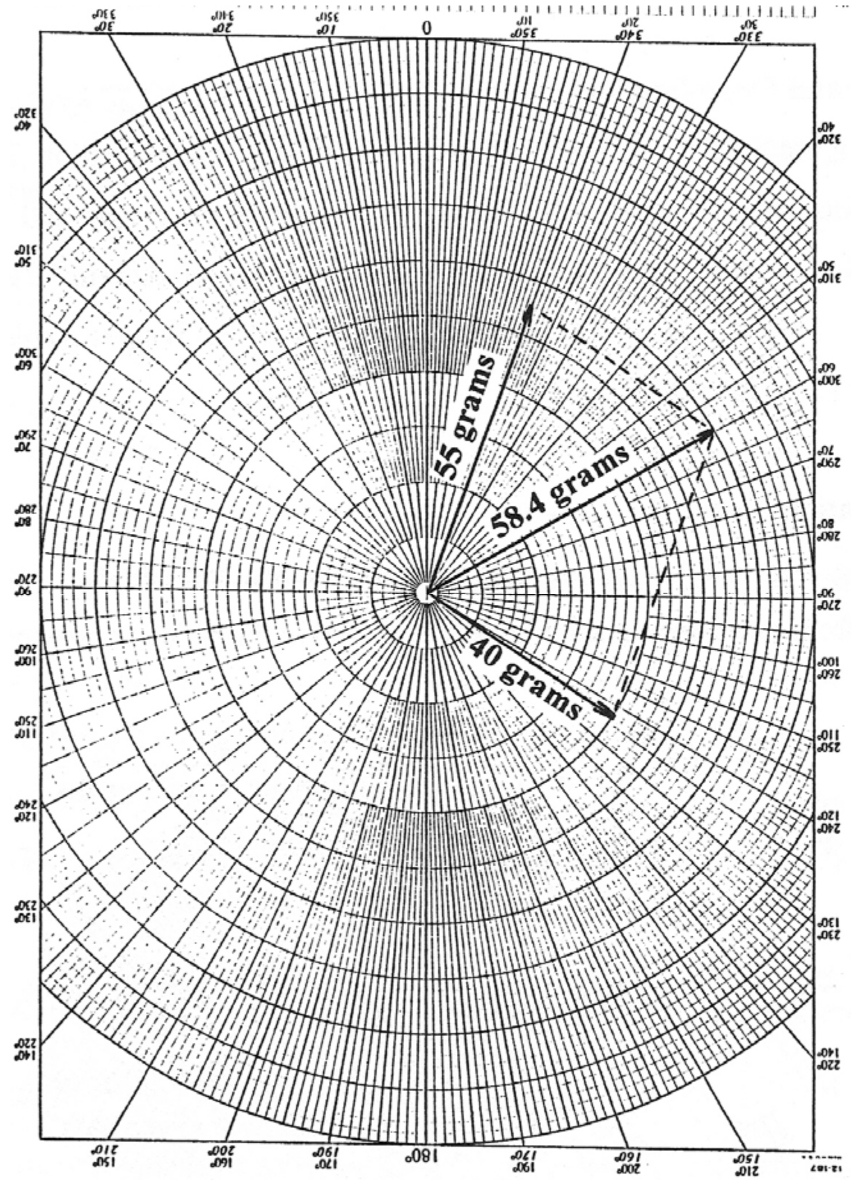


Weight Splitting and Consolidation

- Weight splitting is to place the weights at the desired locations (***a*** and ***b***)
- A parallel rule can be used to determine graphically the magnitudes of the weights at desired locations (***a*** and ***b***) by the lengths of the vectors
- Weight combination is the inverse process used to determine the location and magnitude of the combined weight

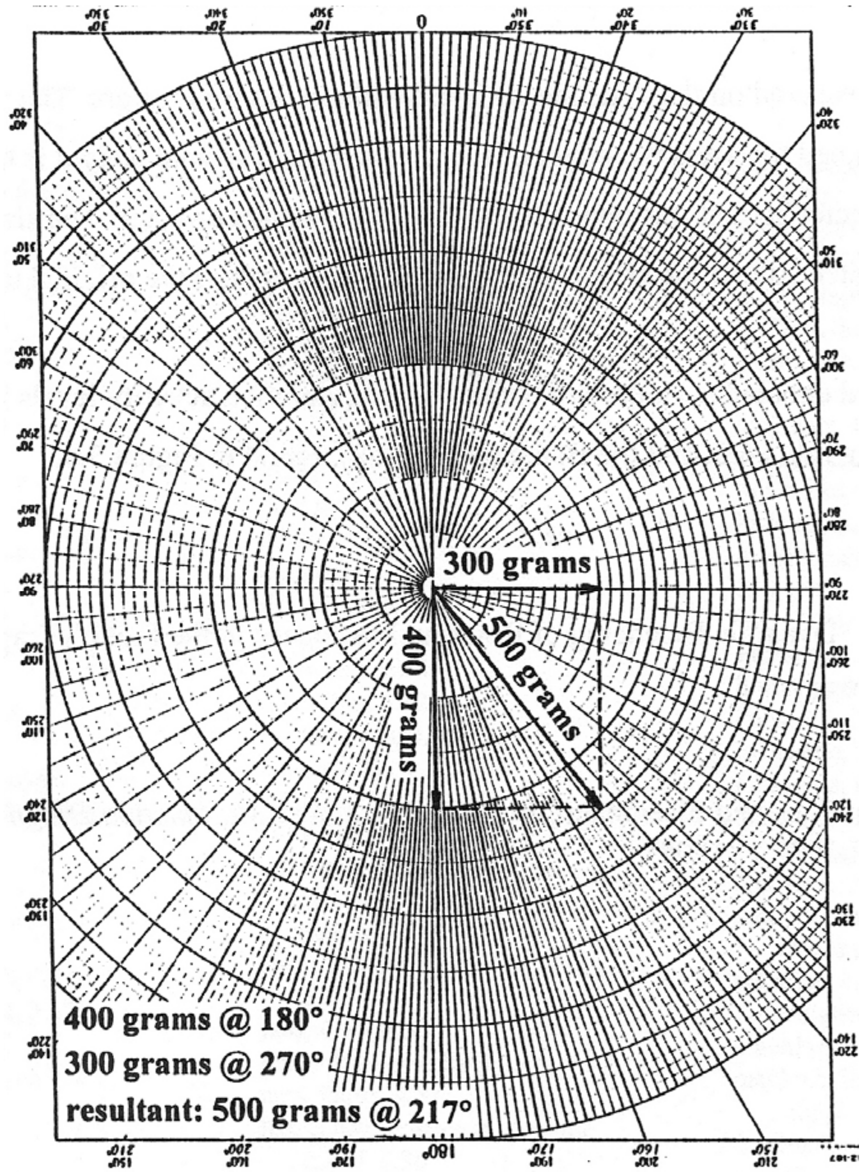
Vector Method with Trial Weight

- Weight splitting

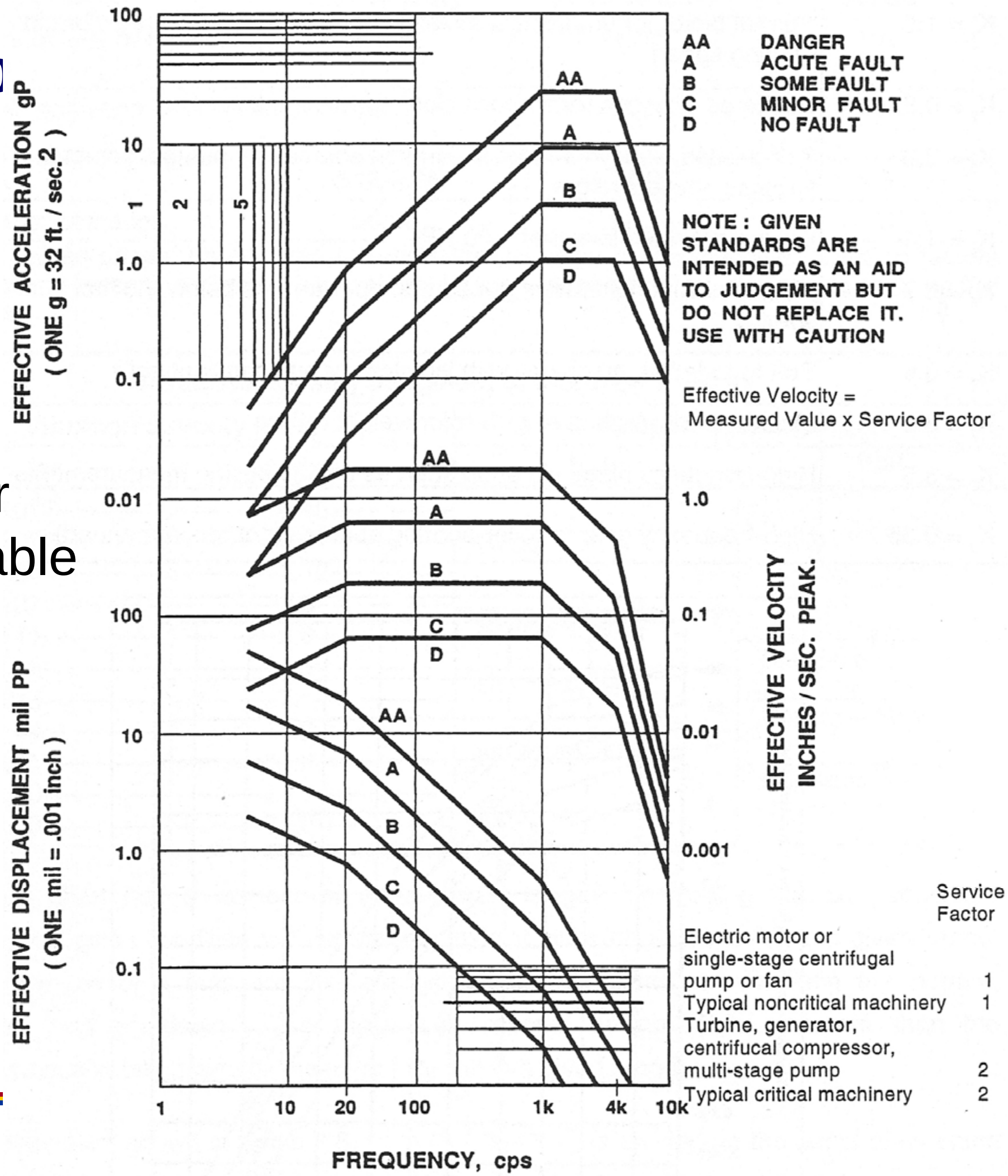


Vector Method with Trial Weight

- Weight combination



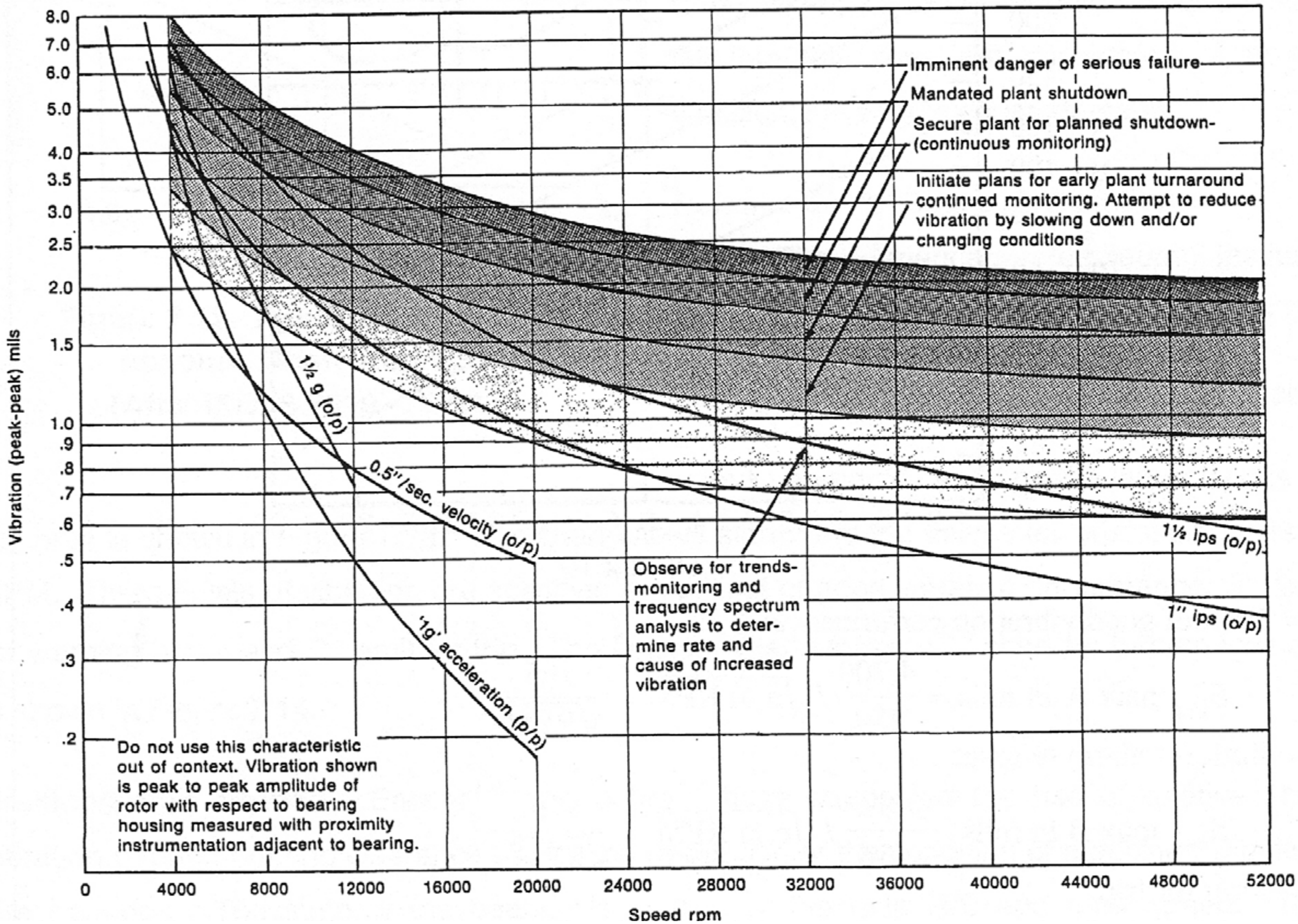
Accep



Modified Blake chart for field balancing: acceptable vibration levels

Acceptable Vibration Levels

Proximity probe measurements – Dresser-Clark chart



Unbalance

Multiple Plane Balancing

- correction planes = number of bearings plus one
- depends on flexibility of rotor.
- several trial runs.
- cross plane effects
- matrix solution

Summary

- Mass unbalance of a rotor results when the mass center is not at the same location as the geometric center
- Mass unbalance causes a rotating force at the frequency of shaft speed
- The amount of mass unbalance force depends on the location of the mass center from the geometric center, the weight of the object, and the square of the speed

Summary

- Balancing is a procedure in which a balance weight that creates a force equal to the mass unbalance is placed opposite the effective location of the mass unbalance
- The heavy spot is the angular location of the mass unbalance on the rotor
- The high spot is the angular location of the peak of vibration (displacement)

Summary

- The high spot is measured during the balancing process; however, the balance weight must be positioned opposite the heavy spot.
- Either displacement, velocity, or acceleration can be measured; however, displacement is preferred
- The high spot lags the heavy spot as a result of electronic (instrument) and mechanical lag

Summary

- Balancing should not be performed until it is evident that misalignment, excessive bearing clearance, looseness, and distortion are not the cause of the vibration at operating speed
- The rotor should be clean and structurally sound prior to balancing
- Trial or calibration weights are used to obtain the mechanical lag

Summary

- The rule of thumb for selecting a trial weight is that it should create a force of not more than 10% of the rotor weight
- The vector method is used to determine the size and location of the correction weight
- Vibration is measured on the machine with and without the trial weight.
- The vectorial difference is determined to access the effect of the trial weight.

Summary

- The trial weight is moved relative to the effect vector so that it is opposite the original unbalance vector
- The size of the trial weight is adjusted so that the effect vector is the same length as the original unbalance vector
- Allowable field unbalance values are obtained from vibration severity levels in ISO 2372 (rms) and the modified Blake chart

Considering a Bearing Redesign?

Before Considering Bearing Redesign

- Check that the oil console or reservoir contains the correct lubricant.
- Check the oil quality for proper density, viscosity, water content, etc.
- Check the oil for the presence of any foreign materials.
- Check for proper oil supply pressure, temperature, and system control.
- Check the oil flow rate to each bearing, and verify that orifices are properly installed, and that orifice diameters are both reasonable and correct.

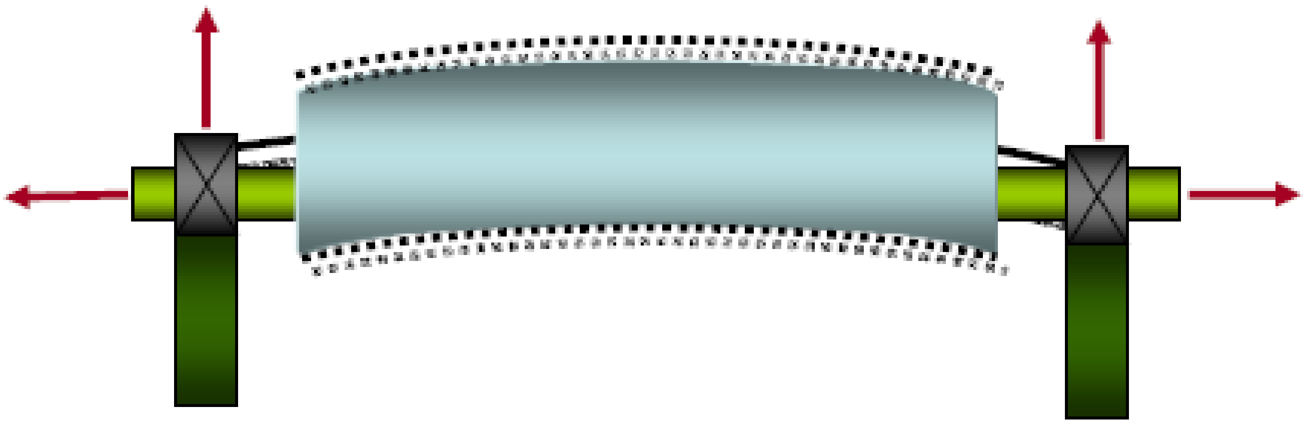
- Check the oil drain temperatures, and relative flow rates.
- Check that the bearing is properly installed with respect to shaft rotation.
- Check that anti-rotation pins are properly installed with respect to rotation.
- Check that the shaft to bearing clearance is correct.
- Check that the bearing to housing clearance is correct.
- Check that the bearing liner is not distorted or warped.
- Check that the bearing splitline is not sealed with RTV, silicone, or other incompressible sealants. Use a thin grade of Permatex® sealant for this job.
- Check for other mechanical changes in the train that would influence bearing load (e.g., changing a gear coupling to a large diaphragm coupling).
- Check rotor balance records, and the last set of transient startup data.
- Check coupling alignment for proper cold offset and hot running position.
- Check for proper temperatures from imbedded thermocouples or RTD's.
- Check bearing temperature trends (day to night, week to week, etc.).
- Check to be sure that shaft is level when hot and running.
- Check bearings, seals, and couplings for evidence of electrical discharge.
- Check pads and backing for evidence of wear, cracking, or fretting.
- Check bearings for evidence of edge wear across bearings and machines.
- Check for proper position of the journal within the bearing with prox probes.
- Check shaft vibration for normal 1X running speed vibration vectors.
- Check shaft vibration for any abnormal frequency components.
- Check the attachment of the bearing housing to the casing and/or baseplate.
- Check grout condition, and the attachment of baseplate to foundation.

Machinery Vibration Forcing Functions

BENT SHAFT (Bowed Rotor)

- a special form of unbalance (same vibrations)
- bent shaft – outside the machine housing
- bowed rotor – inside the housing
- common on large machines with heavy shafts
- when idle - gravity causes sag (slow rotate when not in use), difficult to correct
- may also be caused by local (uneven) heating of the shaft (see rubs)

Bent Shaft or Rotor Bow



Machinery Vibration Forcing Functions

SHAFT MISALIGNMENT

- a major cause of excessive machinery vibration
- due to improper machine installation
- flexible coupling can tolerate some shaft misalignment
- slight misalignment necessary for proper gear teeth lubrication in a gear coupling
- otherwise - shafts of coupled machines should be as closely aligned as possible

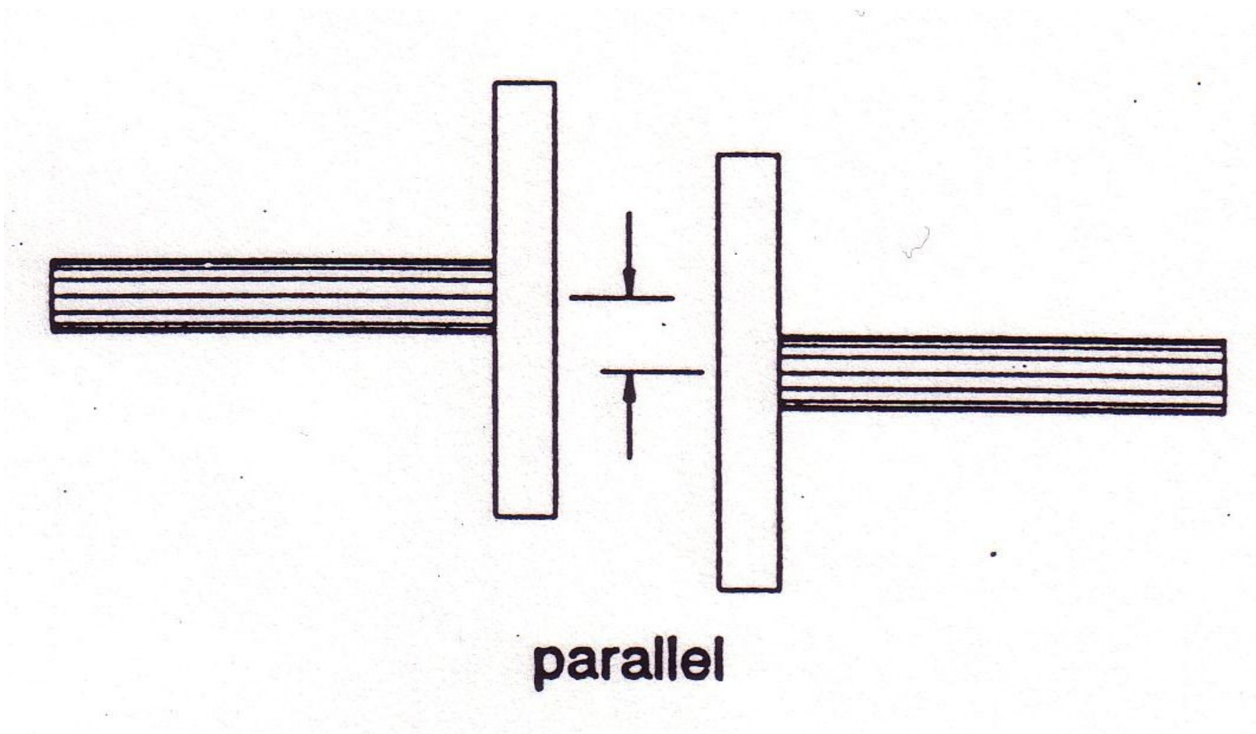
Types of Misalignment

Parallel Misalignment (offset)

- shaft centre lines are parallel but offset from one another
- horizontal, vertical or combination

Machinery Vibration Forcing Functions

Parallel Misalignment (offset)

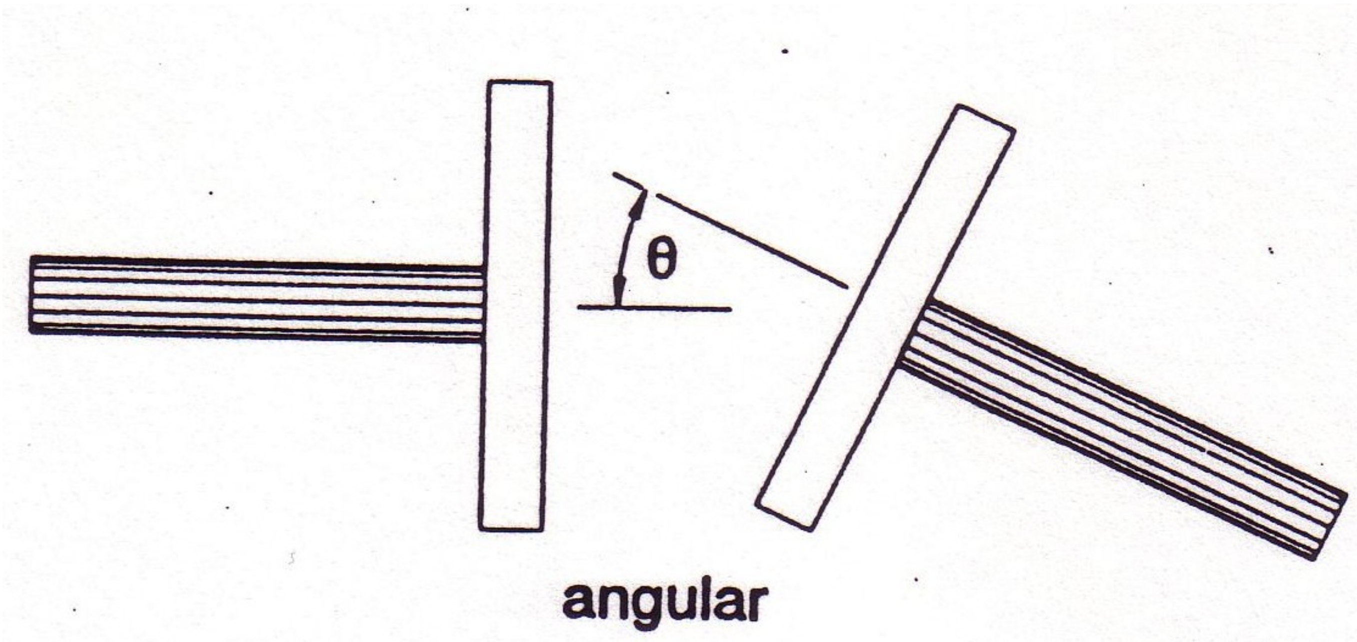


Machinery Vibration Forcing Functions

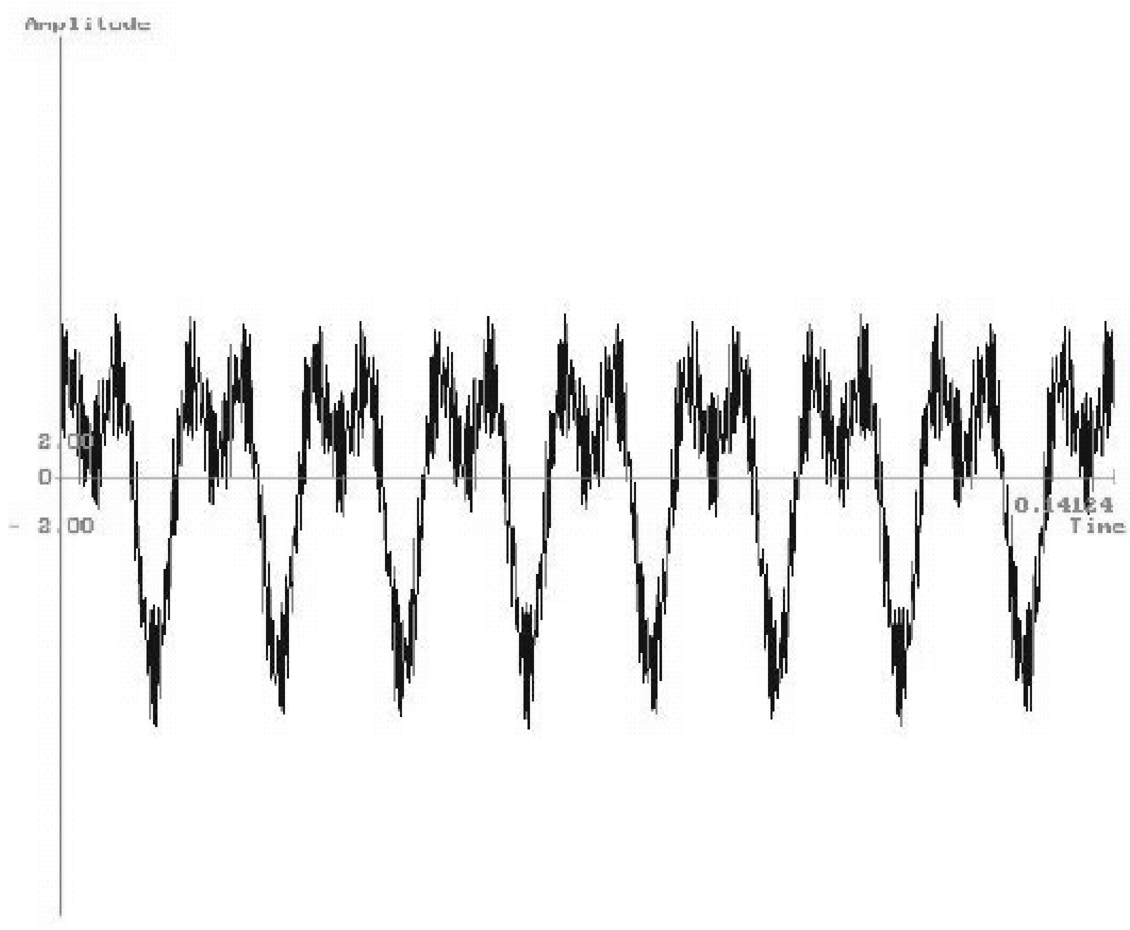
Angular Misalignment

- shaft center lines meet at an angle
- intersection may be at driver or driven end, between units or behind units
- most misalignment is a combination of Parallel and Angular misalignment

Angular Misalignment

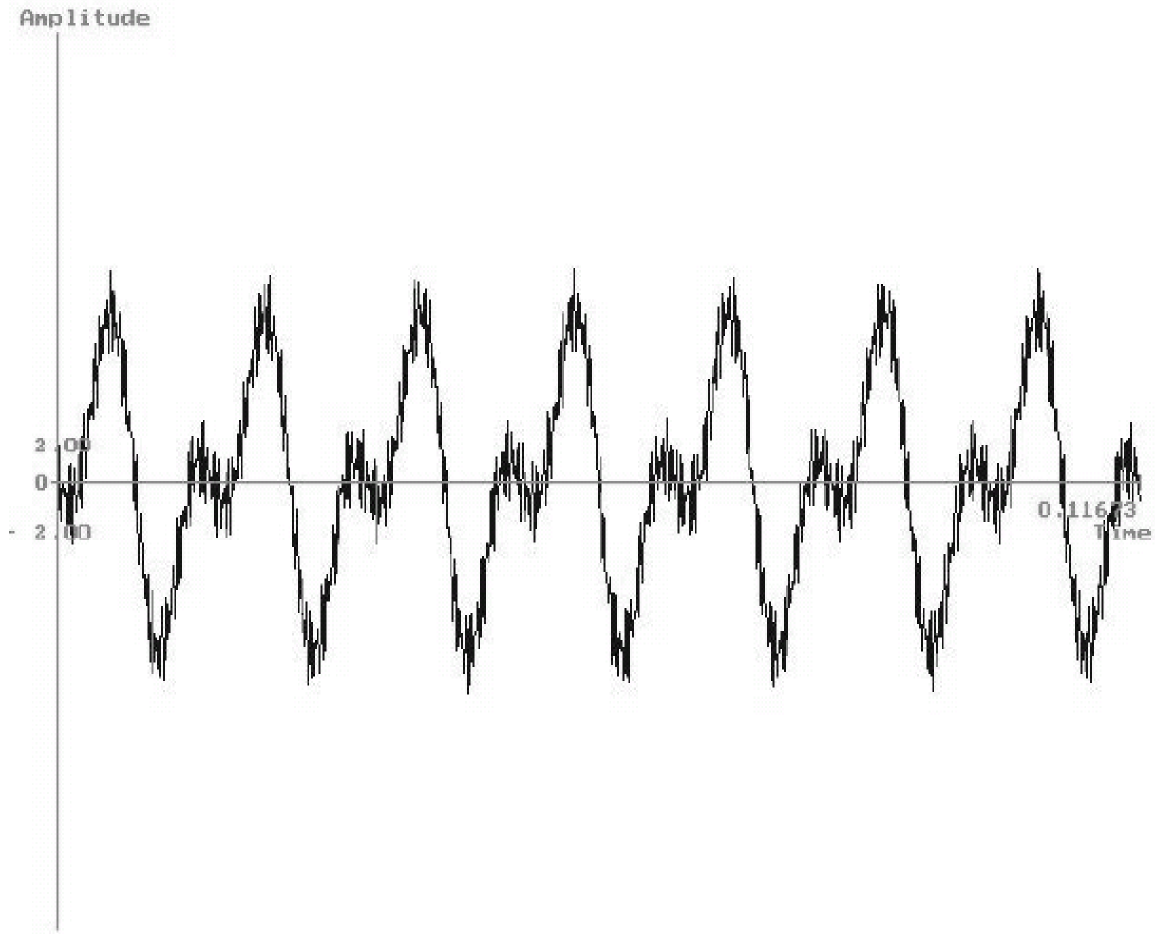


Machinery Vibration Forcing Functions



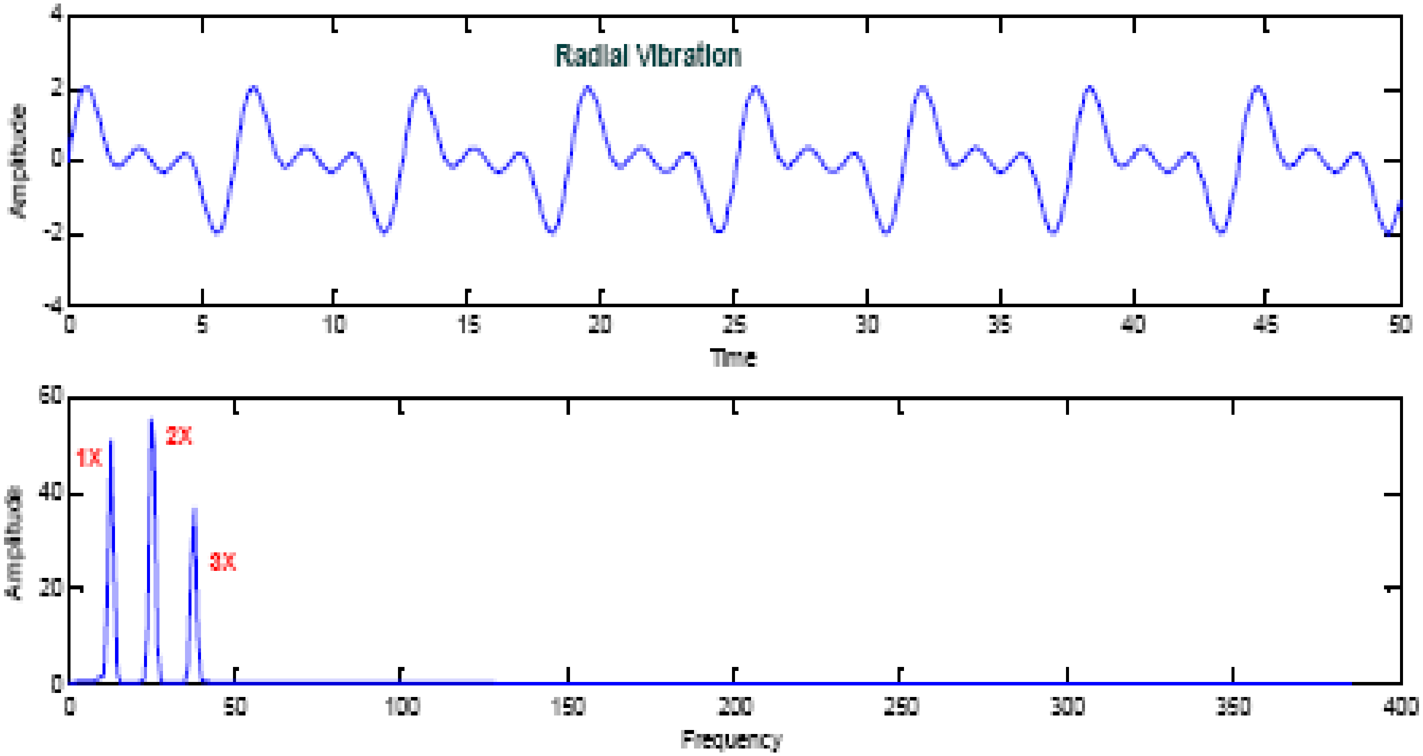
Classic time waveform of misalignment

Machinery Vibration Forcing Functions



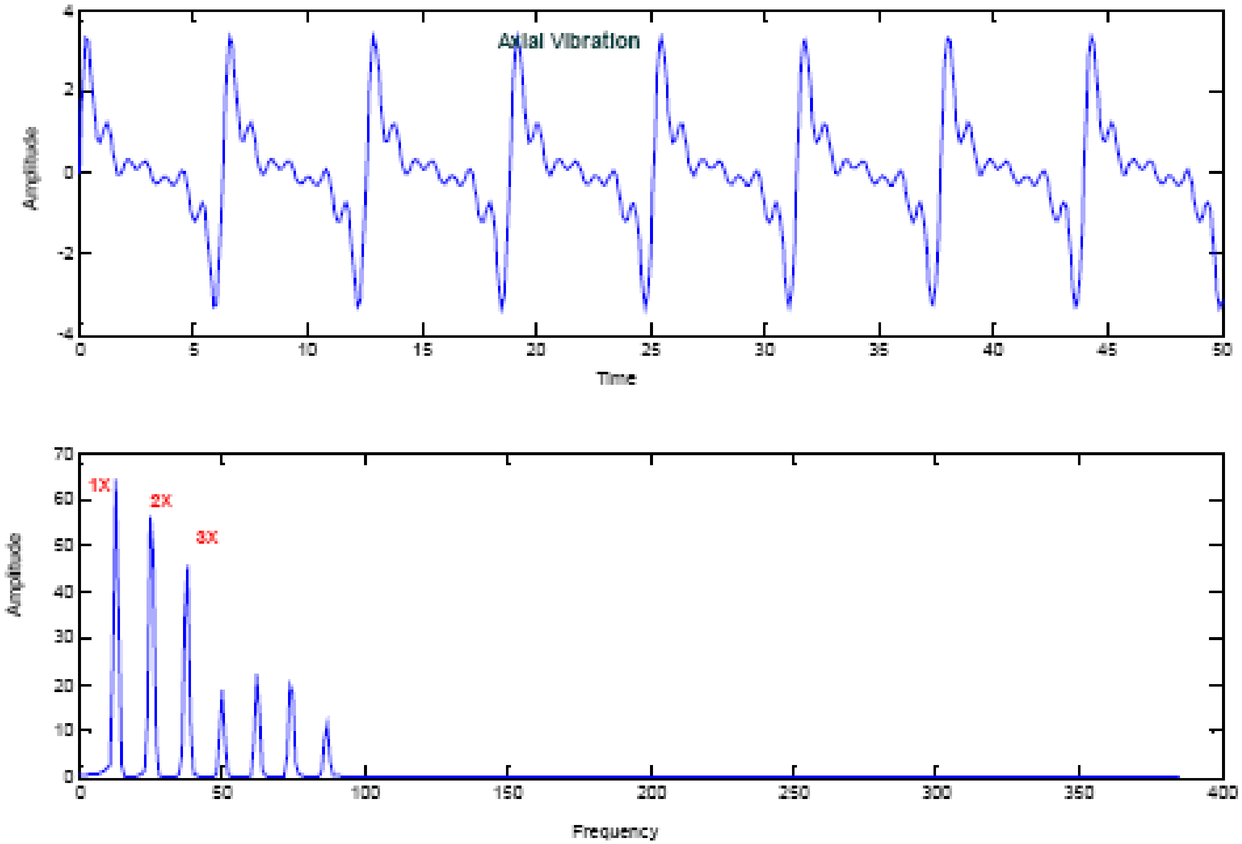
Misalignment time waveform – 90 degrees of phase shift between 1X and 2X components

Machinery Vibration Forcing Functions



Misalignment time waveform and frequency spectrum

Machinery Vibration Forcing Functions



Misalignment time waveform and frequency spectrum

Machinery Vibration Forcing Functions

Bearing Misalignment

- shaft center lines are properly aligned
- bearings on one side of coupling are misaligned
- not mounted in the same plane
- not normal to shaft
- machine distorts in use (soft foot, uneven base, thermal growth)

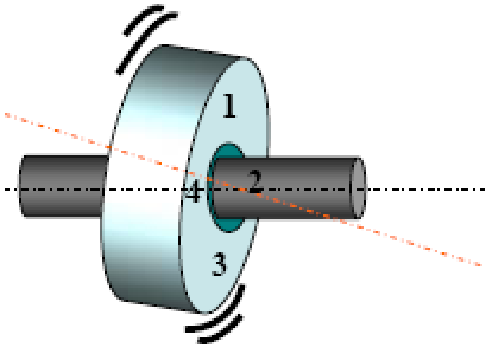
Machinery Vibration Forcing Functions

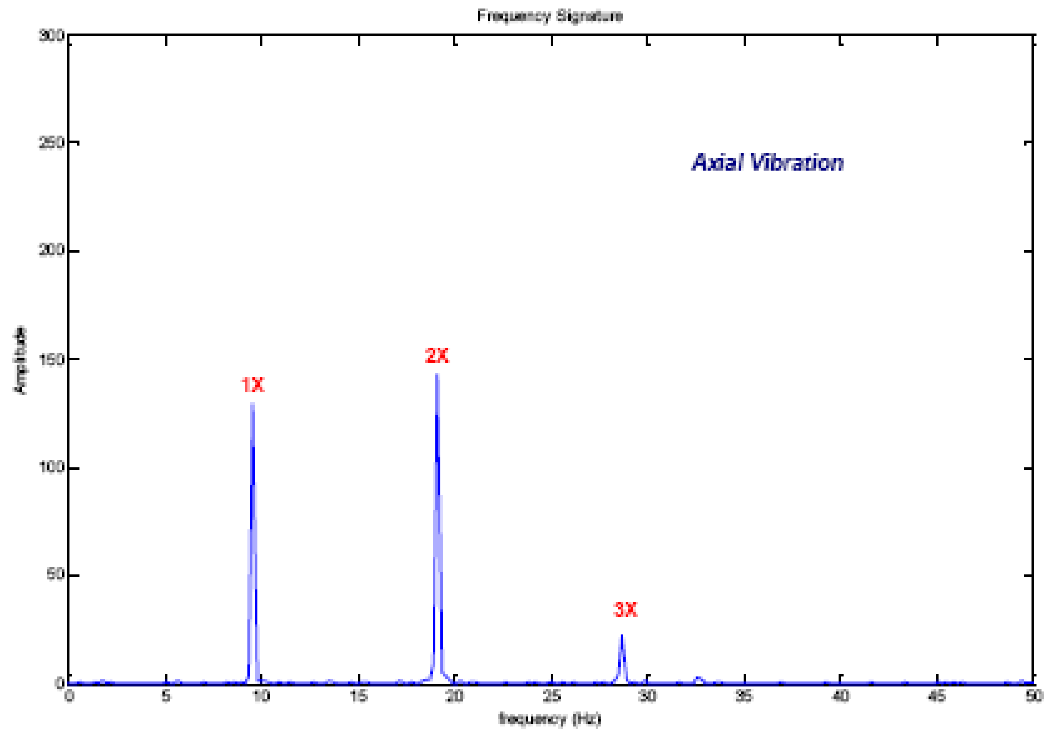
- Cocked Bearing will generate considerable axial vibration

- Will cause twisting motion with approximately 180° phase shift top to bottom and/or side to side as measured in the axial direction of the same bearing housing

- Attempts to align the coupling or balance the rotor will not alleviate the problem. The bearing must be removed and correctly installed.

Machinery Vibration Forcing Functions



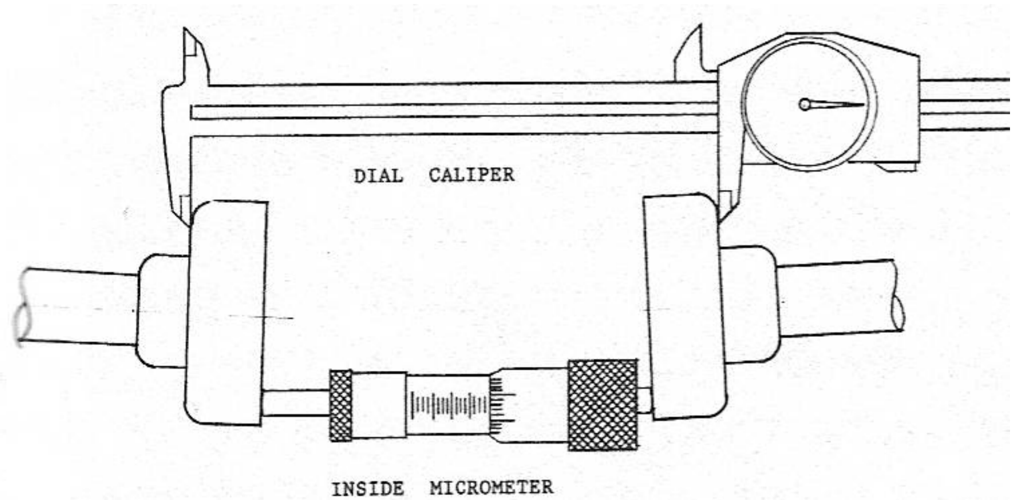


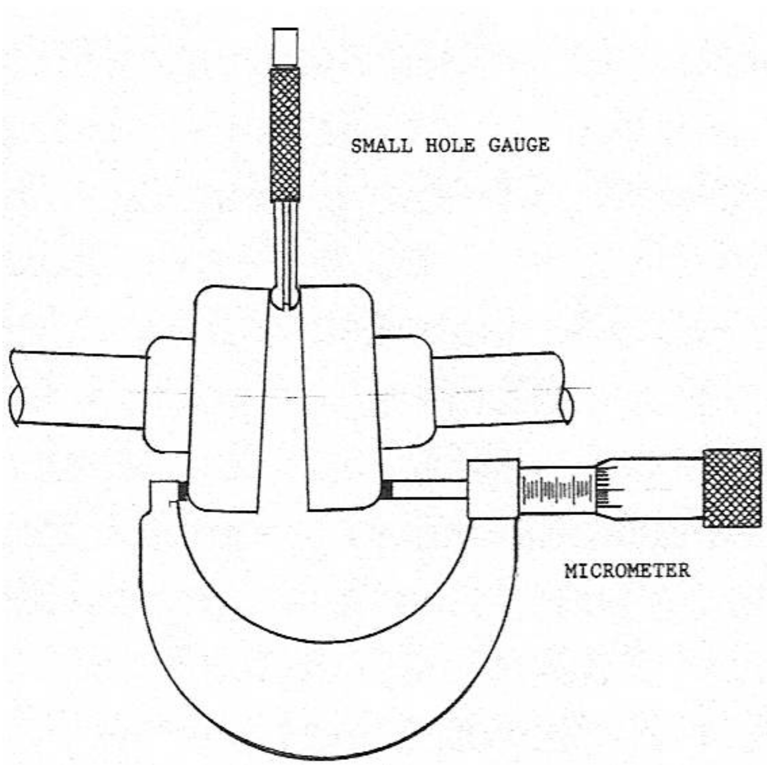
Machinery Vibration Forcing Functions

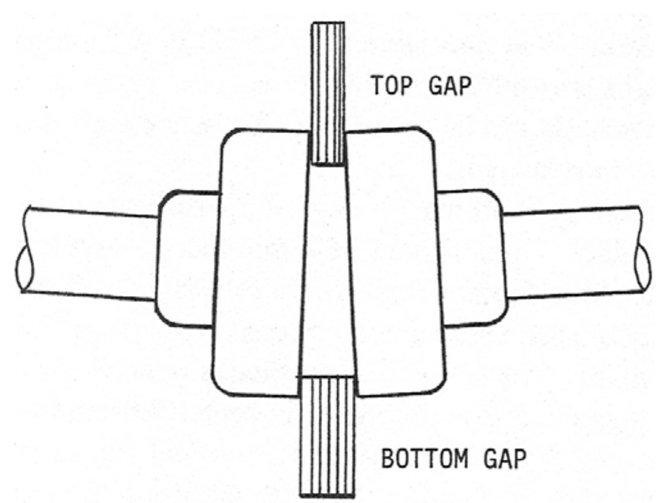
Alignment Methods

- reverse dial method
- face and rim method
- dial indicators or laser sensors

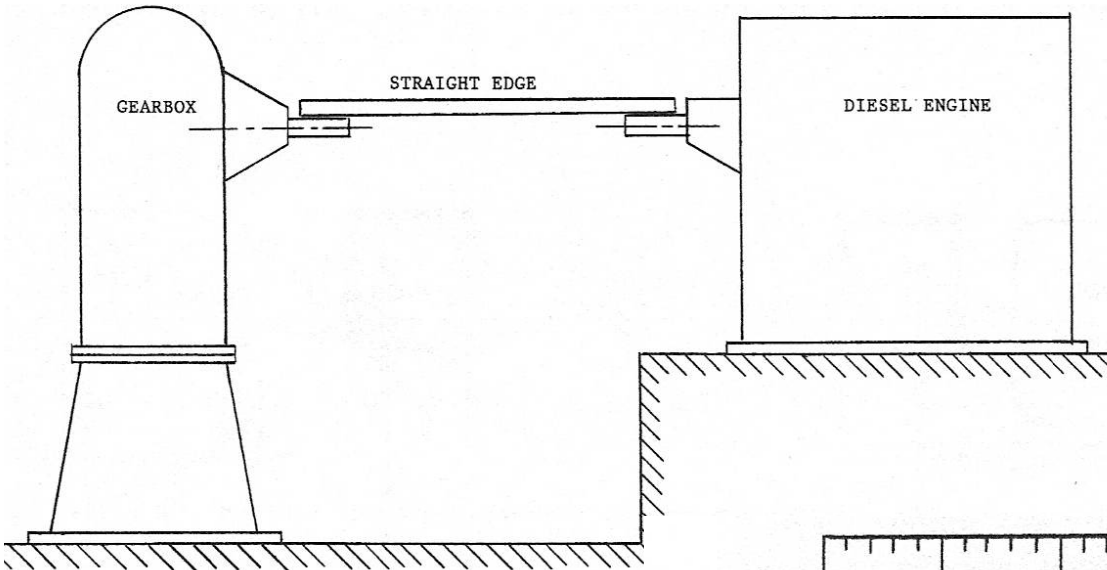
Alignment Methods

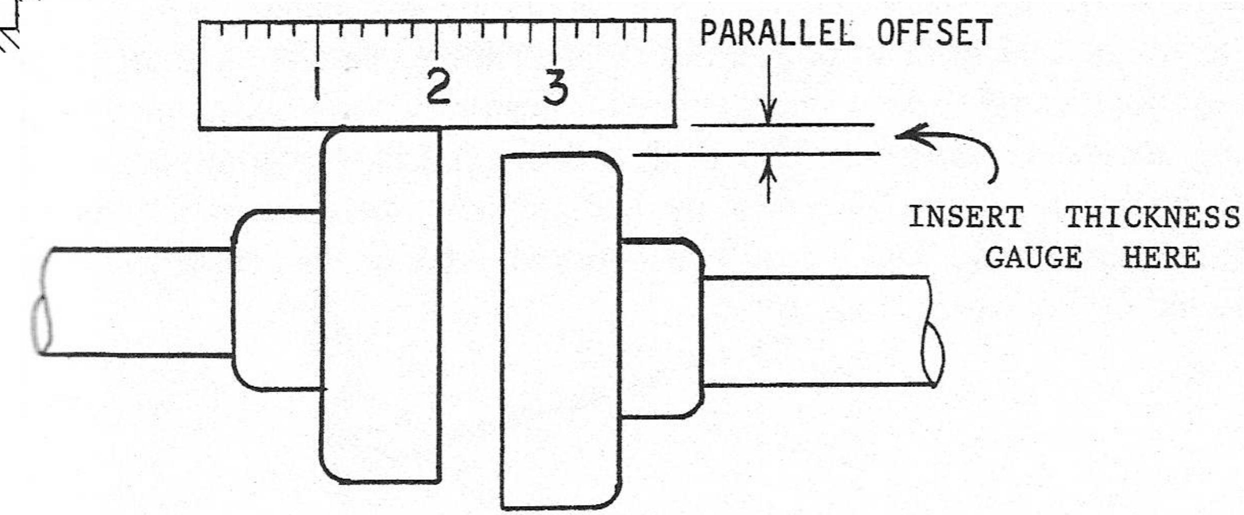






Machinery Vibration Forcing Functions



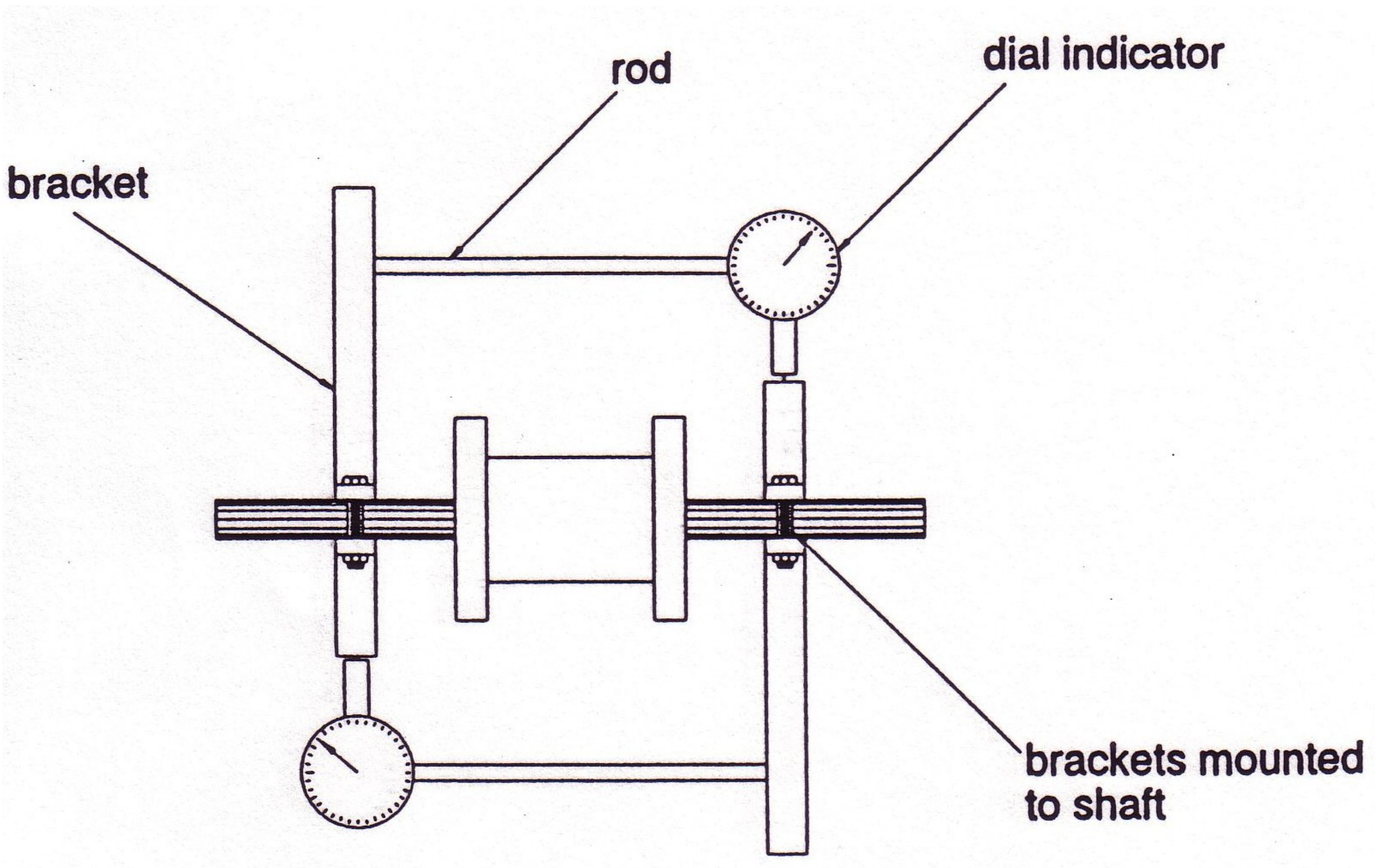


Reverse Dial Alignment Method

- simple & accurate
- brackets on both shafts, opposite sides of coupling
- each bracket holds a rod which spans the coupling
- both rods rest on dial indicators attached to the opposite bracket
- long rods between brackets improve accuracy
- for long spool pieces - position dial indicator stems against spool piece surface

Machinery Vibration Forcing Functions

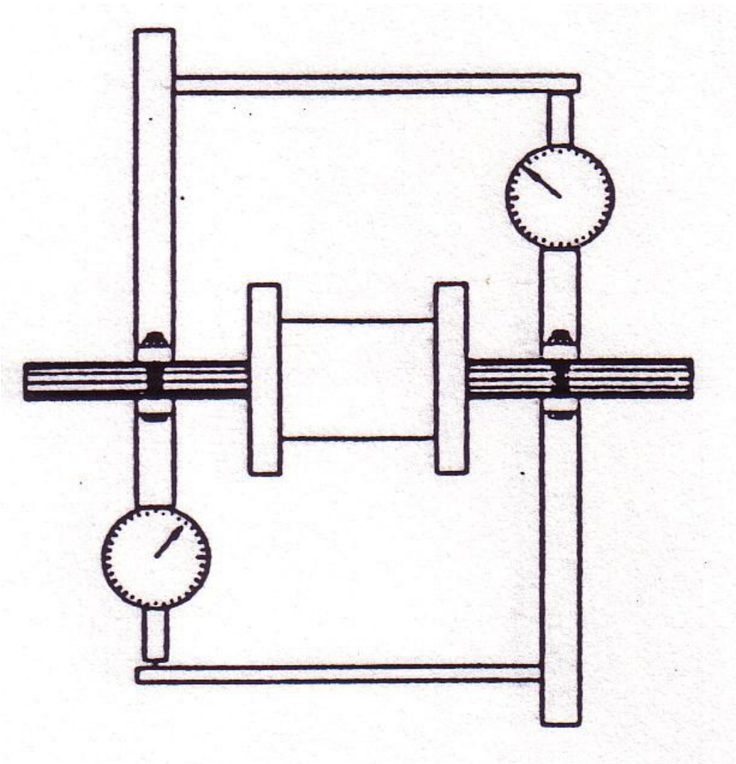
Reverse Dial Alignment Method

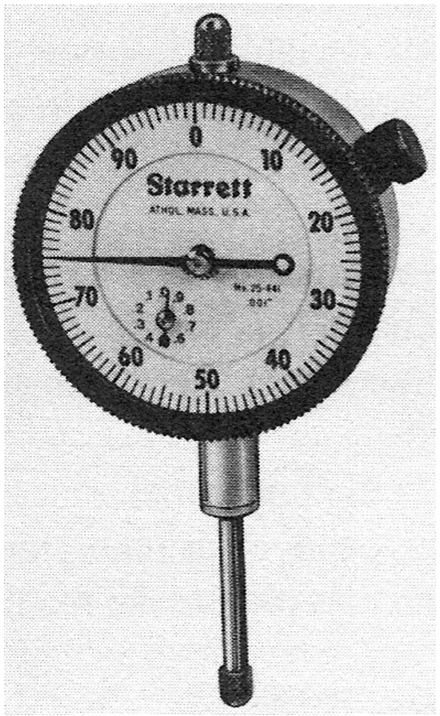


Machinery Vibration Forcing Functions

Reverse Dial Alignment Method

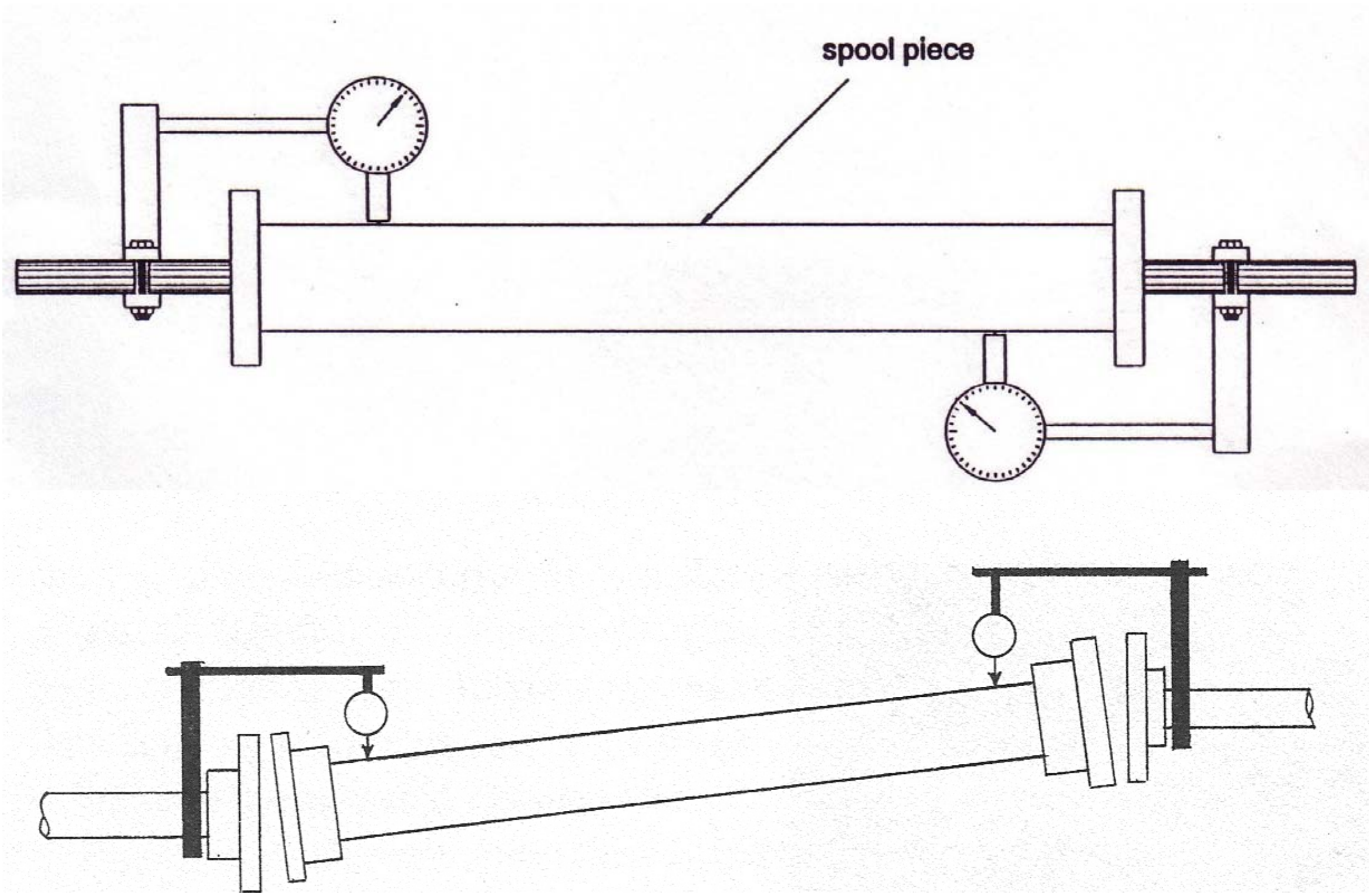
- mounting dial on bracket reduces rod sag





Machinery Vibration Forcing Functions

Reverse Dial Alignment Method



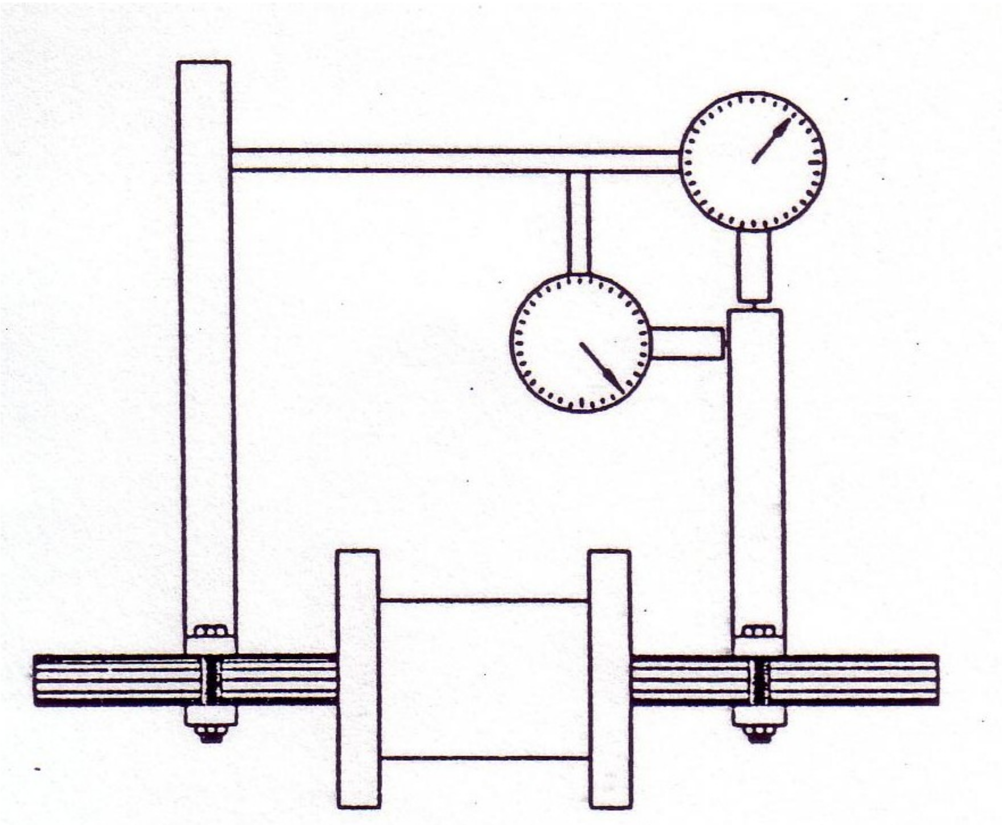
Machinery Vibration Forcing Functions

Face and Rim Alignment Method

- one bracket holds both dials
- brackets as far apart as possible
- rod as high above shaft center line as possible (this amplifies even small angles of misalignment)
- long rods sag due to their own weight & the dial indicator weight

Machinery Vibration Forcing Functions

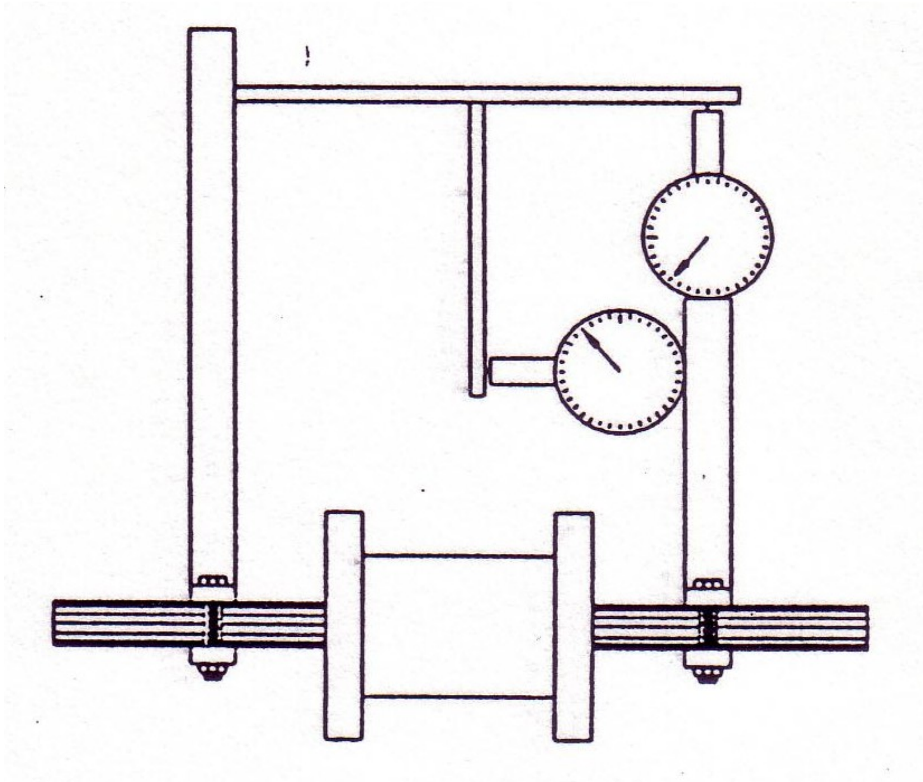
Face and Rim Alignment Method



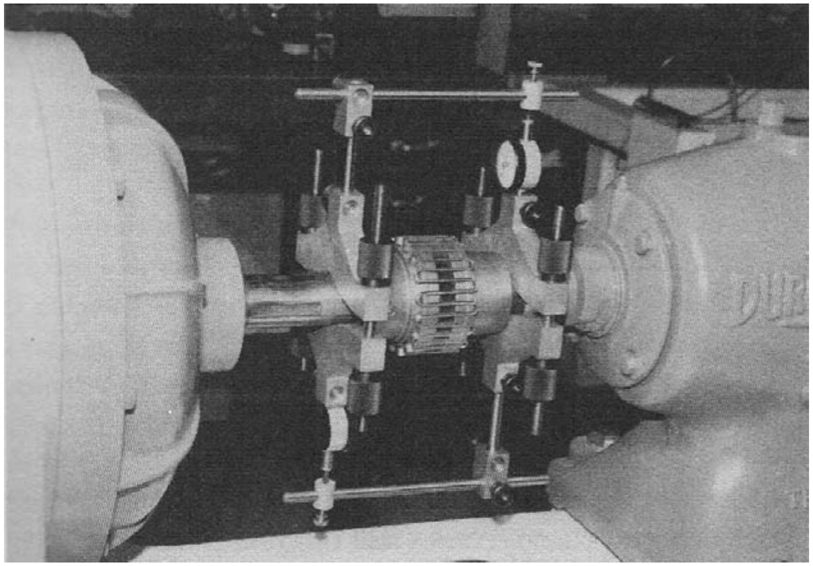
Machinery Vibration Forcing Functions

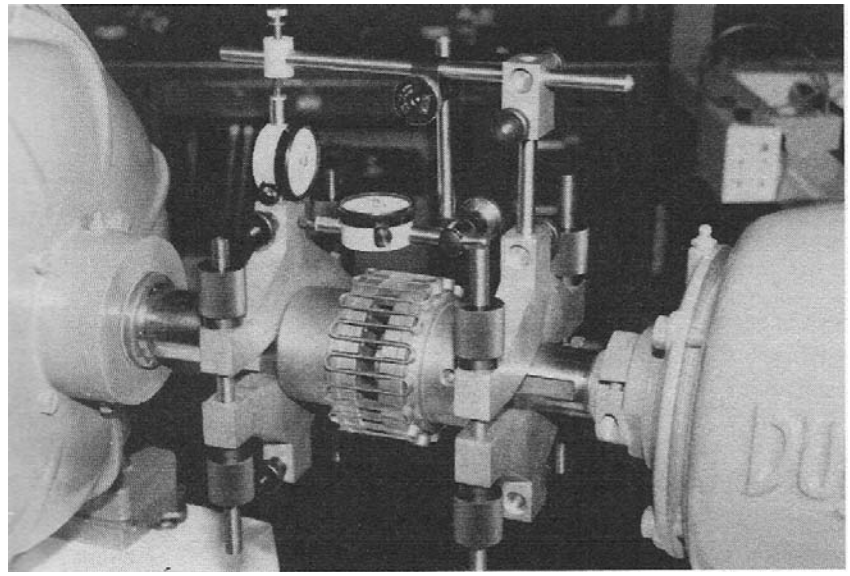
Face and Rim Alignment Method

- can move dial indicator to bracket and counter weight rod to reduce sag

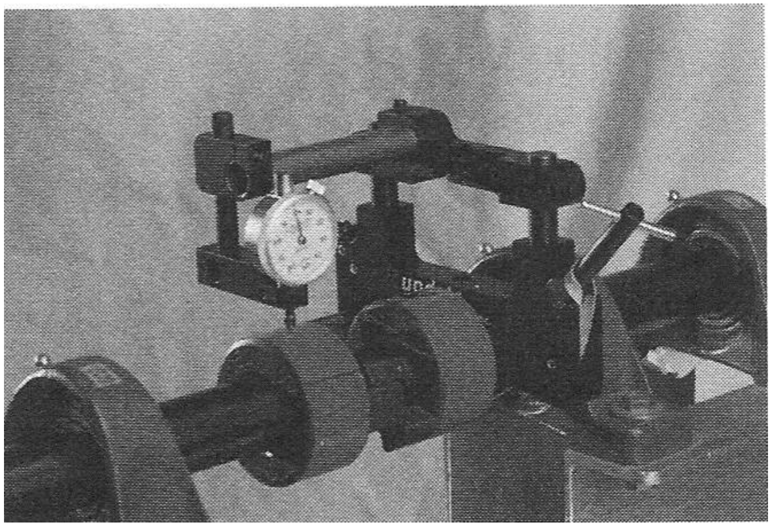


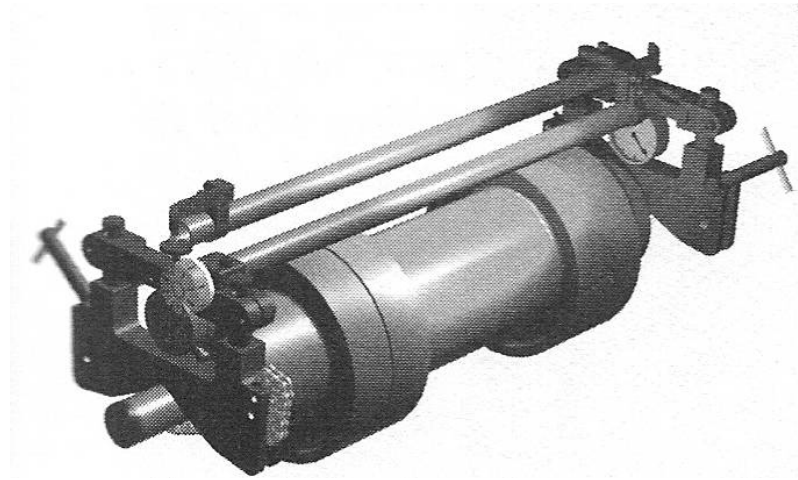
Machinery Vibration Forcing Functions

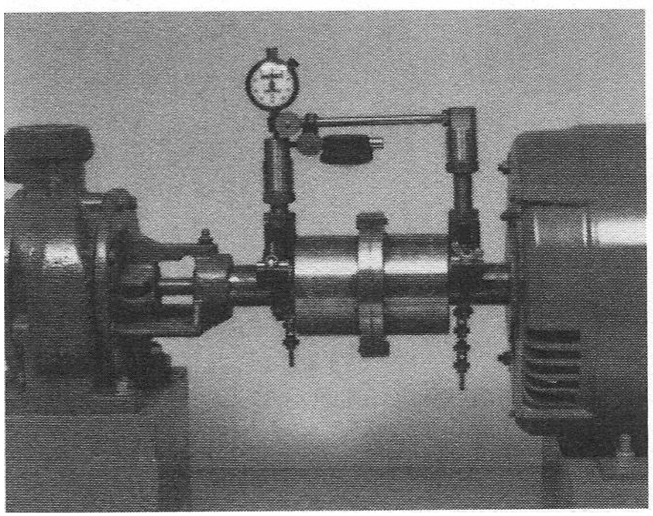


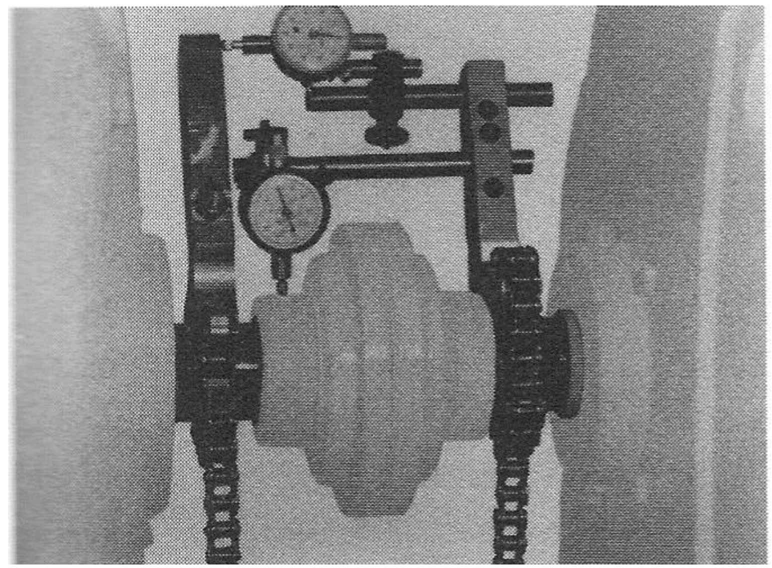


Machinery Vibration Forcing Functions







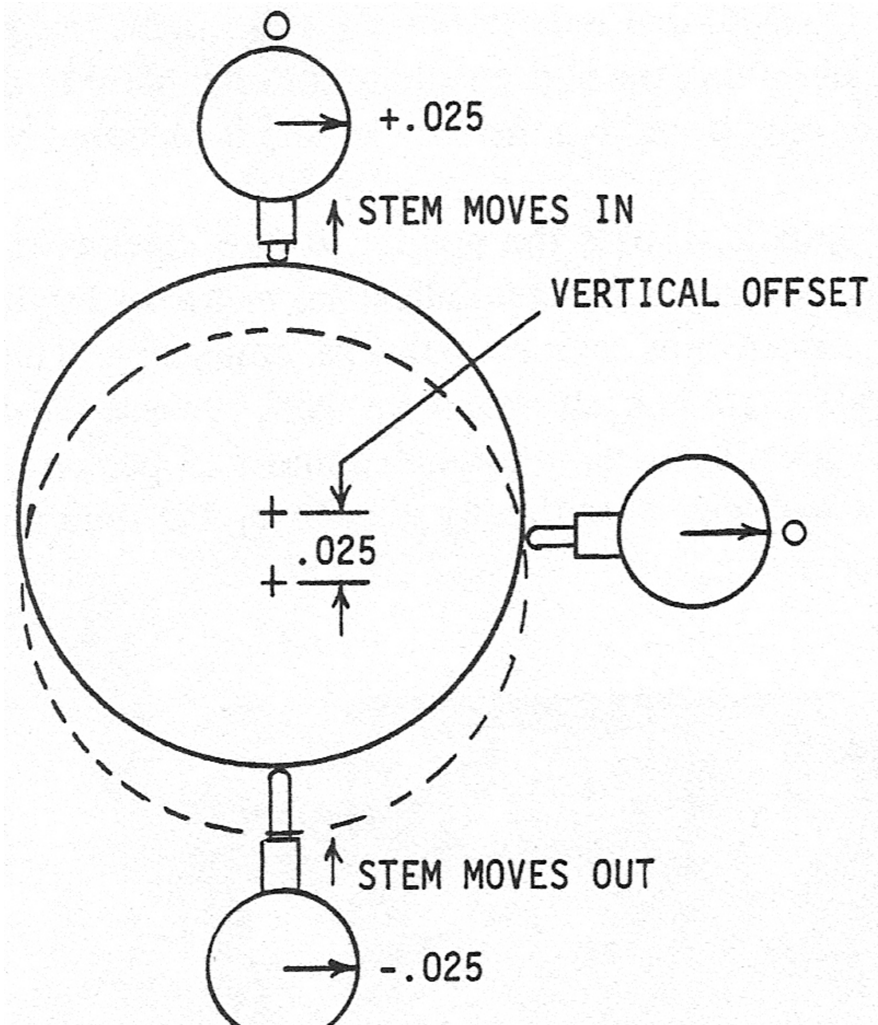


Machinery Vibration Forcing Functions

Alignment Procedures

- set dial indicators to zero after mounting
- take four equally spaced readings (rotate brackets 90° each time)
- if a full rotation is not possible, three spaced at 90° will do
- the sum of opposite readings should always be equal
- shafts must rotate together

Machinery Vibration Forcing Functions



(b)

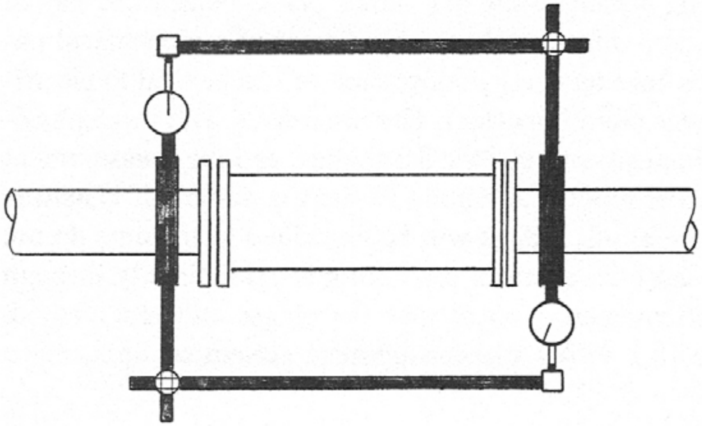
Alignment Procedures (Cont'd)

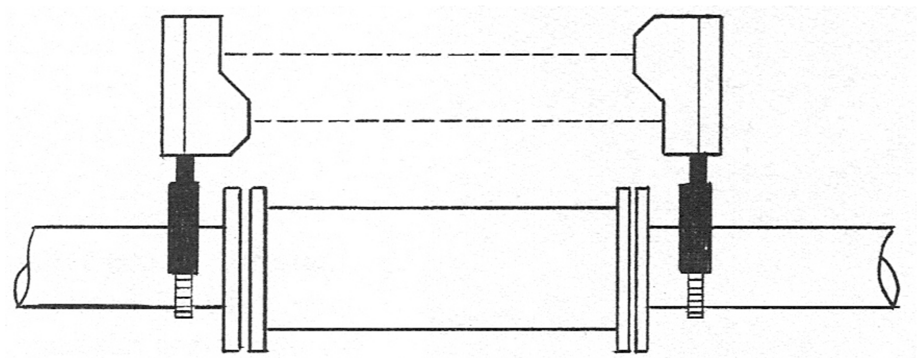
- do not uncouple shafts during alignment (axial shaft movement causes inaccuracies)
- always rotate shaft in the same direction (coupling backlash - inaccuracies)
- if coupling allows some axial movement this must be restricted

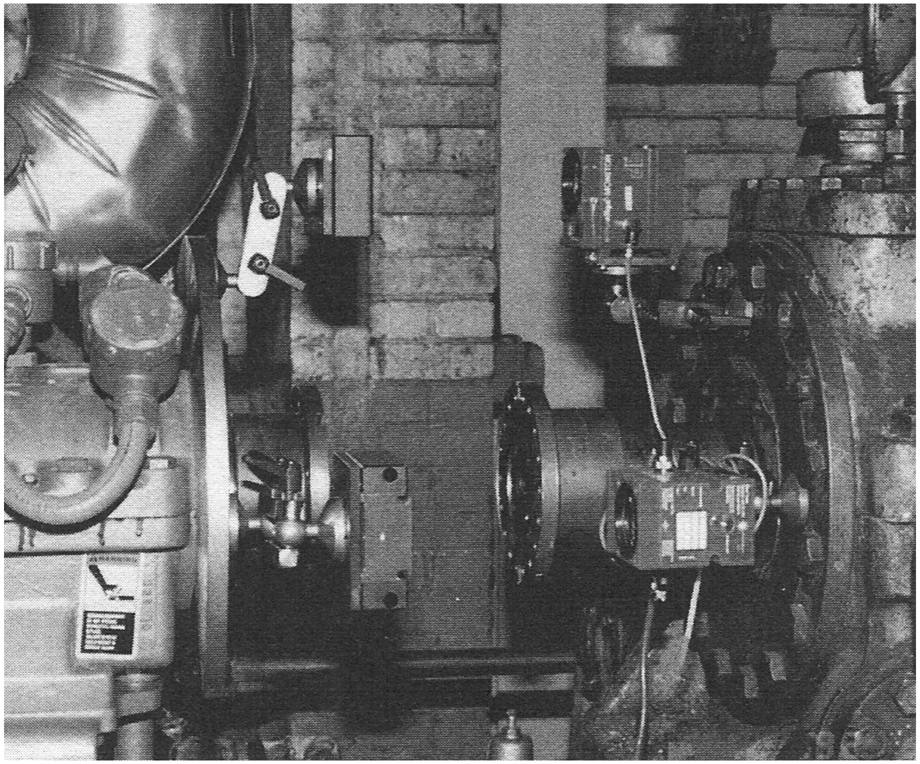
Laser Based Alignment Methods

- laser beam used in place of rod
- detector measures beam deflection as shaft is rotated.
- emitter and detector on opposite shafts
- long coupling spans
- no sag (high accuracy)
- quick set up
- costly to purchase, but quick to use

Machinery Vibration Forcing Functions







Machinery Vibration Forcing Functions

Alignment Preparation (General)

Base preparation

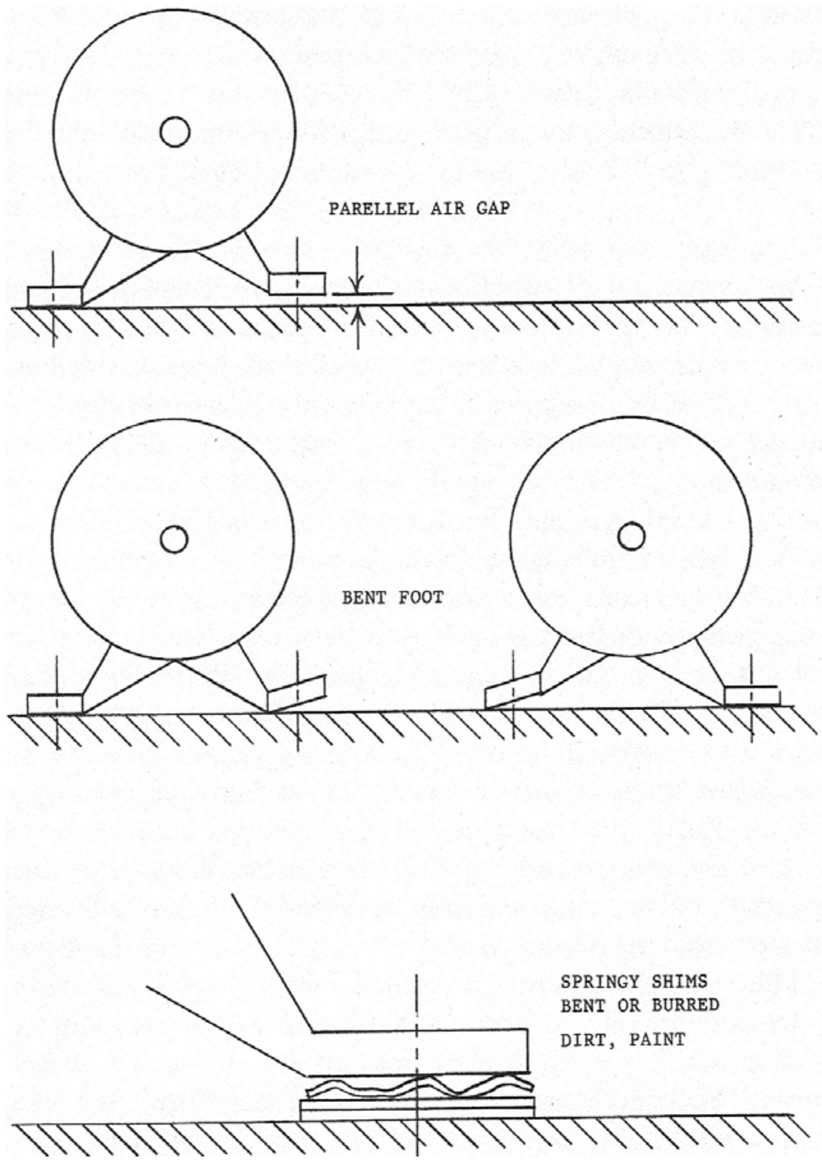
- base clean and free of defects

Soft feet and frame twists

- set dial indicator on foot
- loosen hold down nut
- foot movement of more than 1 mil. (1/40 mm) should be shimmed
- check each foot, tighten and loosen in a set sequence

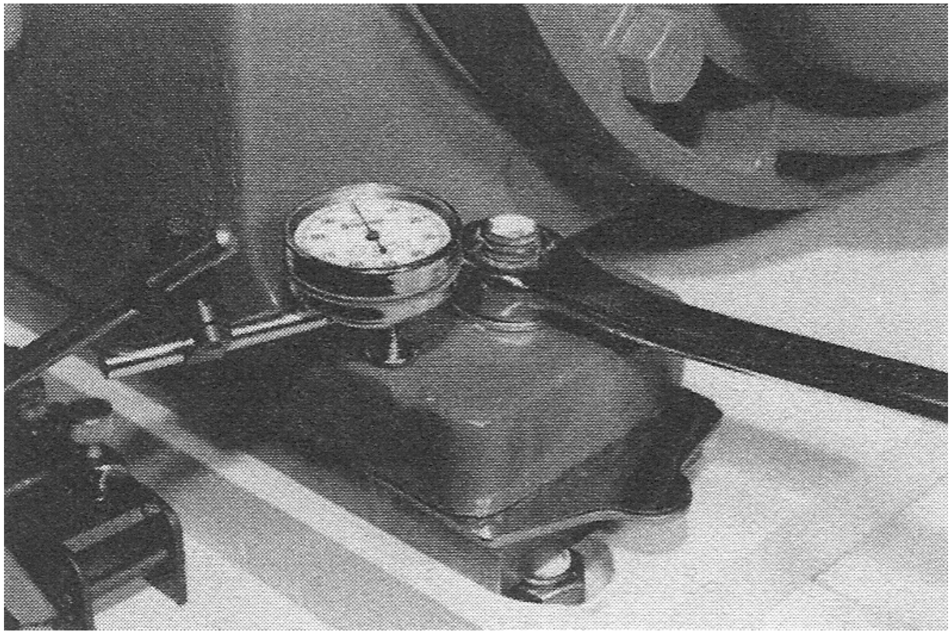
Machinery Vibration Forcing Functions

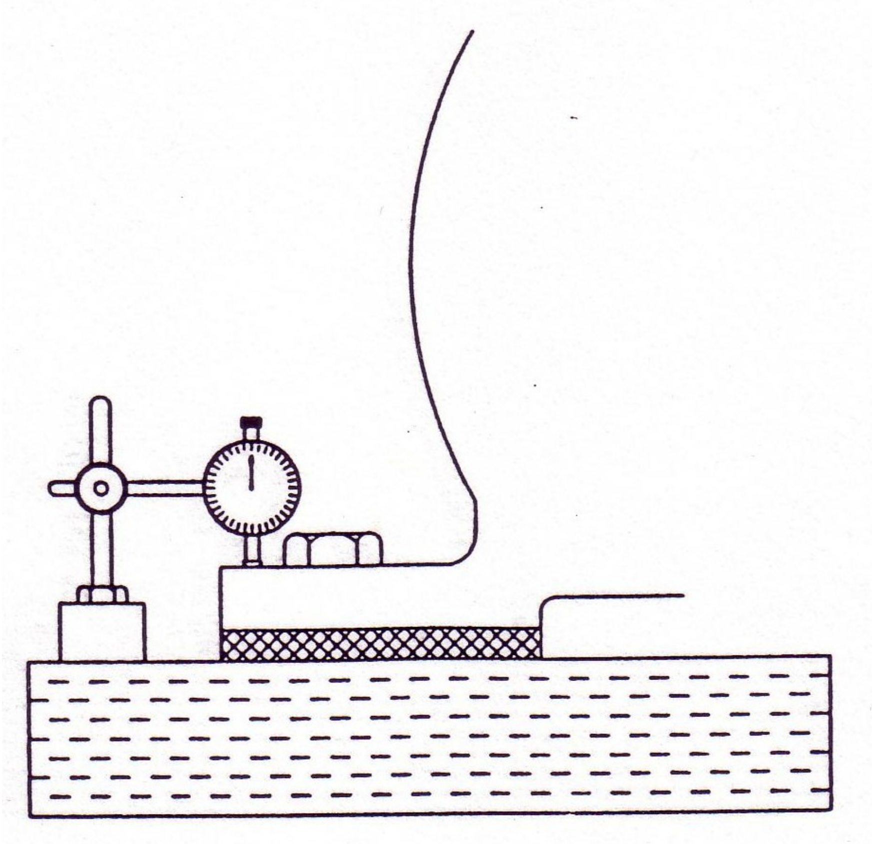
Soft Feet



Machinery Vibration Forcing Functions

Detecting Soft Feet

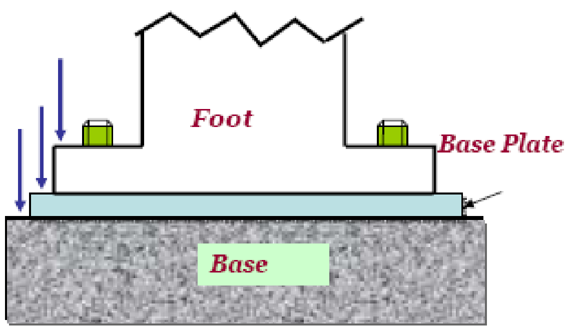


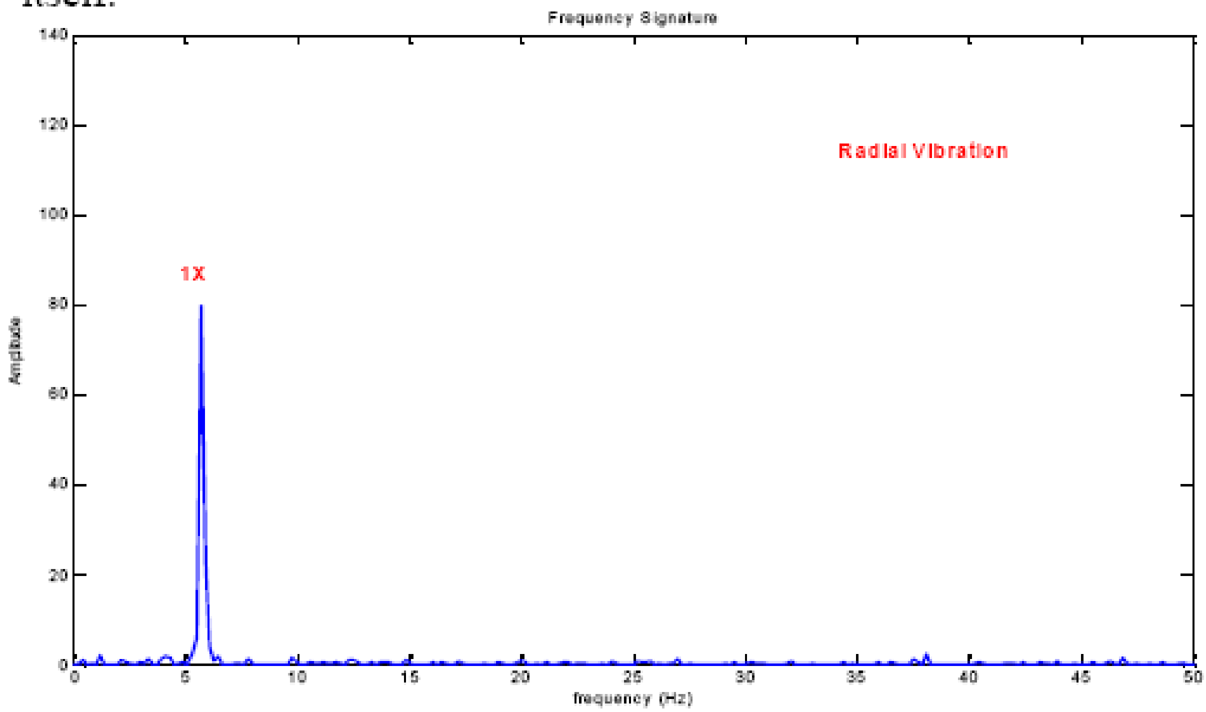


Machinery Vibration Forcing Functions

Soft Feet

- **Caused by structural looseness/weakness of the machine feet; base plate or foundation; deteriorated grouting and** loose hold-down bolts at the base and distortion of the frame or base (i.e Soft Foot).
- Phase analysis may reveal approx. 180° phase difference between vertical measurements on the machine foot, base plate and base itself.





Machinery Vibration Forcing Functions

Lifting and moving machine

- use jack screws wherever possible for vertical & horizontal movements
- never move a machine with a sledge hammer

Piping connections

- disconnect during alignment
- keep dial indicators in place during reconnection as a check
- piping should have its own supports

Machinery Vibration Forcing Functions

Dial indicator rod sag

- can be calculated
- should not be ignored
- can be measured using a straight piece of pipe

Machinery Vibration Forcing Functions

Sag in round rods

$$S_g = 2.829 \times 10^{-5} \times L^3 \times \left(\frac{K_r}{D^4 - d^4} \right)$$

S_g - dial indicator sag (mils)

L - length of rod (inches)

D - Outside diameter (inches)

d - Inside diameter (inches)

K_r - spring constant of circular rod (mild steel)

$$K_r = 1.334 \times (D^2 - d^2) \times (L + W_d)$$

W_d - weight of dial indicator (ounces)

Machinery Vibration Forcing Functions

Sag in square rods

$$S_g = 2.833 \times 10^{-5} \times L^3 \times \left(\frac{K_s}{D^4 - d^4} \right)$$

S_g - dial indicator sag (mils)

L - length of rod (inches)

D - Outside width or height (inches)

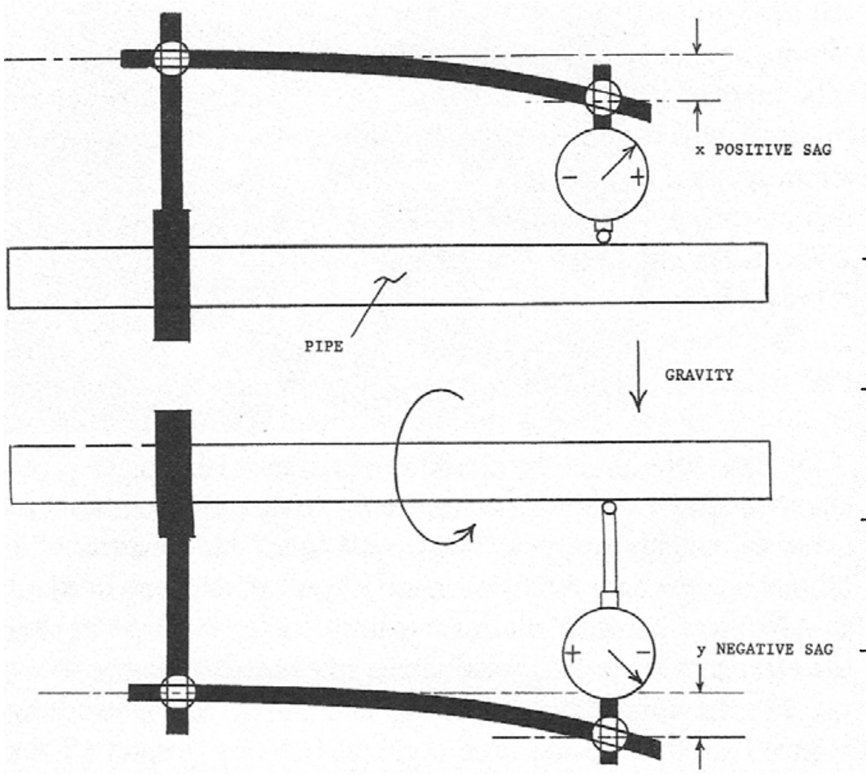
d - Inside width or height (inches)

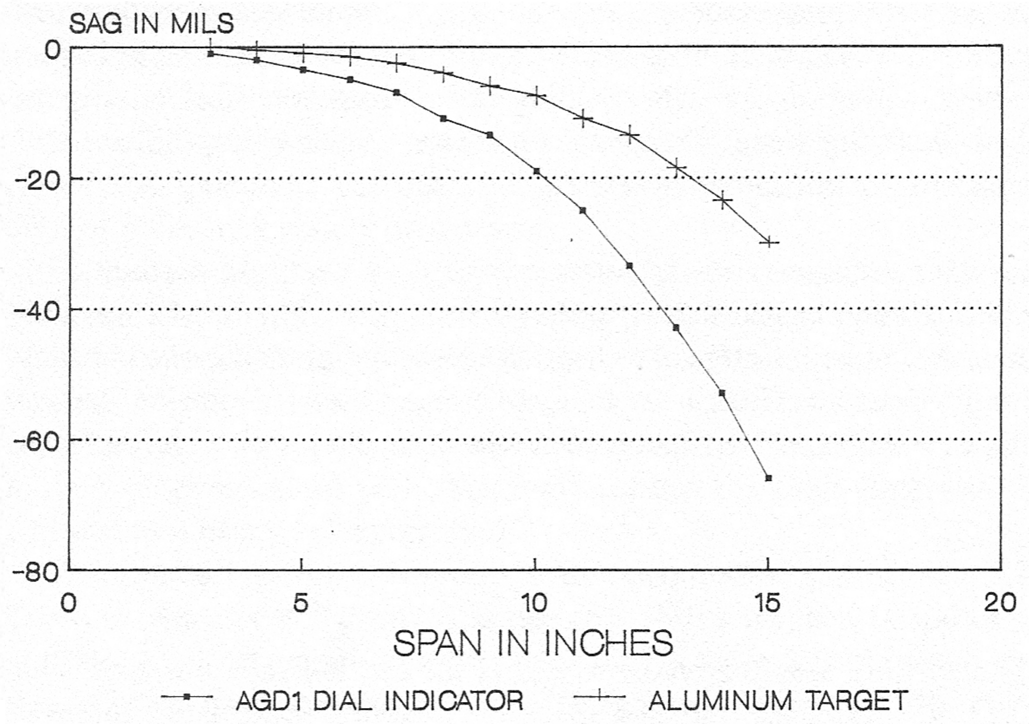
K_s - spring constant of square rod (mild steel)

$$K_s = 1.699 \times (D^2 - d^2) \times (L + W_d)$$

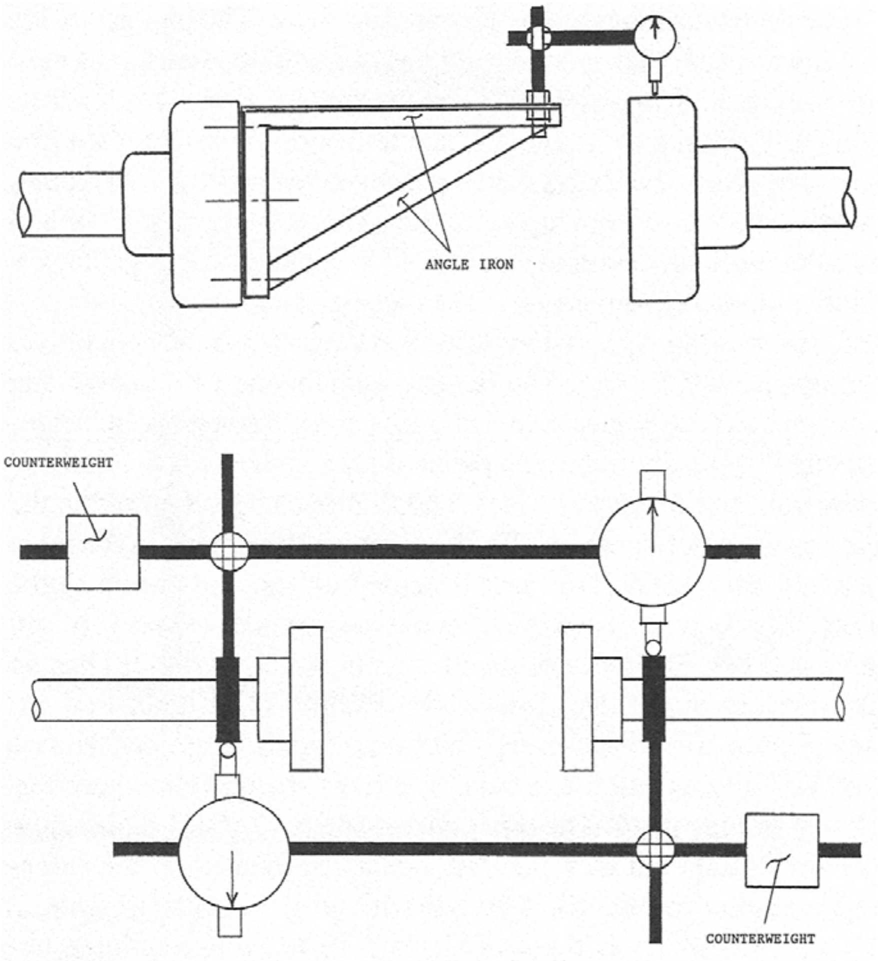
W_d - weight of dial indicator (ounces)

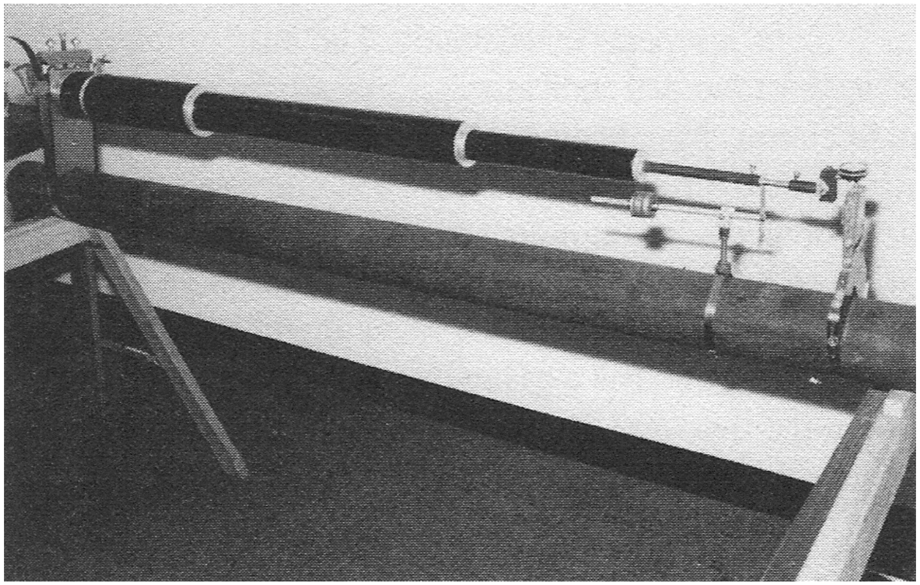
Machinery Vibration Forcing Functions



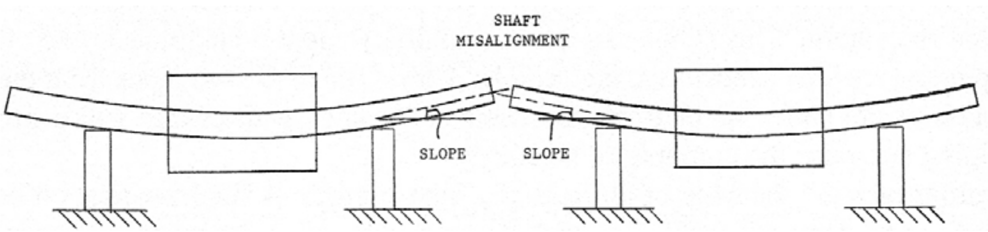


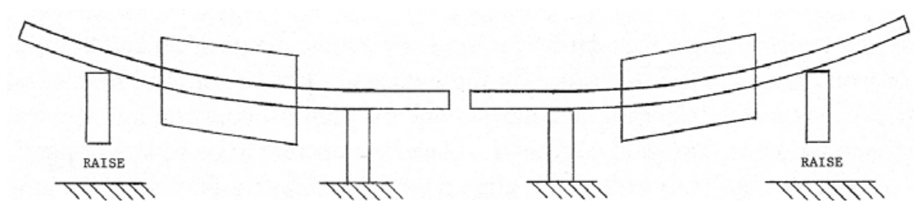
Machinery Vibration Forcing Functions

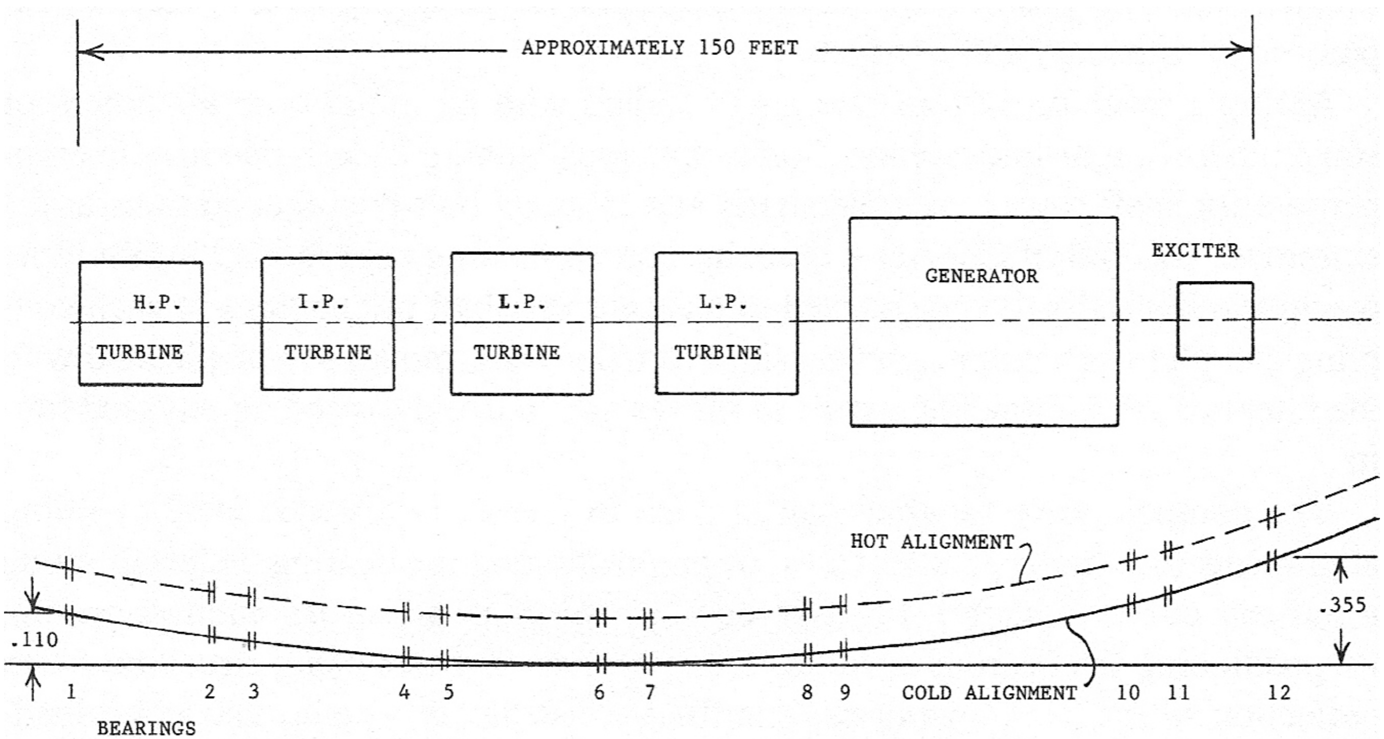




Machinery Vibration Forcing Functions







Machinery Vibration Forcing Functions

Thermal growth

- heat of operation causes metal to expand
- vertical growth most important
- may be minimal but should always be measured
- laser equipment, micrometers, alignment bars are all subject
- take readings when cold and again after normal operating temperature has been reached