Queen's University
Mechanical Engineering

# Machine Condition Monitoring

# and

# Fault Diagnostics

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# Current Topic

- Machinery Vibration Testing and Trouble Shooting
- Fault Diagnostics Based on Forcing Functions
- Fault Diagnostics Based on Specific Machine Components
- Fault Diagnostics Based on Specific Machine Type
- Automatic Diagnostic Techniques
- Non-Vibration Based Machine Condition Monitoring and Fault Diagnosis Methods

# Fault Diagnostics Based on Forcing Functions

- Unbalance
- Mechanical Looseness
- Rubs
- Oil Whirl
- Structural Vibrations
- Hydraulic Forces
- Misalignment
- Soft Foot
- Resonances
- Oil Whip
- Foundation Problems
- Aerodynamic Forces

# Fault Diagnostics Based on Forcing Functions

## Forcing frequencies associated with machines

| Source | Frequency (multiple of RPM) |
|---|---|
| **Fault Induced** | |
| mass unbalance | 1x (frequency in once per revolution) |
| Misalignment | 1x, 2x |
| bent shaft | 1x |
| mechanical looseness | odd orders of x |
| casing and foundation distortion | 1x |
| antifriction bearing | bearing frequencies, not integer ones |
| impact mechanisms | multi-frequency depending on waveform |
| **Design Induced** | |
| universal joints | 2x |
| asymmetric shaft | 2x |
| gear mesh (n teeth) | nx |
| coupling (m jaws) | mx |
| fluid-film bearings (oil whirl) | 0.43x to 0.47x |
| blades and vanes (m) | mx |
| reciprocating machines | half &full multiples of speed, depending on design |

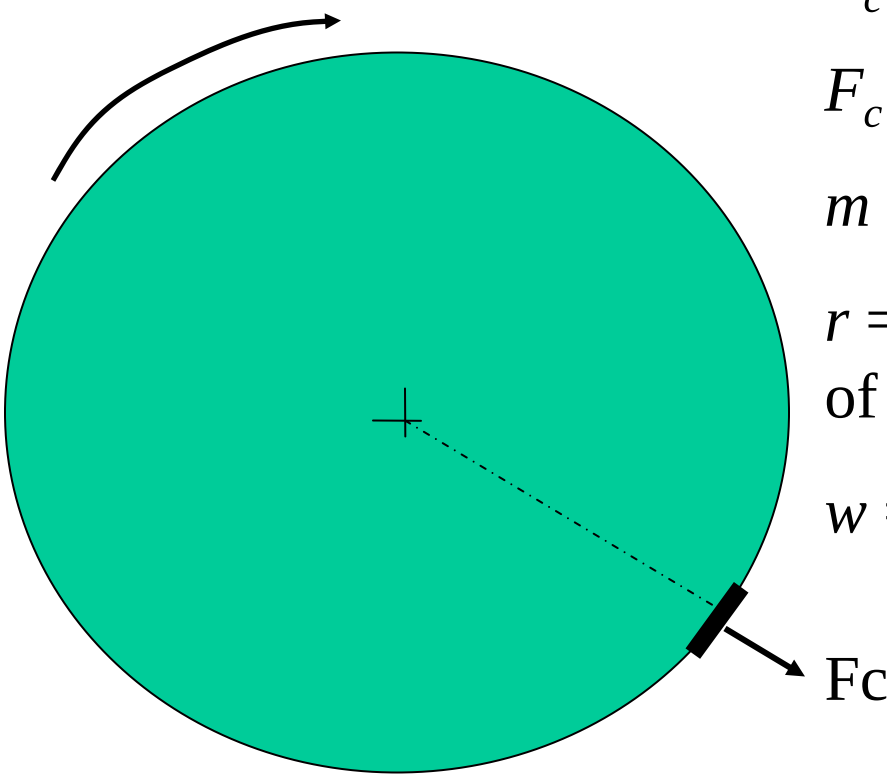
# Unbalance

**Definition of Unbalance:**

The unequal distribution of weight of a rotor about its centreline

A condition in which a rotor imparts vibration force to its bearings as a result of centrifugal forces

# Unbalance




$F_c = mrw^2$

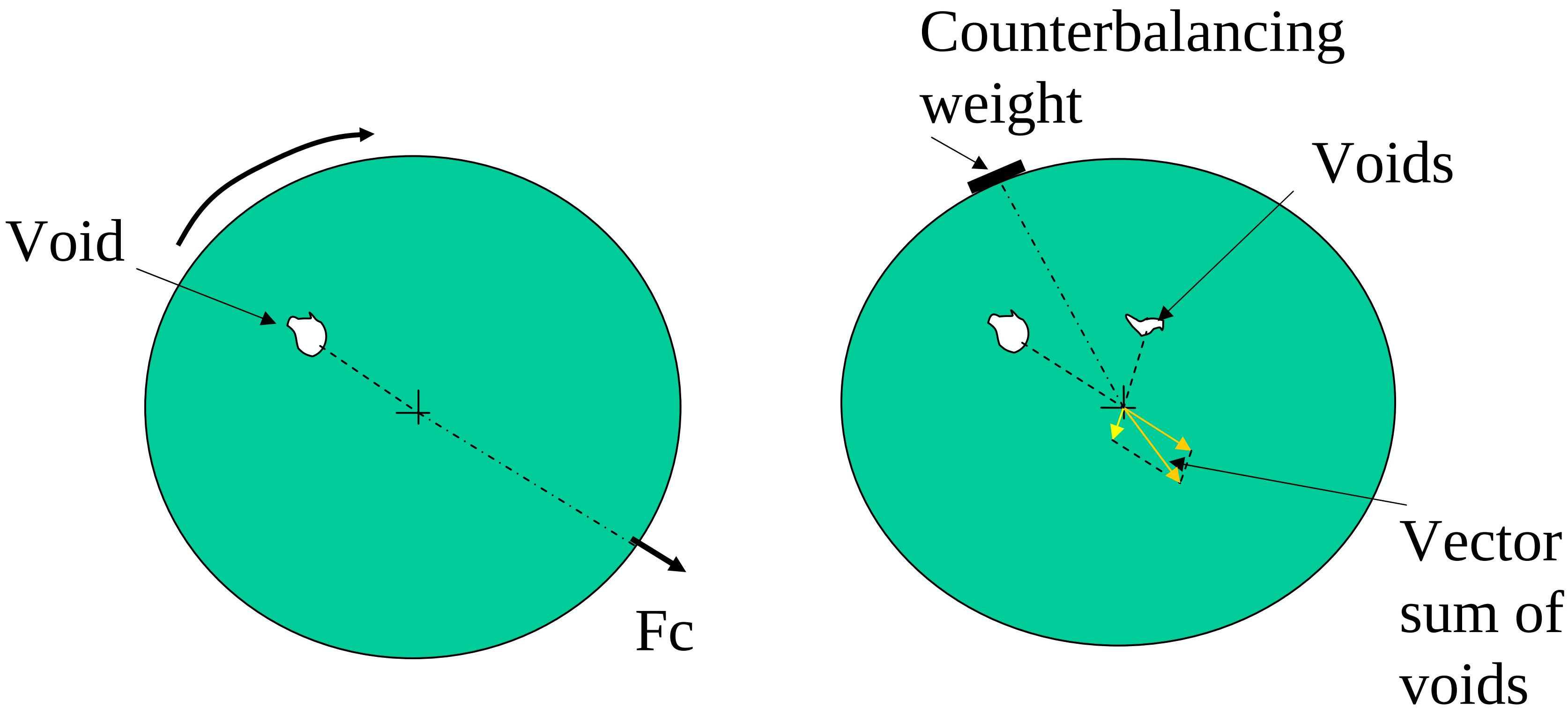
$F_c$ = centrifugal force

$m$ = mass

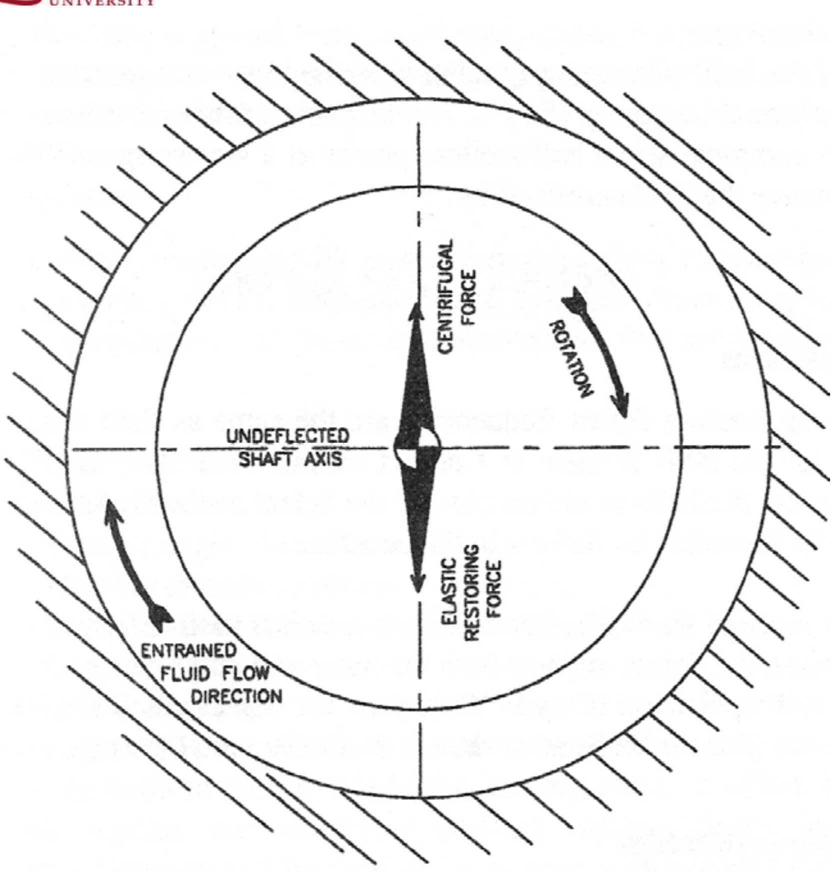
$r$ = radius from centre of rotation

$w$ = rotational speed

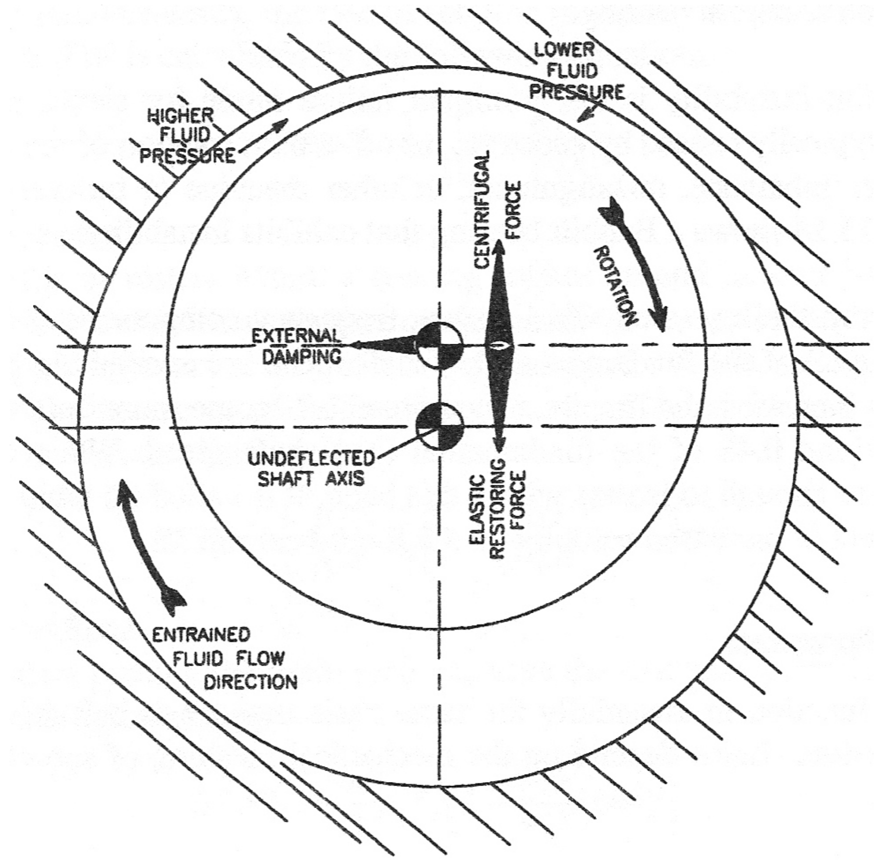
# Unbalance



# Unbalance

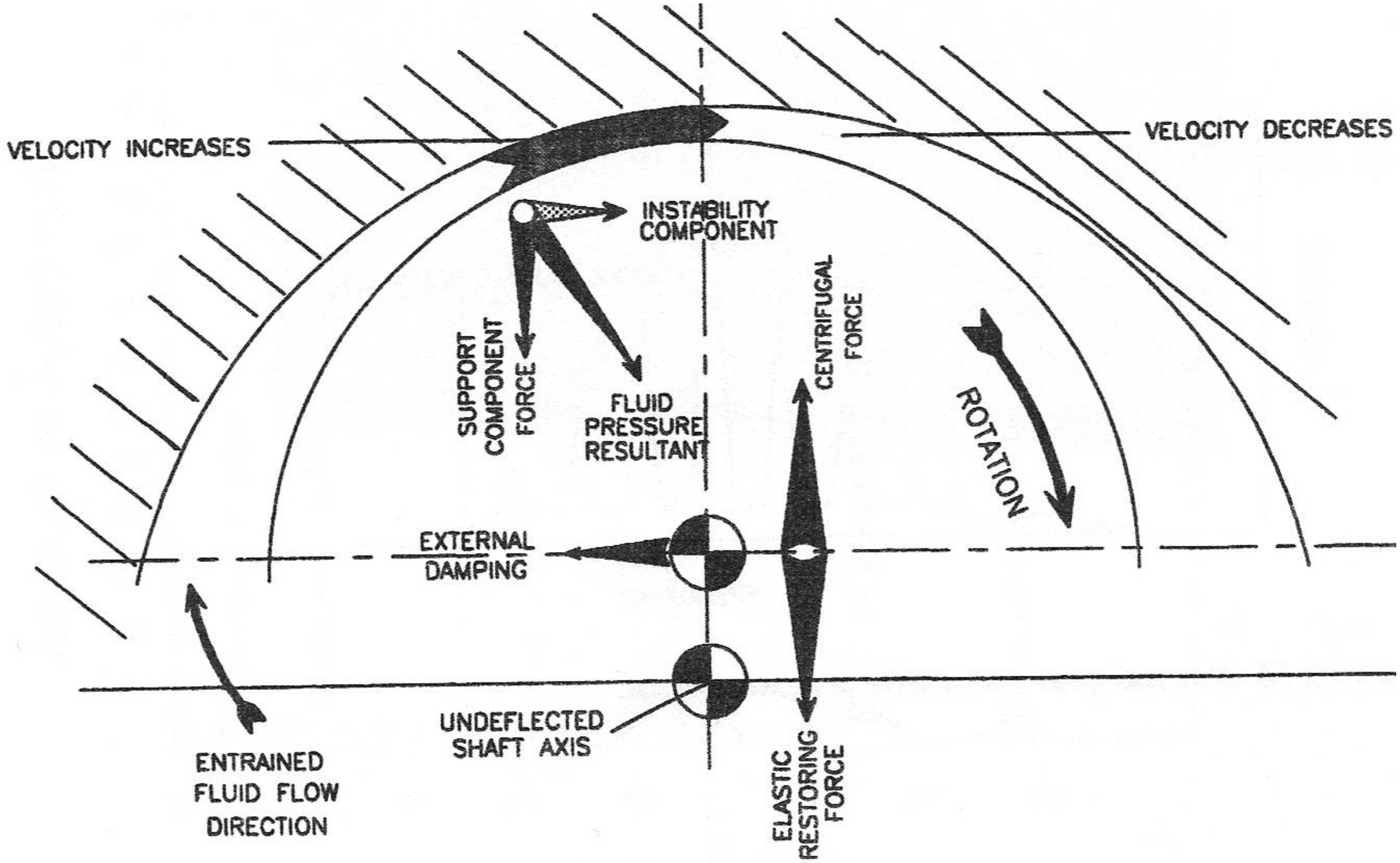



Normal journal bearing – balanced forces




Journal bearing instability – unbalanced forces

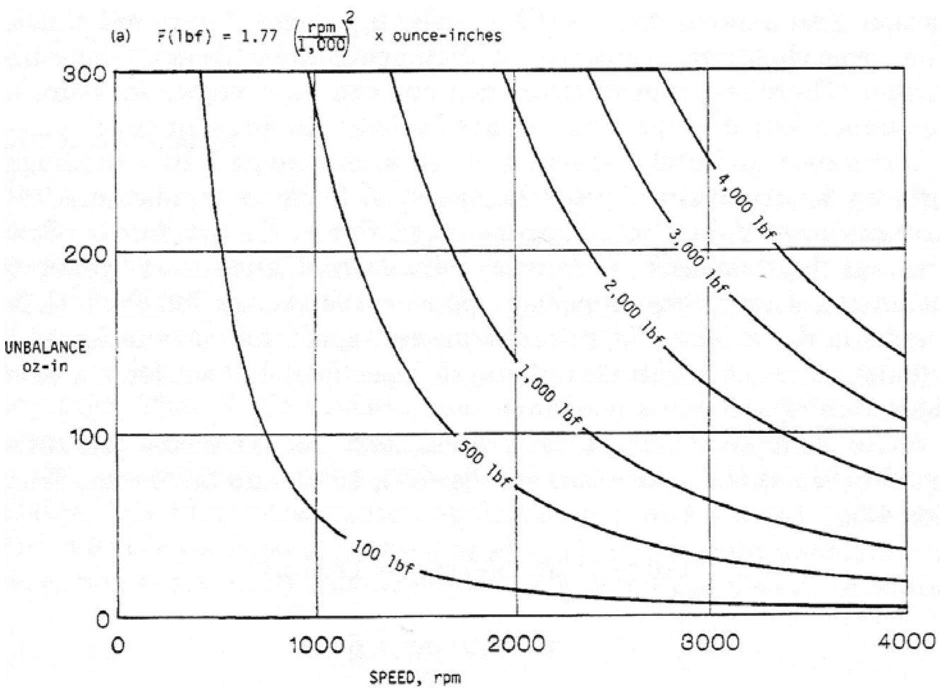
# Unbalance



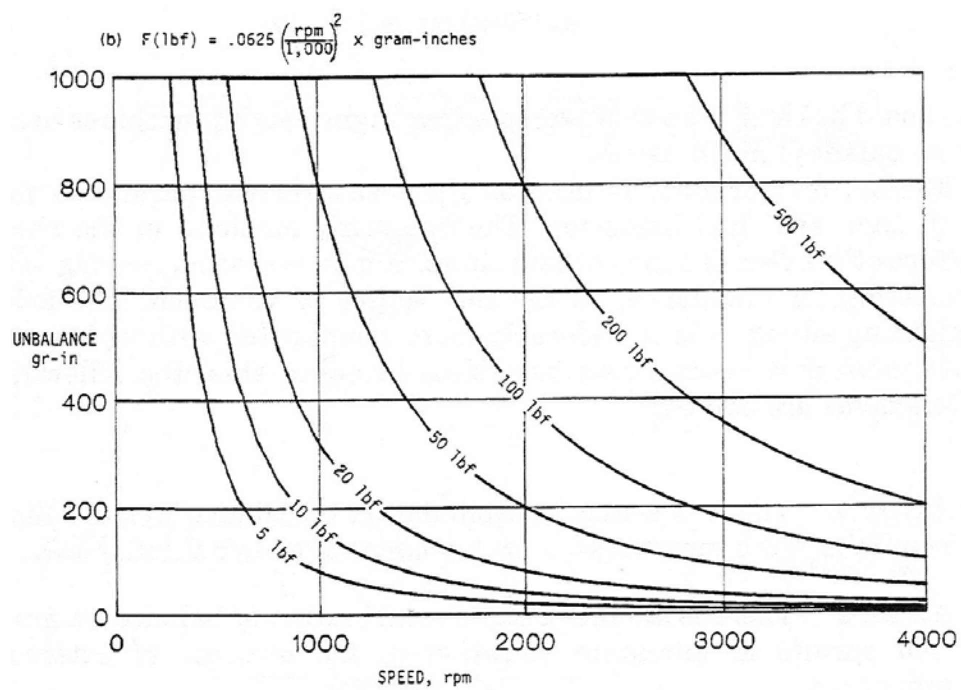

Increased velocity may generate an unbalance force

# Unbalance

Centrifrugal force due to unbalance




Once-Inches




Gram-Inches

## UNBALANCE

- linear problem
- periodic time signal
- 360° cycle
- strong radial vibration at fundamental frequency (1 × rotational speed, 1X)
- if rotor is overhung - radial & axial vibration
- response amplitude proportional to rotational speed squared

# Unbalance

**Results in:**

- excessive bearing wear (gears, bushings, etc.)
- fatigue in support structures
- decreased product quality
- power losses
- disturbed adjacent machinery

# Unbalance

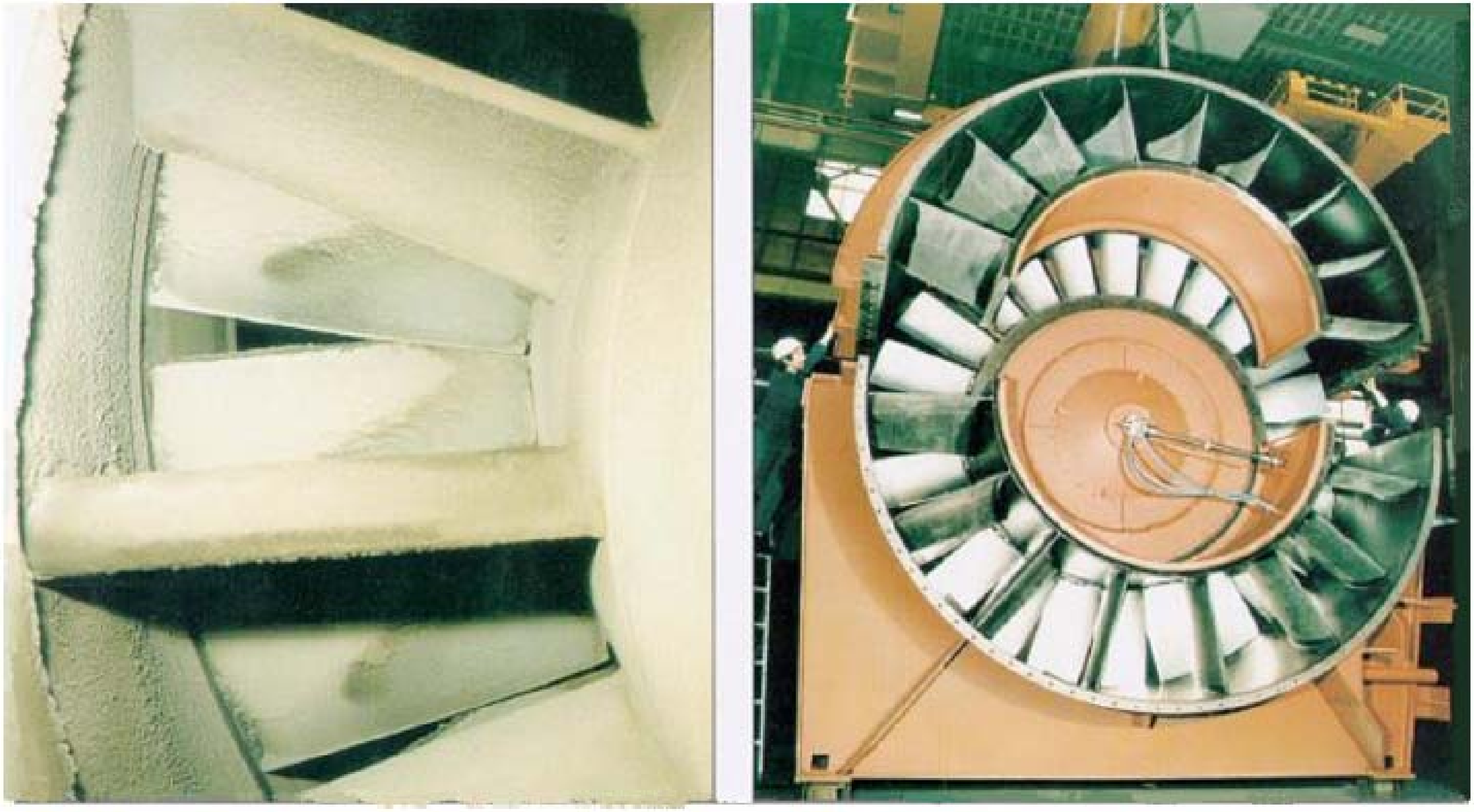
**Causes of unbalance:**

- excess of mass on one side of rotor
- centrifugal force pulls rotor toward heavy side
- low tolerances in fabrication (casting, machining, assembly)
- variation within materials - voids, porosity, inclusions, variable density, finishes, etc.
- non symmetry of design - motor windings, part shapes, locations

# Causes of Unbalance

- non symmetry in use - distortion, size changes, shifting parts due to stress, aerodynamic forces, temperature changes, etc
- manufacturing processes are a major cause of unbalance
- cost plays a role - perfect balance is always possible but at a cost
- unbalance can be corrected by adding or removing weight from rotor at the appropriate location
- pros and cons to both practices
- consider unbalance problems last

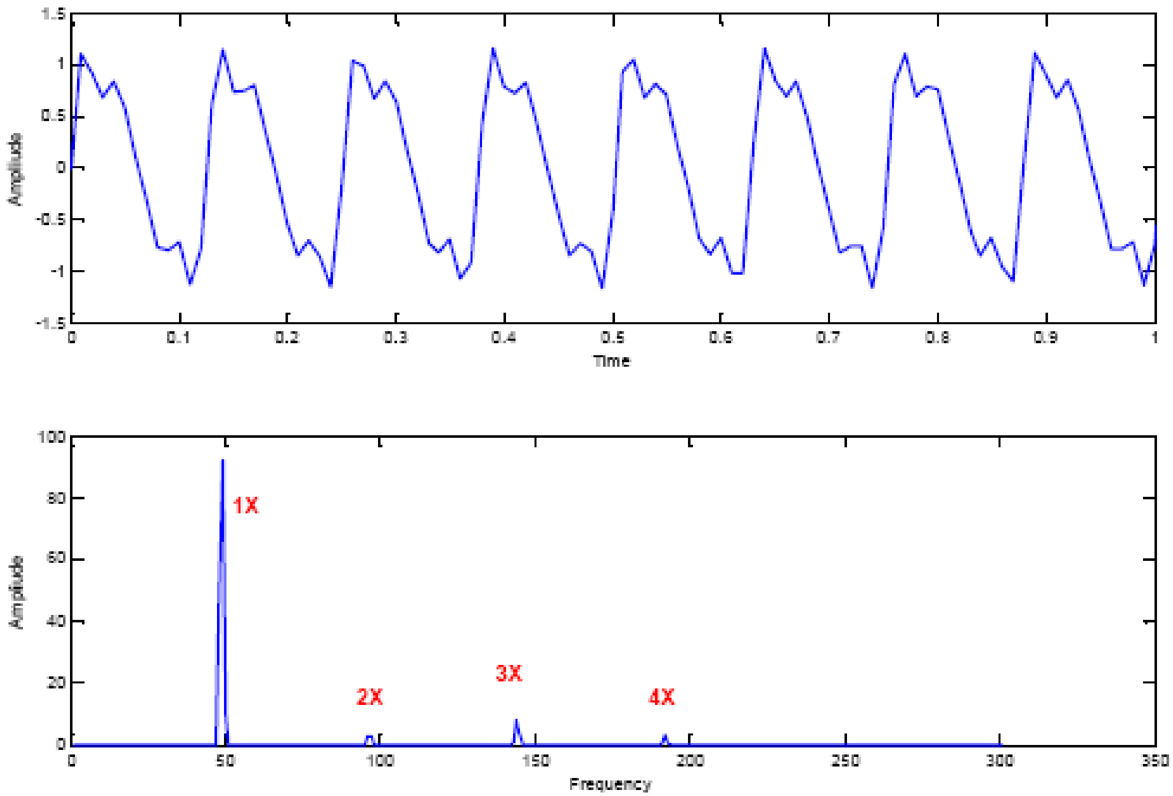
# Unbalance



# Causes of Unbalance

Note: some machinery is designed to operate "out-of-balance" – shakers, sieves, materials transport….

# Unbalance



# Unbalance

## Unbalance Correction Methods

Addition of mass:

- up to 20:1 vibration amplitude reduction on first try (if done carefully)
- if space limitations exist more than one addition of mass may be required

# Unbalance Correction Methods

## Addition of mass

a) addition of solder or epoxy

- centre of gravity difficult to control
- takes time

b) addition of standard washers

- bolted or riveted
- incremental sizes
- quick

# Unbalance Correction Methods

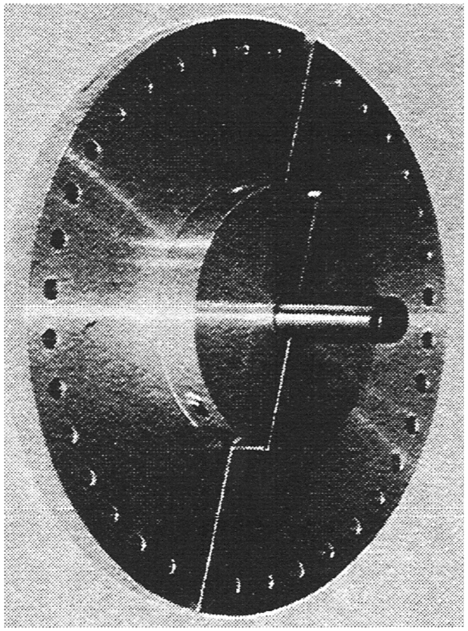
## Addition of mass

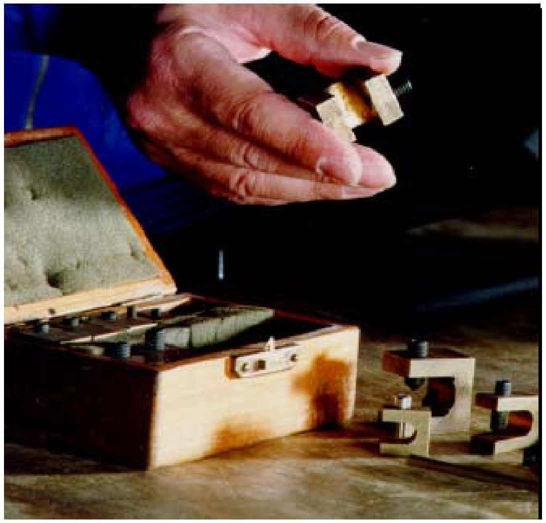
c) addition of pre-manufactured weights

- incremental sizes
- quick

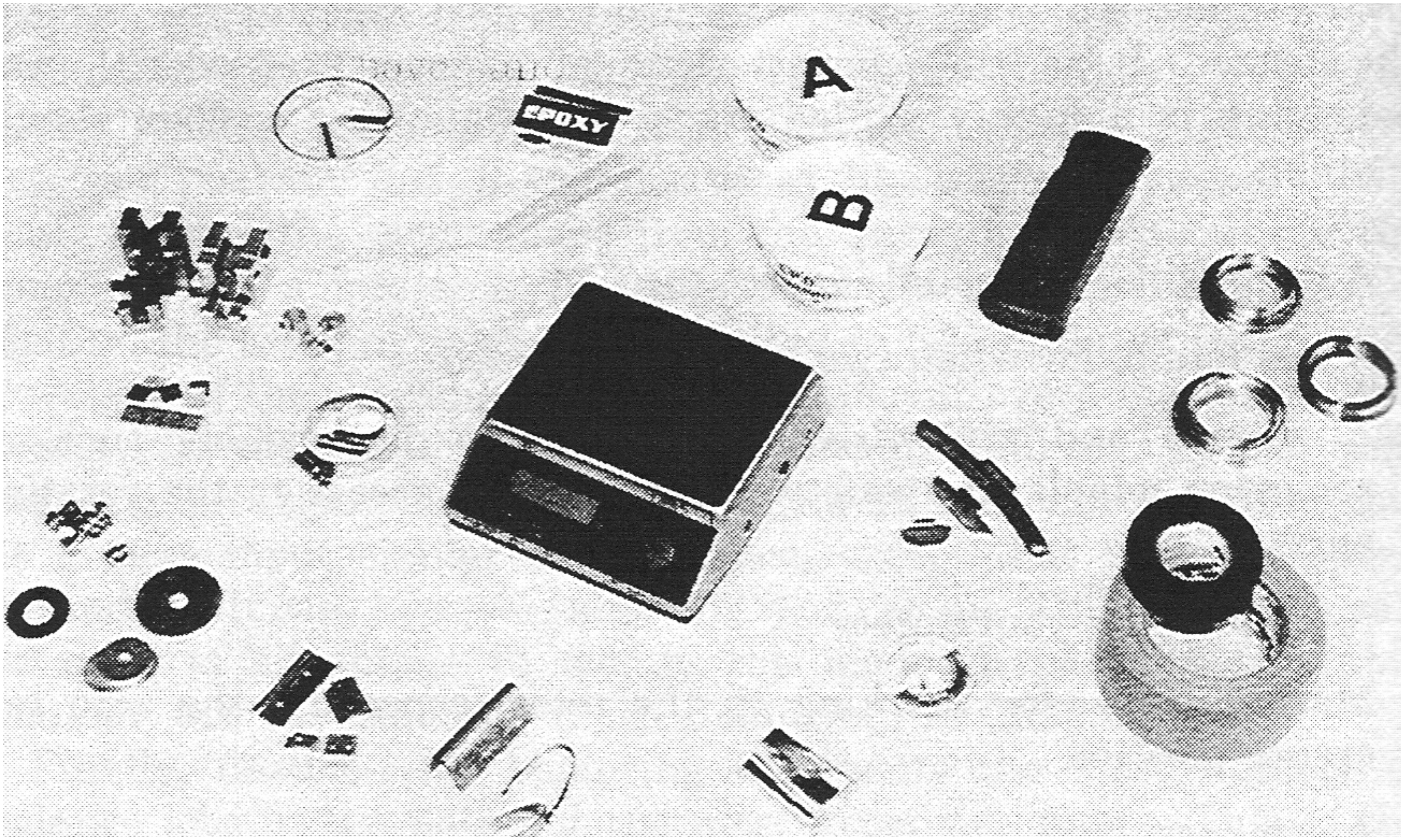
d) addition of cut to size masses

- welded in place





# Unbalance Correction Methods



# Unbalance Correction Methods

**Removal of mass** - 10:1 vibration reduction first try

a) - drilling

- very accurate, quick

b) milling

- used for large corrections, accurate

c) grinding

- trial & error method
- accurate removal of mass difficult

# Unbalance Correction Methods

**Mass centering**

- rotor principal axis of inertia found
- journal & shaft machined to match this axis
- very expensive

# Unbalance

## Units of Unbalance

- gram - inches, gram - millimetres
- 100 g - in (10 g $\times$ 10 inches, 20g $\times$ 5 inches)
- rigid shafts may be balanced at any speed (theoretically)

# Types of Unbalance

## Four General Types of Unbalance

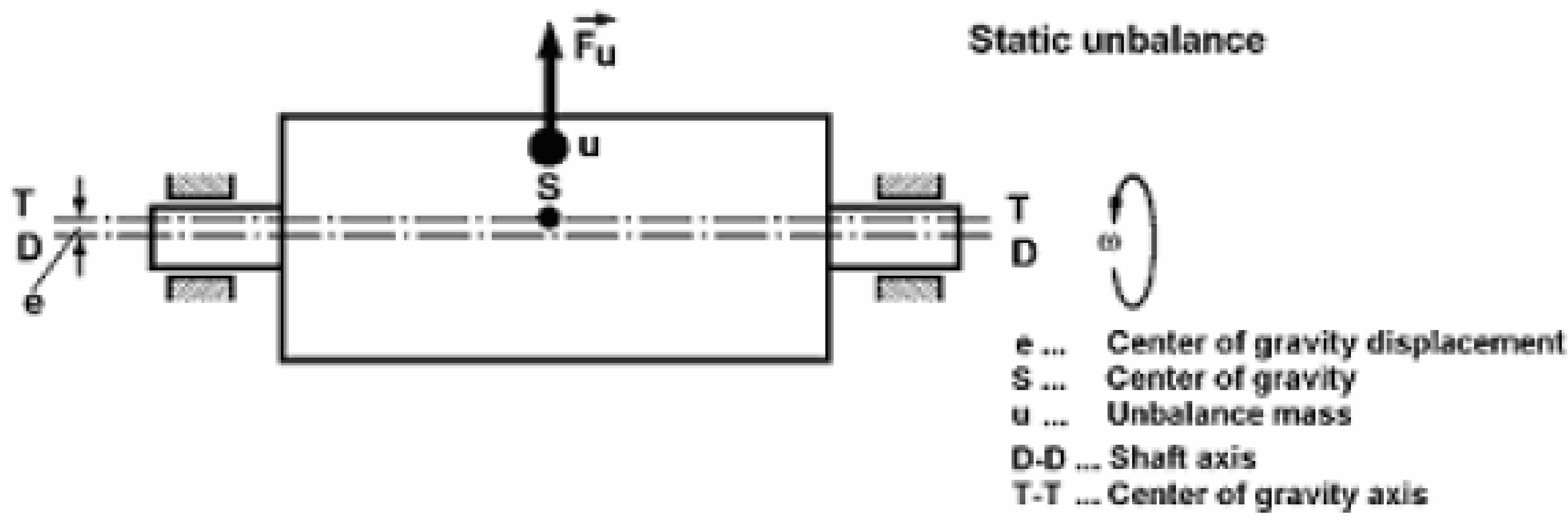
- Static Unbalance
- Quasi-Static Unbalance
- Couple Unbalance
- Dynamic Unbalance

# Types of Unbalance

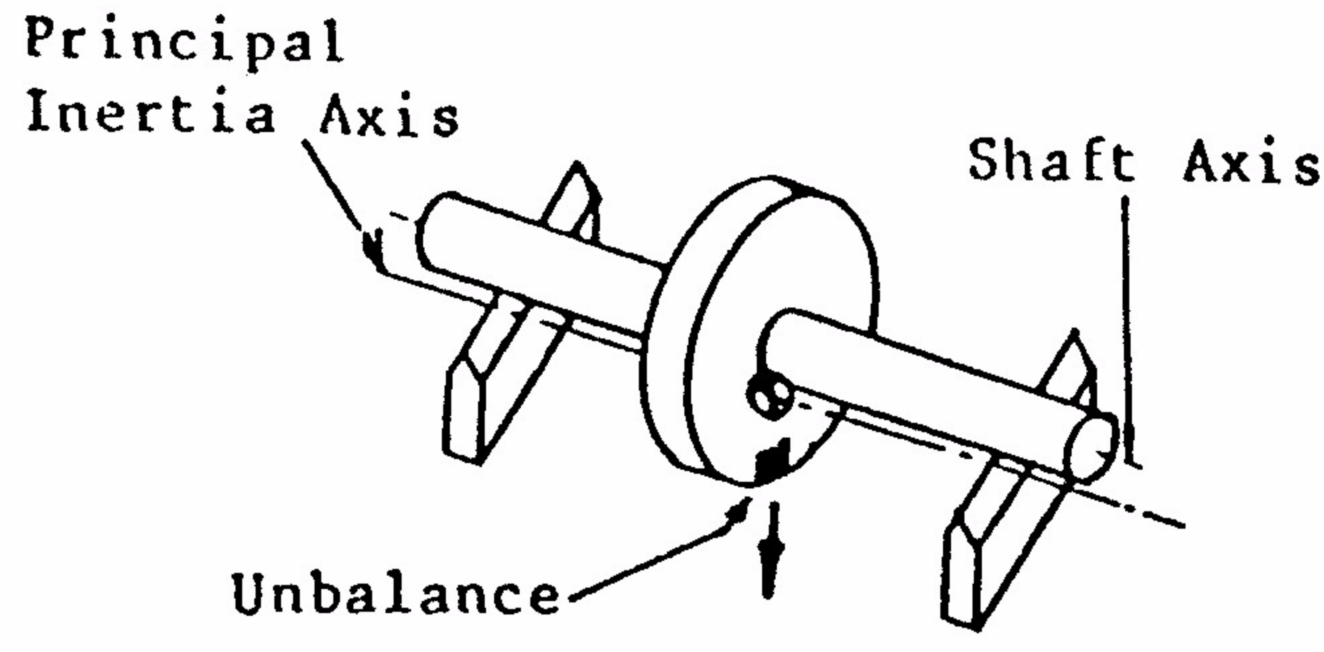
## Static Unbalance (force unbalance)

- principal axis of inertia is displaced parallel to the shaft axis
- found mostly in narrow, disc-shaped parts (fly wheels, turbine wheels)
- single mass correction placed opposite the centre-of-gravity in a plane ⊥ to shaft axis and intersecting the centre-of-gravity
- knife edge balancing possible

# Static Unbalance

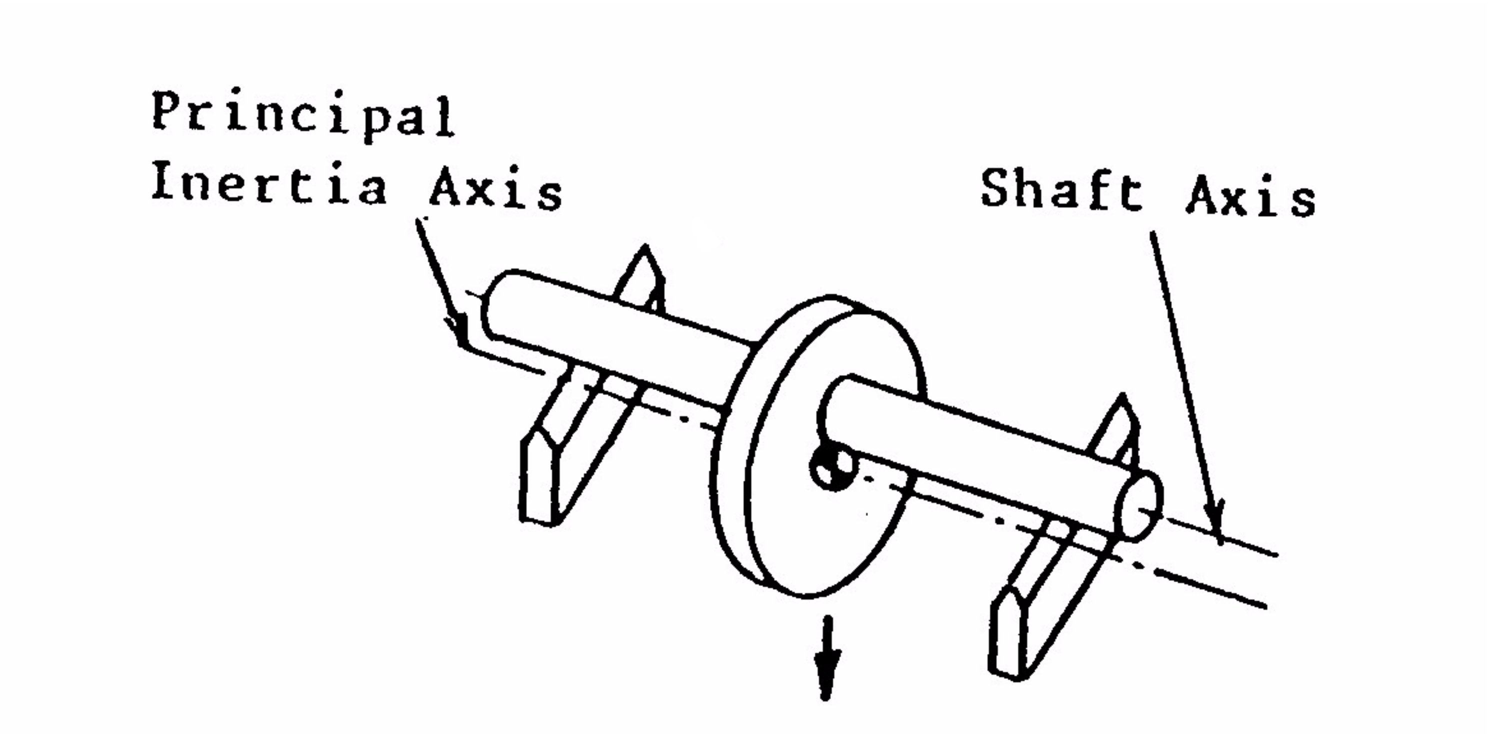


# Static Unbalance



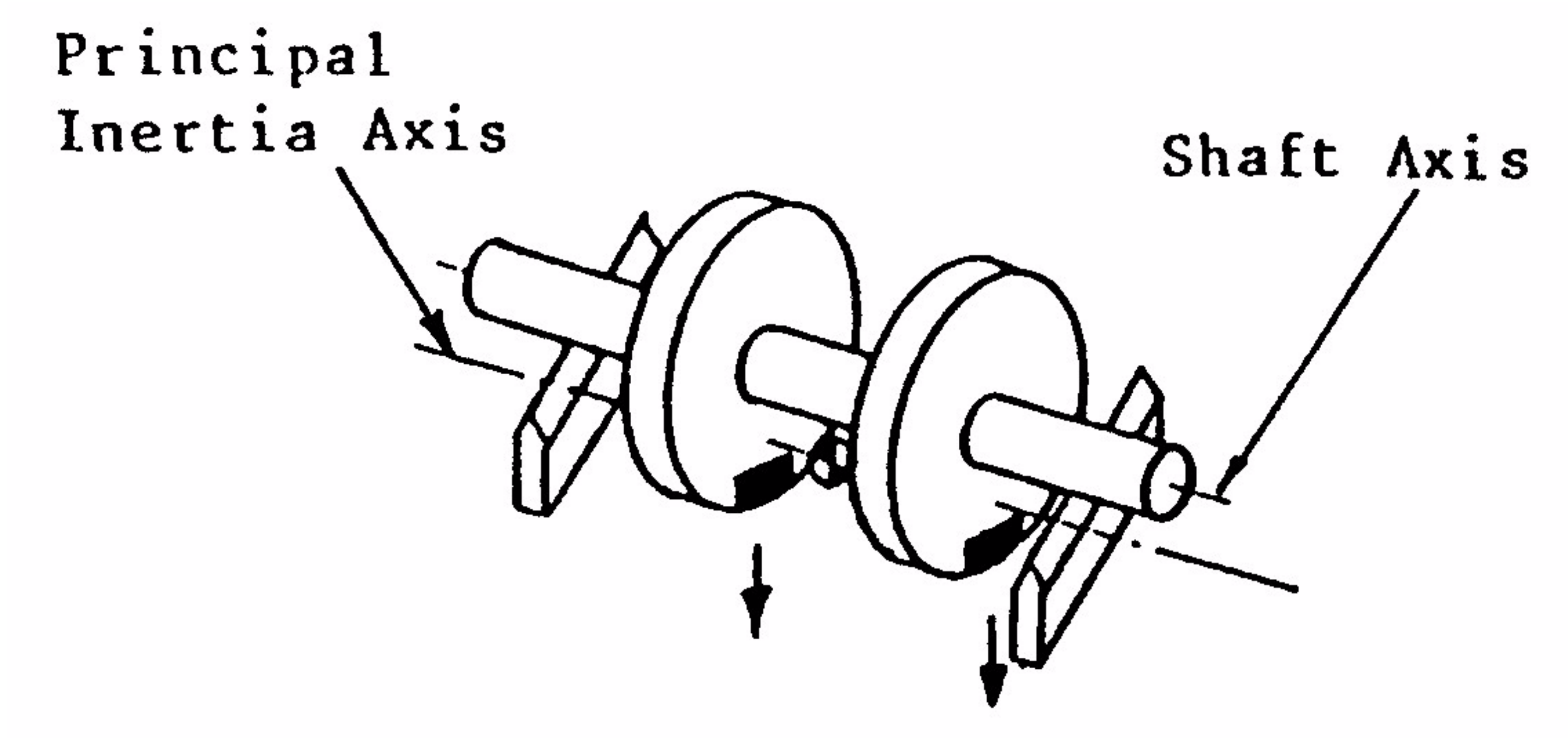

Concentric disc with Static Unbalance

# Static Unbalance



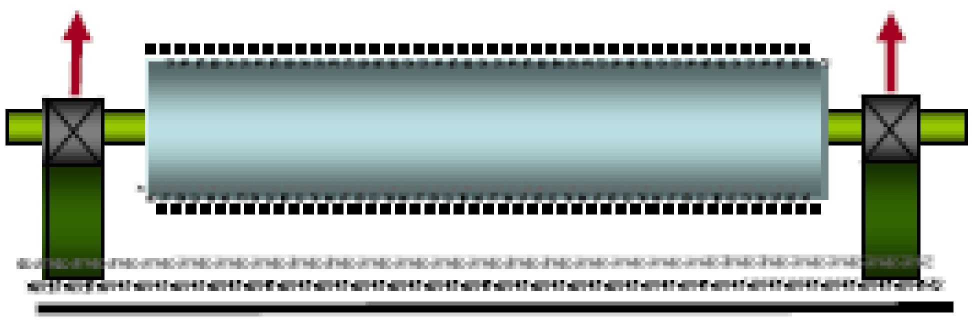

Eccentric disc - Static Unbalance

# Static Unbalance




Two discs of Equal Mass and Identical Static Unbalance

# Static Unbalance

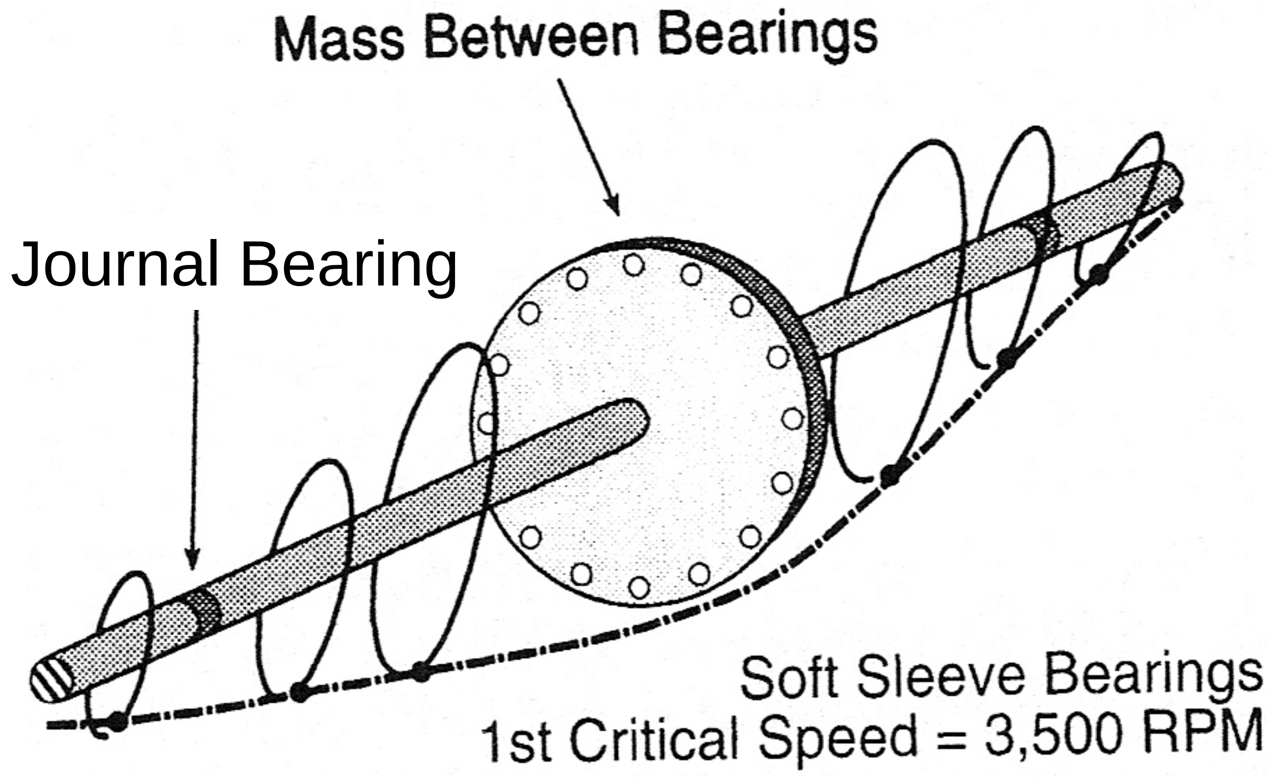


Static Unbalance vibrations will be in-phase and steady.

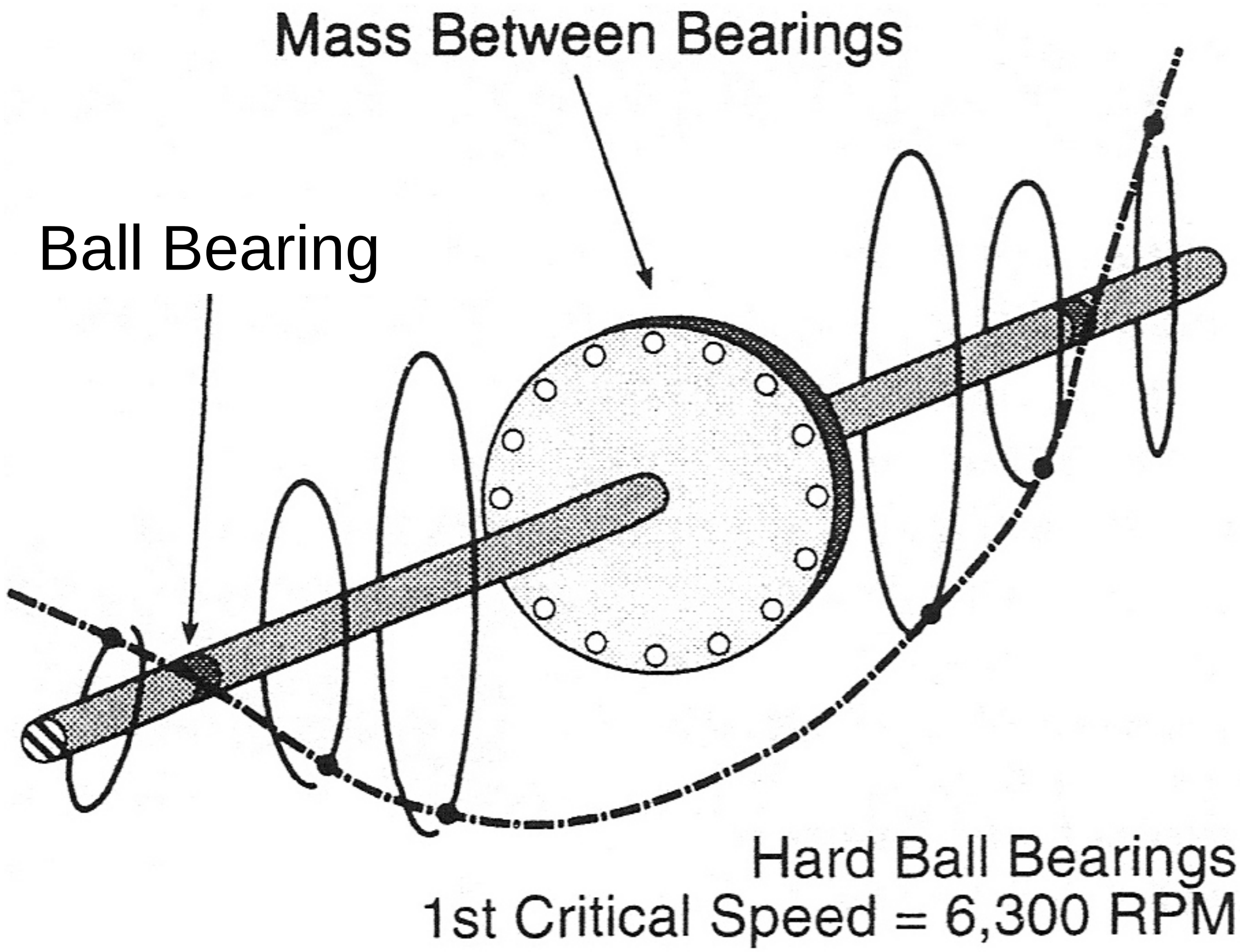
Amplitude will increase as the square of the speed of rotation. (3X speed increase = 9X higher vibration)

1X RPM vibration is always present and dominates spectrum.

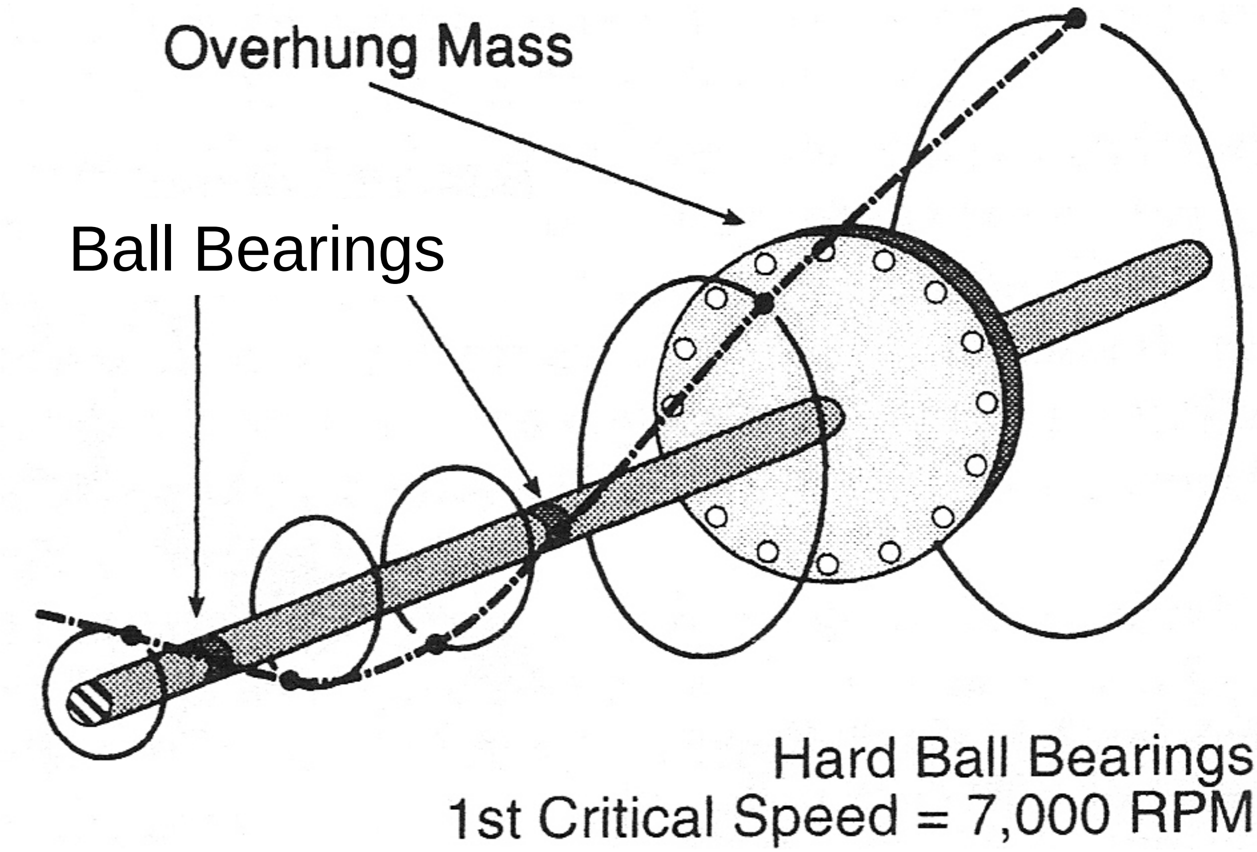
# Static Unbalance



# Static Unbalance



# Static Unbalance

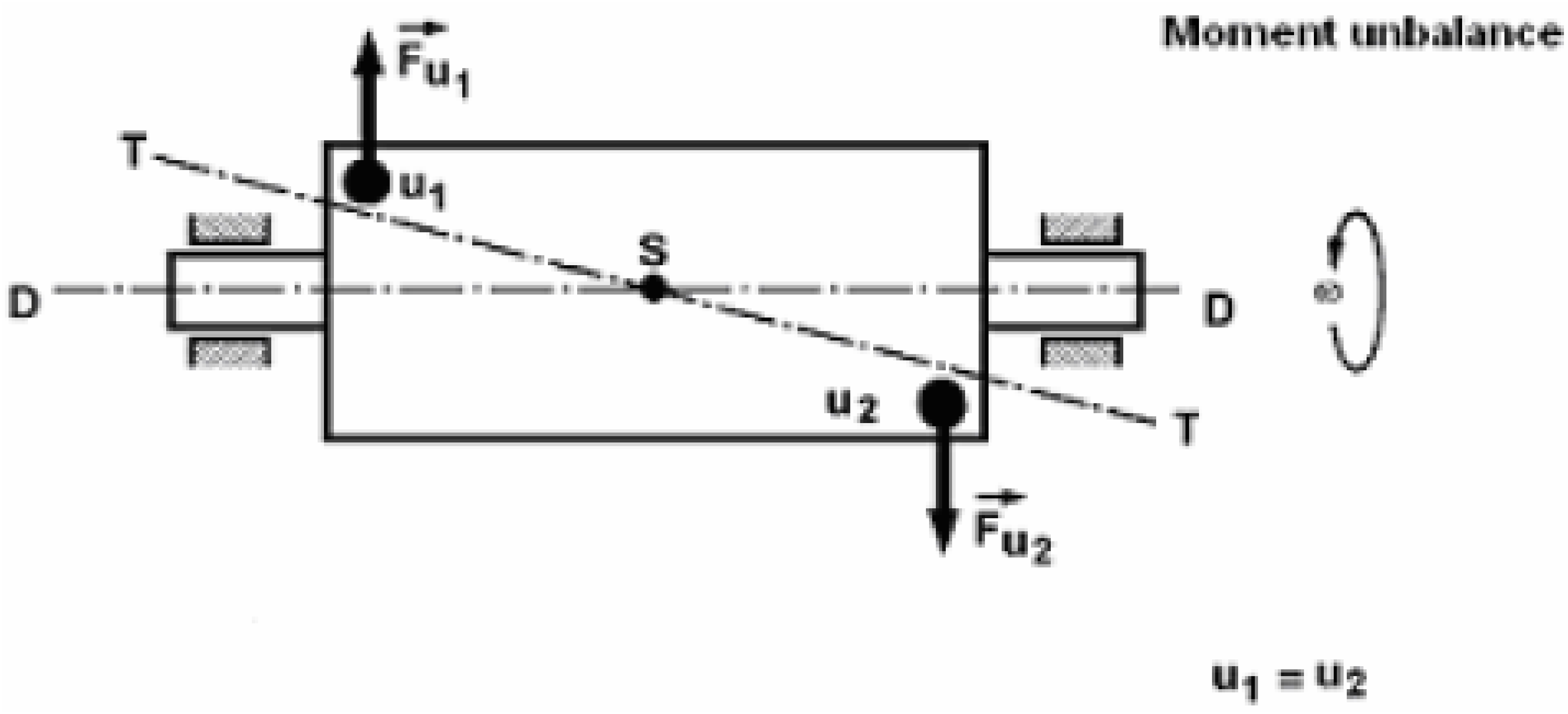


# Couple Unbalance

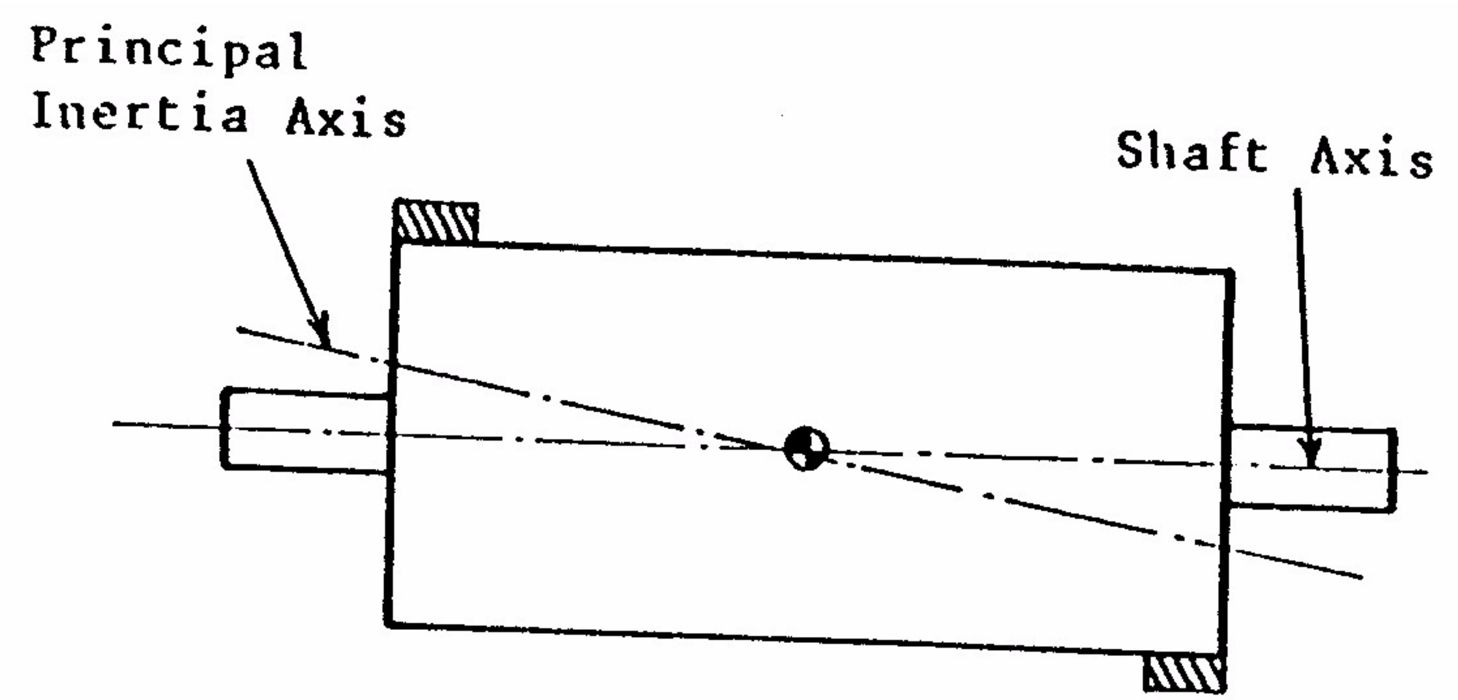
**Couple Unbalance (moment unbalance)**

- principal axis of inertia intersects the shaft axis at the centre of gravity
- two equal unbalances at opposite ends of shaft and 180° apart
- dynamic balancing methods needed

# Couple Unbalance

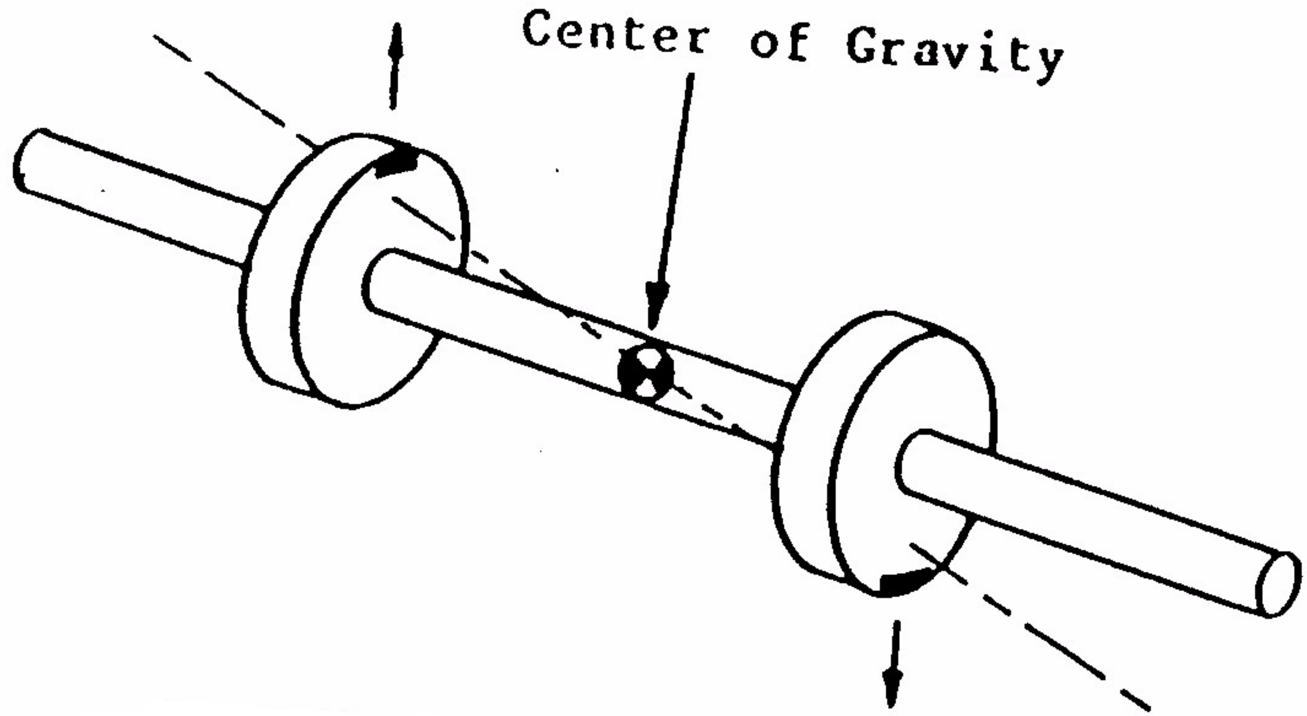


# Couple Unbalance



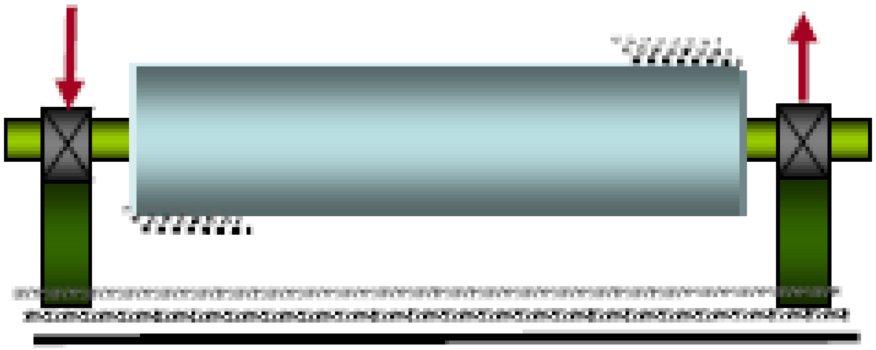

Couple Unbalance in a Solid Rotor

# Couple Unbalance




Couple Unbalance in two Discs of Equal Mass

# Couple Unbalance



Couple Unbalance vibrations will be 180º out-of-phase.

1X RPM vibration is always present and dominates spectrum.

Amplitude will increase as the square of the speed of rotation.

May be high axial vibrations as well as radial.

# Couple Unbalance

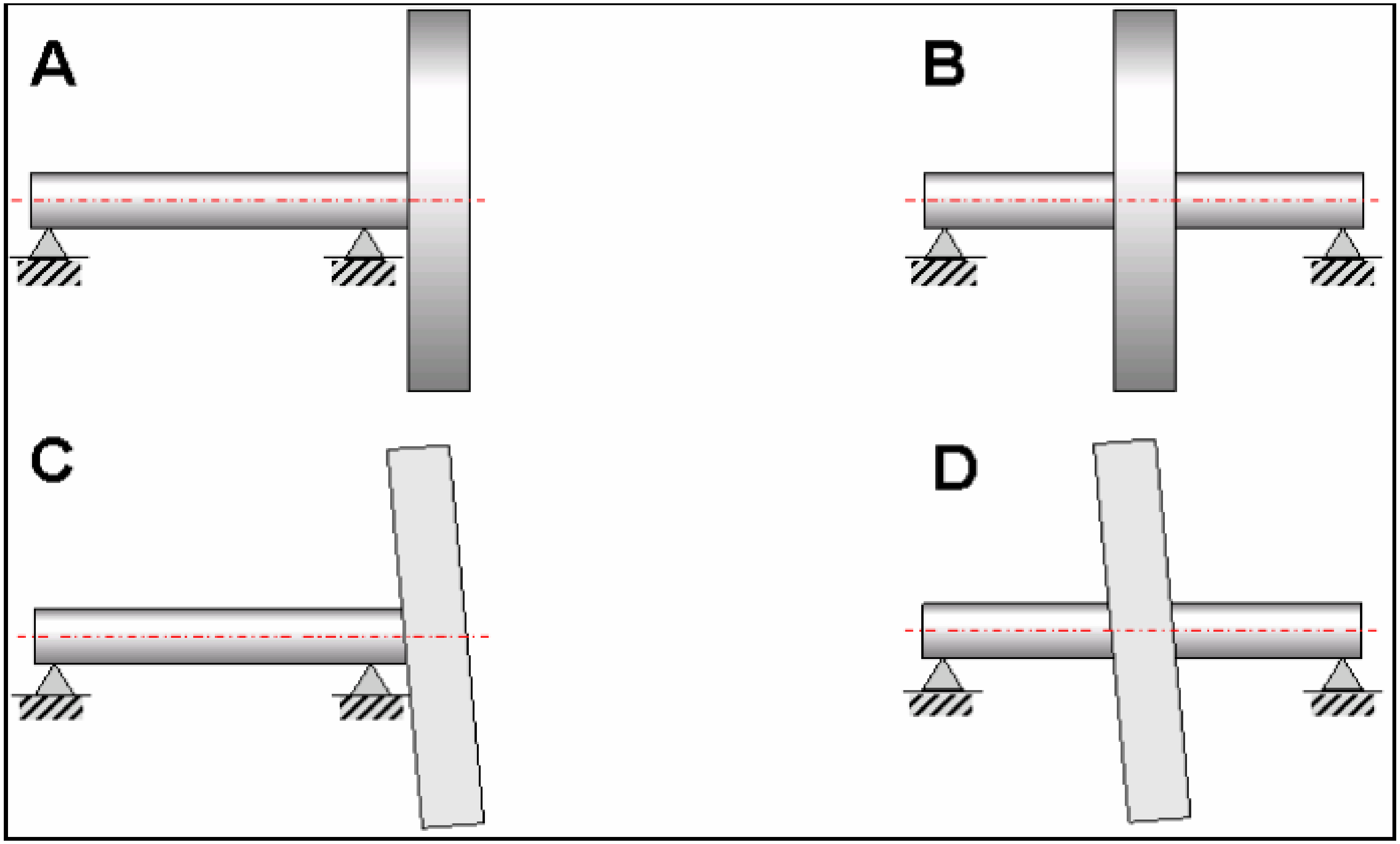
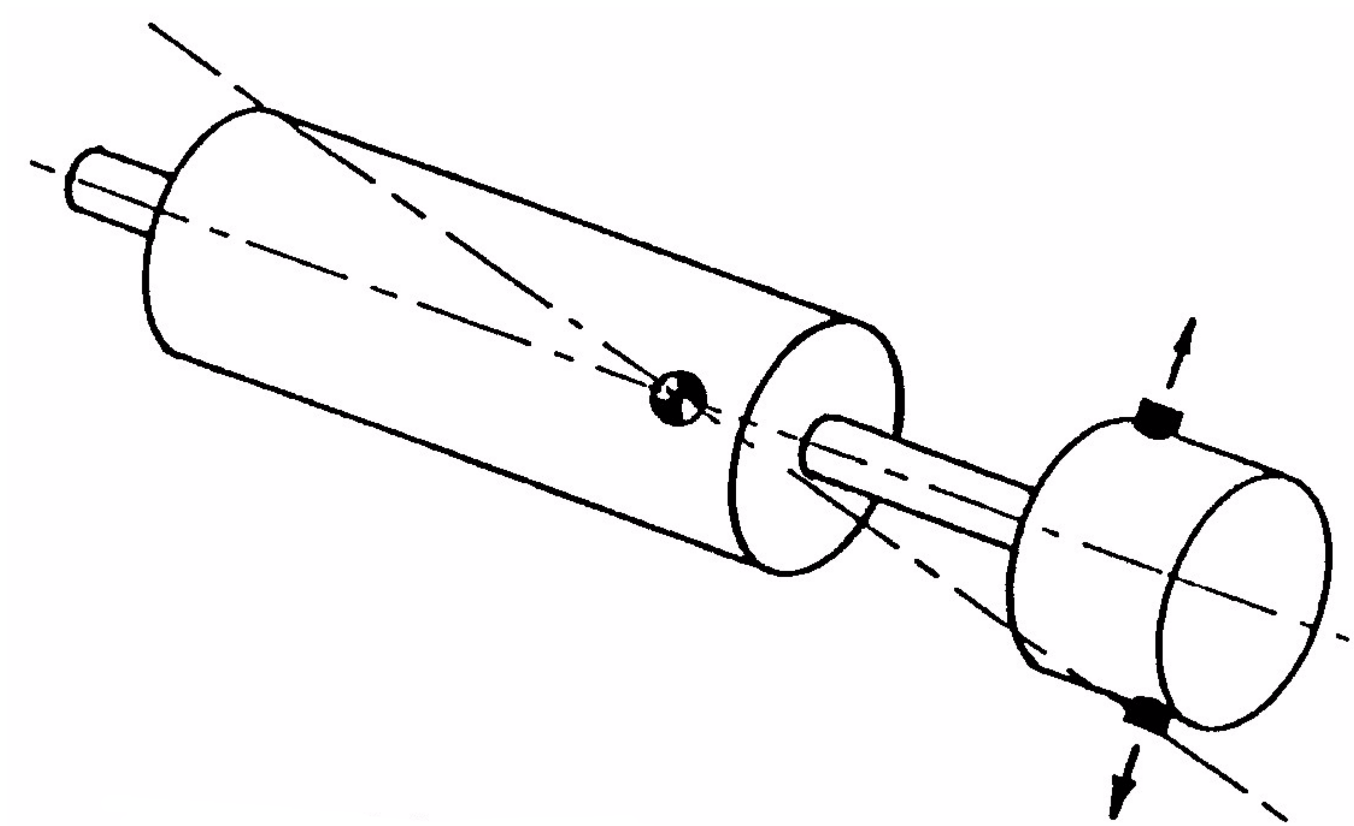


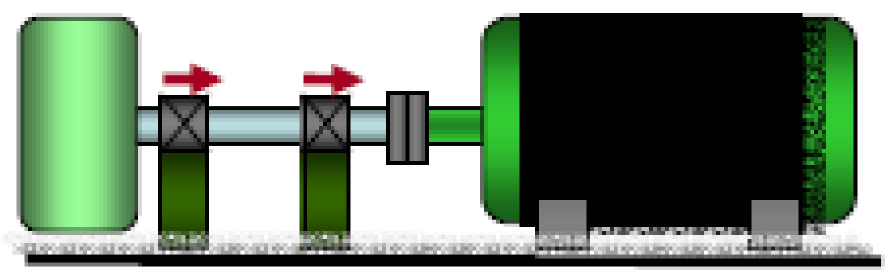

*Figure 3.1: The disc-shaped rotor mounted with minimum axial swash motion (A and B) requires only single-plane balancing. Rotors with mounting errors similar to C and D exhibit unacceptable moment unbalance and must be balanced in two planes.*

# Couple Unbalance



Couple Unbalance in an Outboard Rotor Component

# Couple Unbalance



Overhung Rotor Unbalance vibrations are at 1X RPM and in axial and radial directions.

Axial vibrations tend to be in-phase while radial vibrations may have unsteady phase readings.

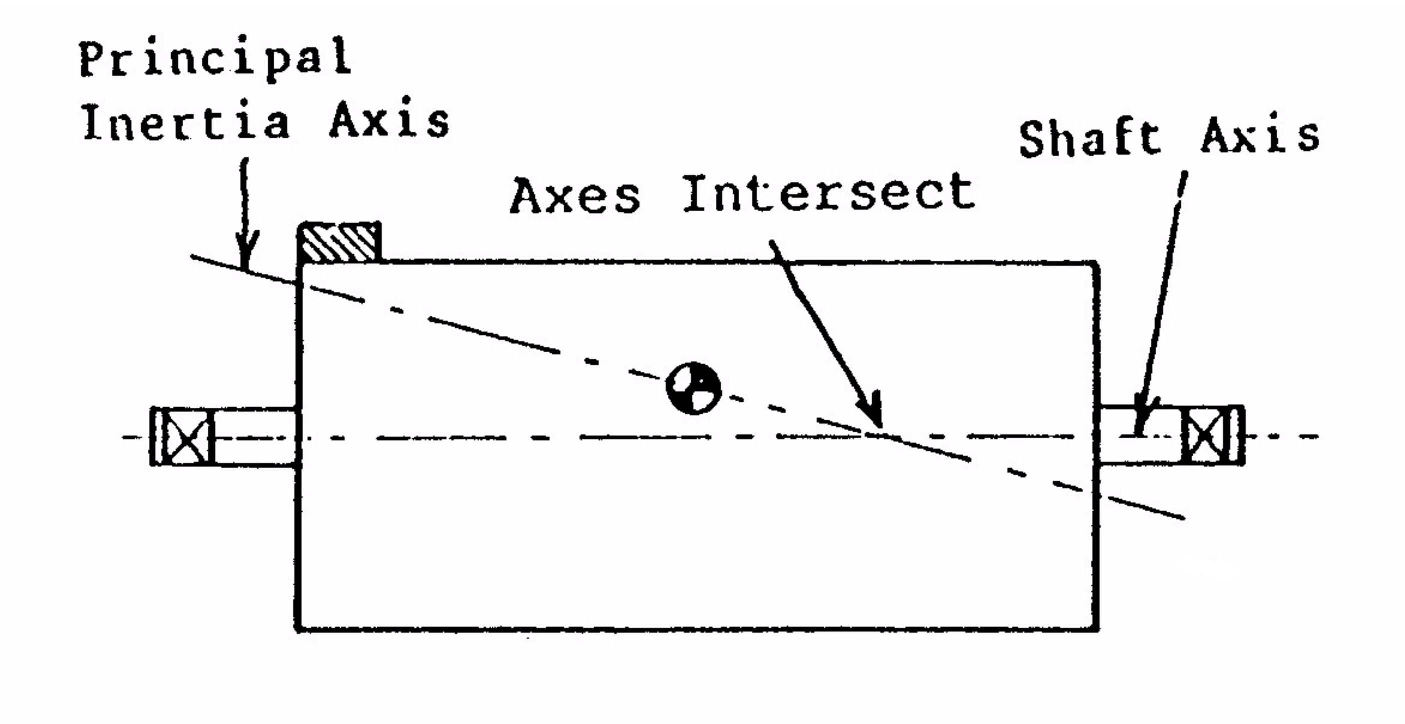
Overhung rotors usually have a combination of static and couple unbalance.

# Types of Unbalance

## Quasi-Static Unbalance

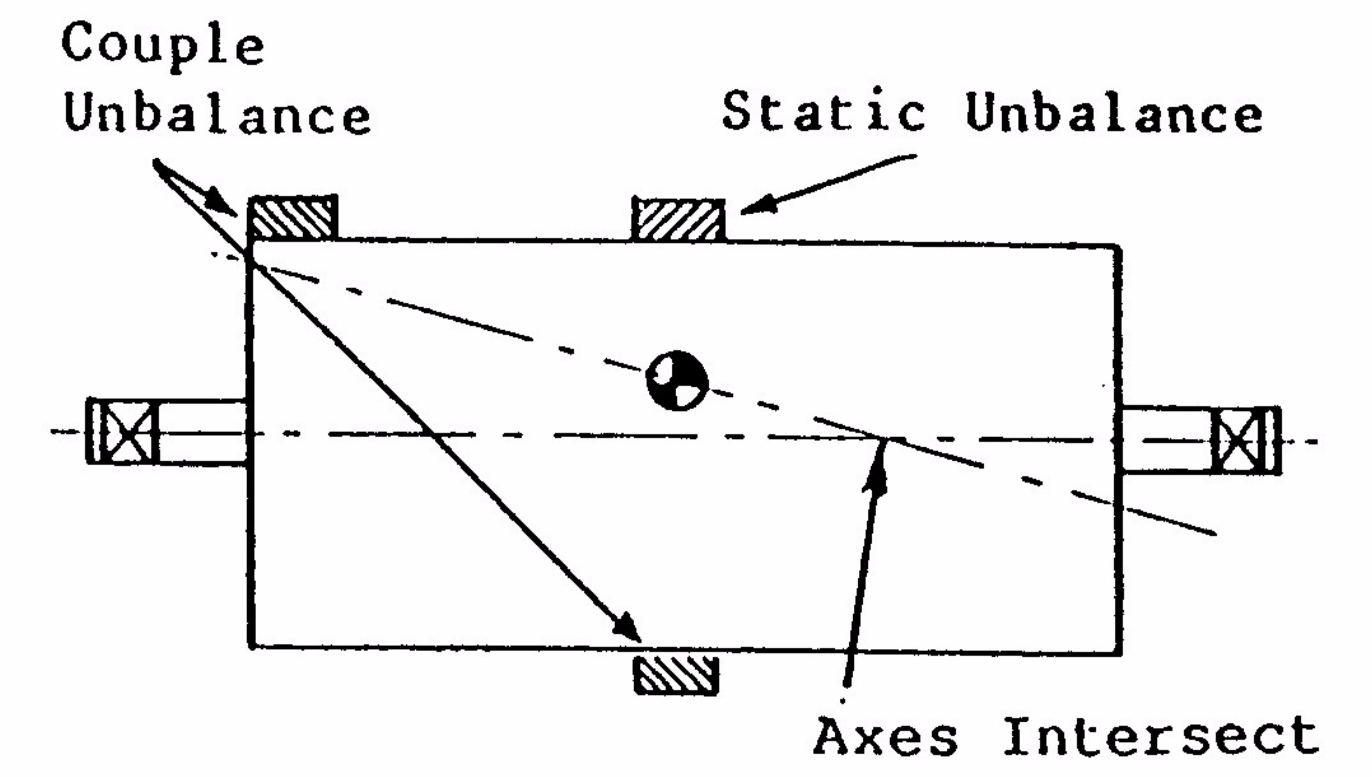
- principal axis of inertia intersects the shaft axis at a point other than the centre of gravity
- combination of static & couple unbalance

# Quasi-Static Unbalance



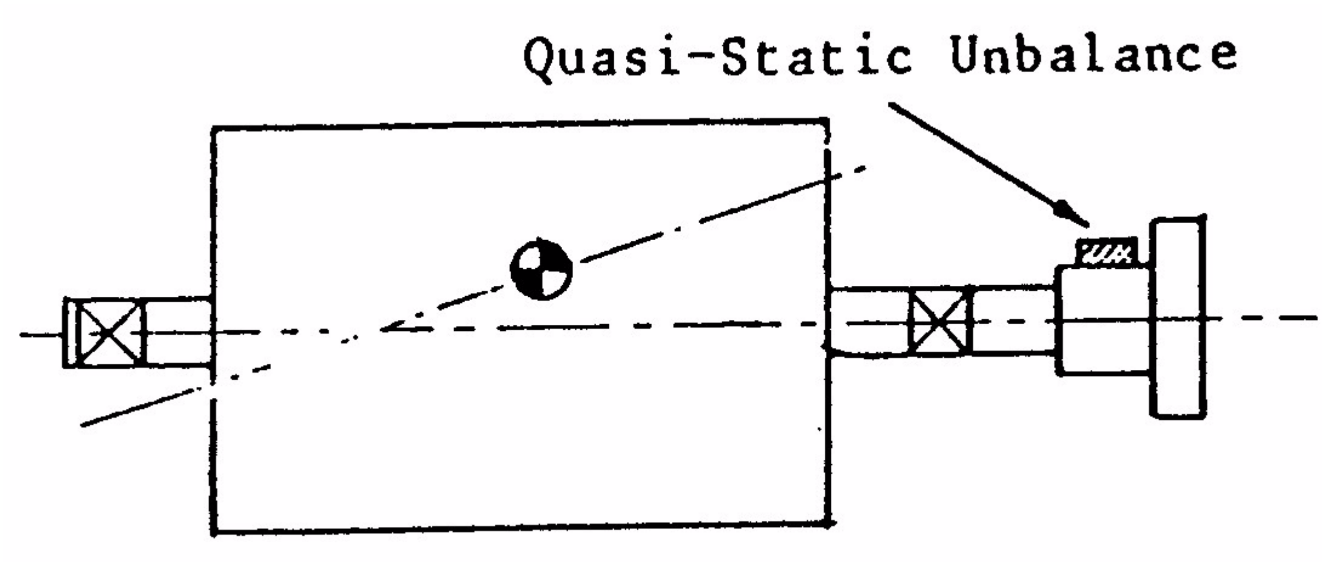

Quasi-Static Unbalance

# Quasi-Static Unbalance




Couple Plus Static Unbalance – Quasi-Static Unbalance

# Quasi-Static Unbalance



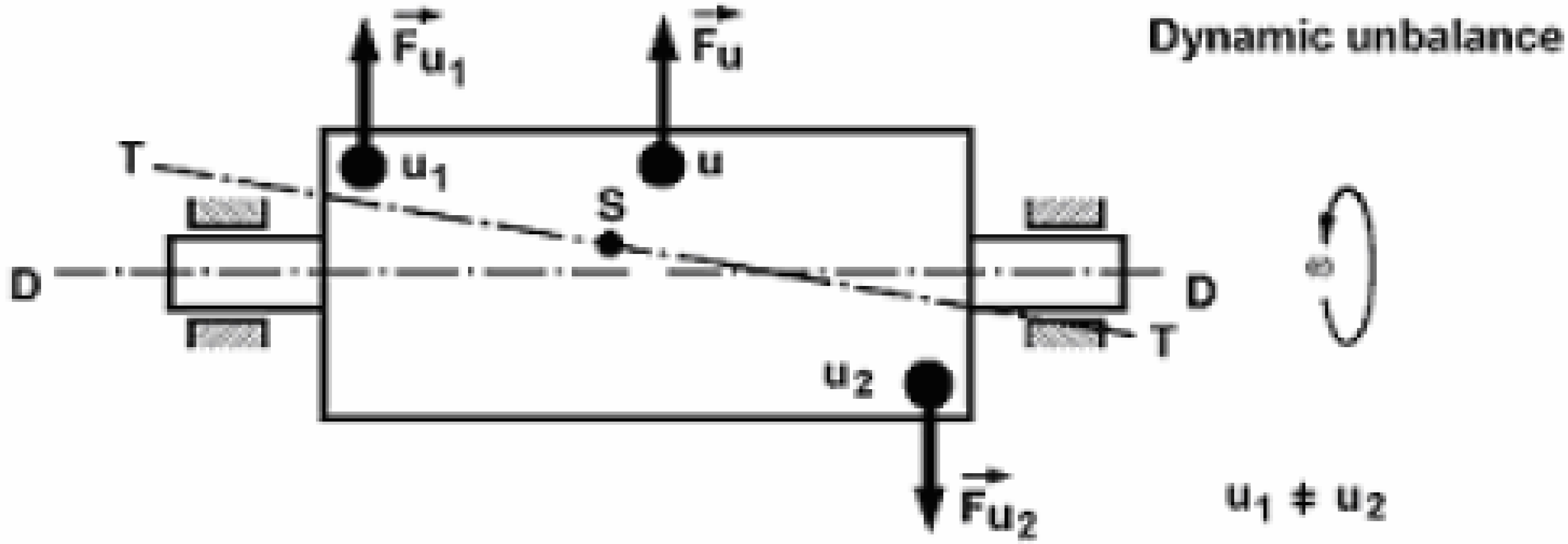

Rotor Assembly with Unbalance in Coupling
– Quasi-Static Unbalance

# Types of Unbalance

## Dynamic Unbalance

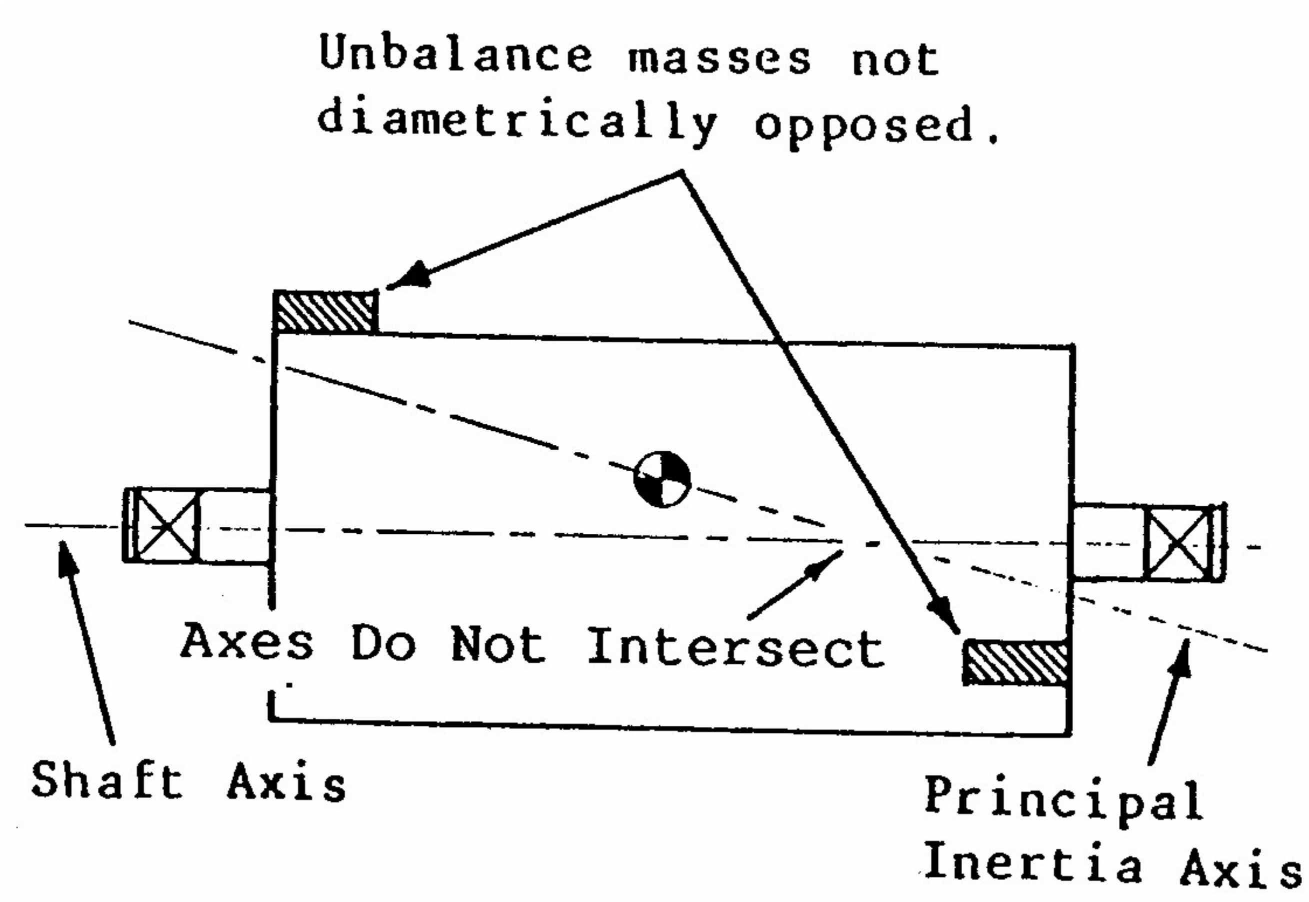
- principal axis of inertia is neither parallel to, nor intersects the shaft axis.
- corrected in at least two planes ⊥ to the shaft axis

# Dynamic Unbalance



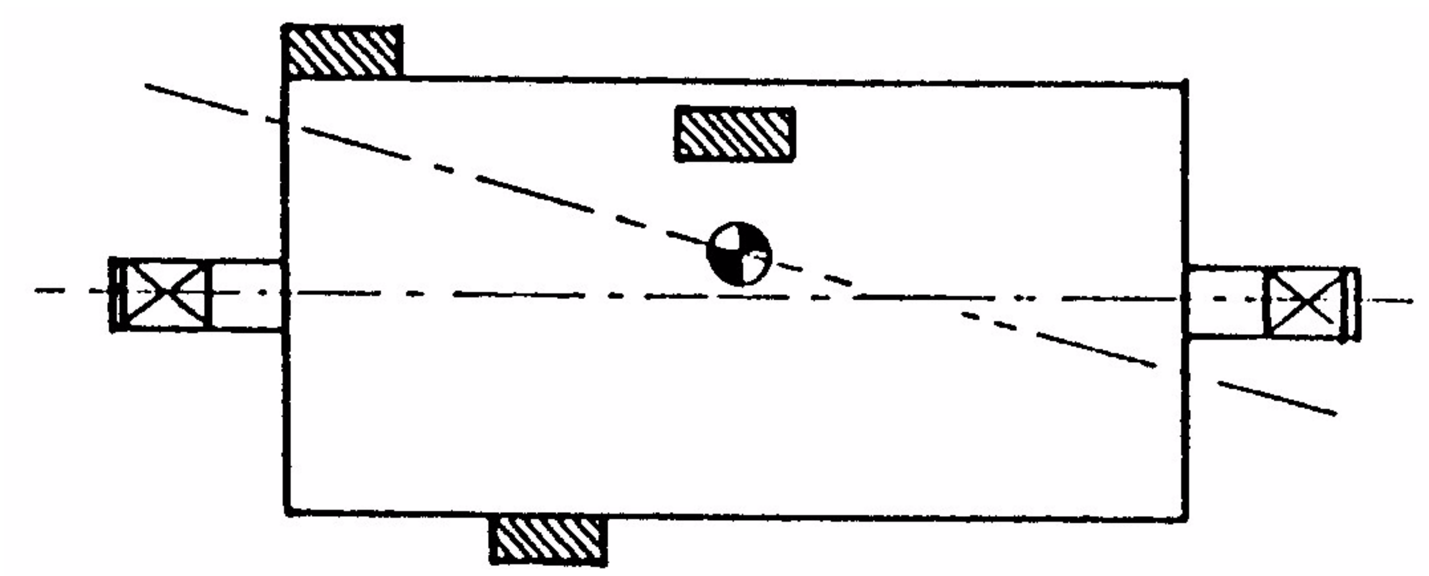

Dynamic Unbalance

# Dynamic Unbalance



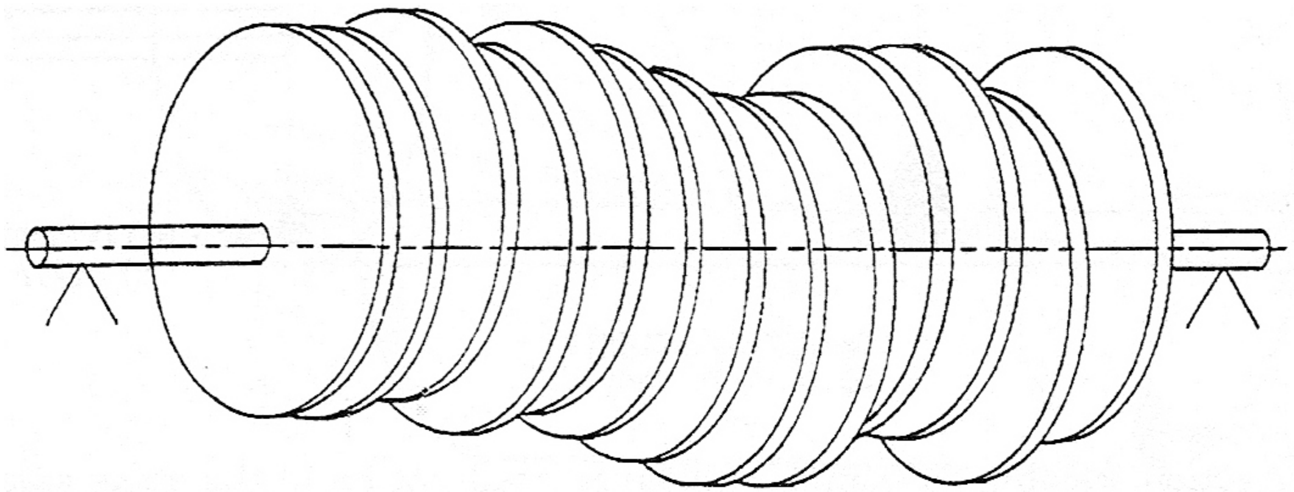

Dynamic Unbalance

# Dynamic Unbalance



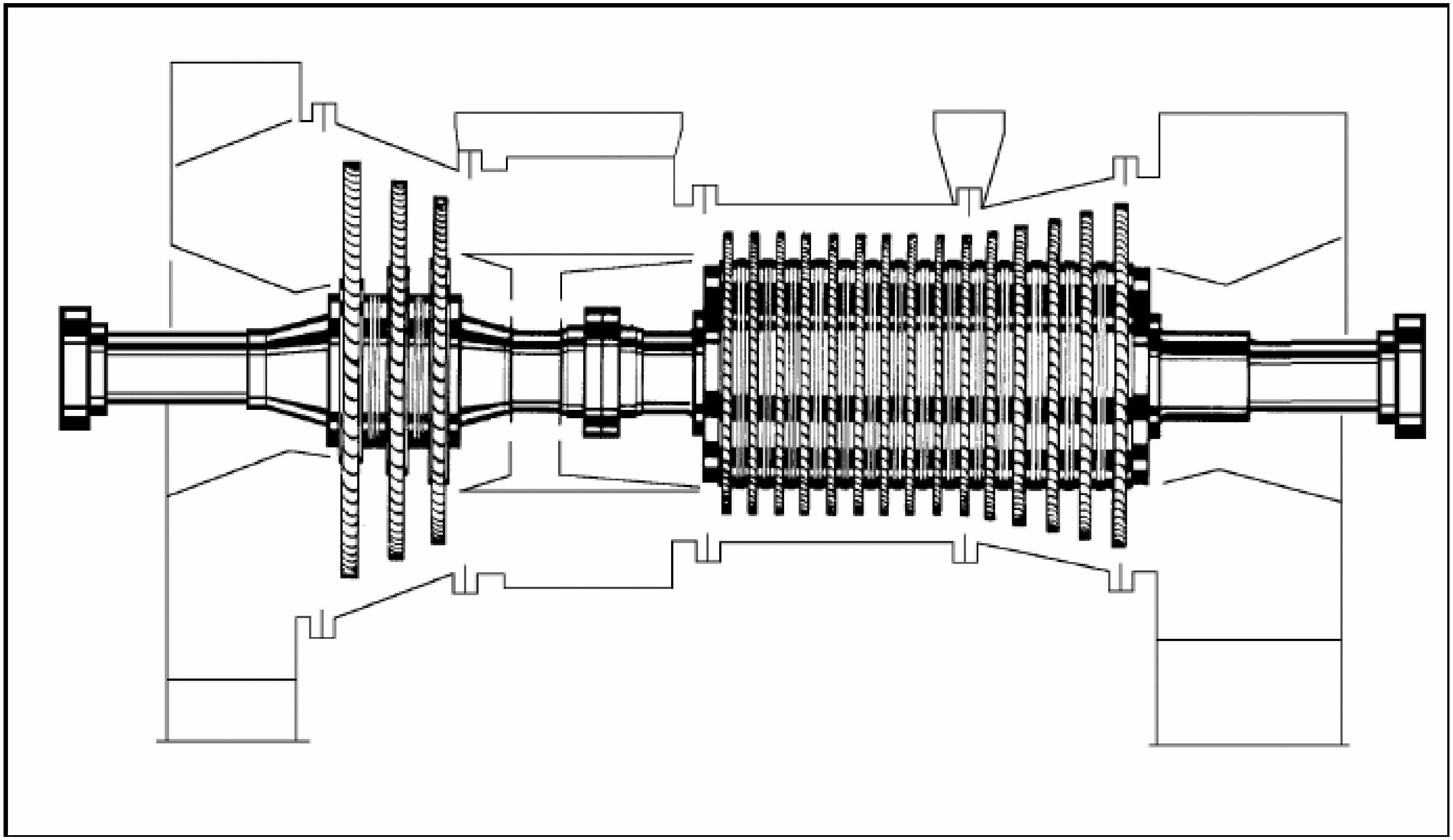
Couple Plus Static Unbalance – Dynamic Unbalance

# Dynamic Unbalance



Dynamic unbalance may be considered as a multitude of unbalanced disks

# Dynamic Unbalance



# Unbalance

## Rotor Motions

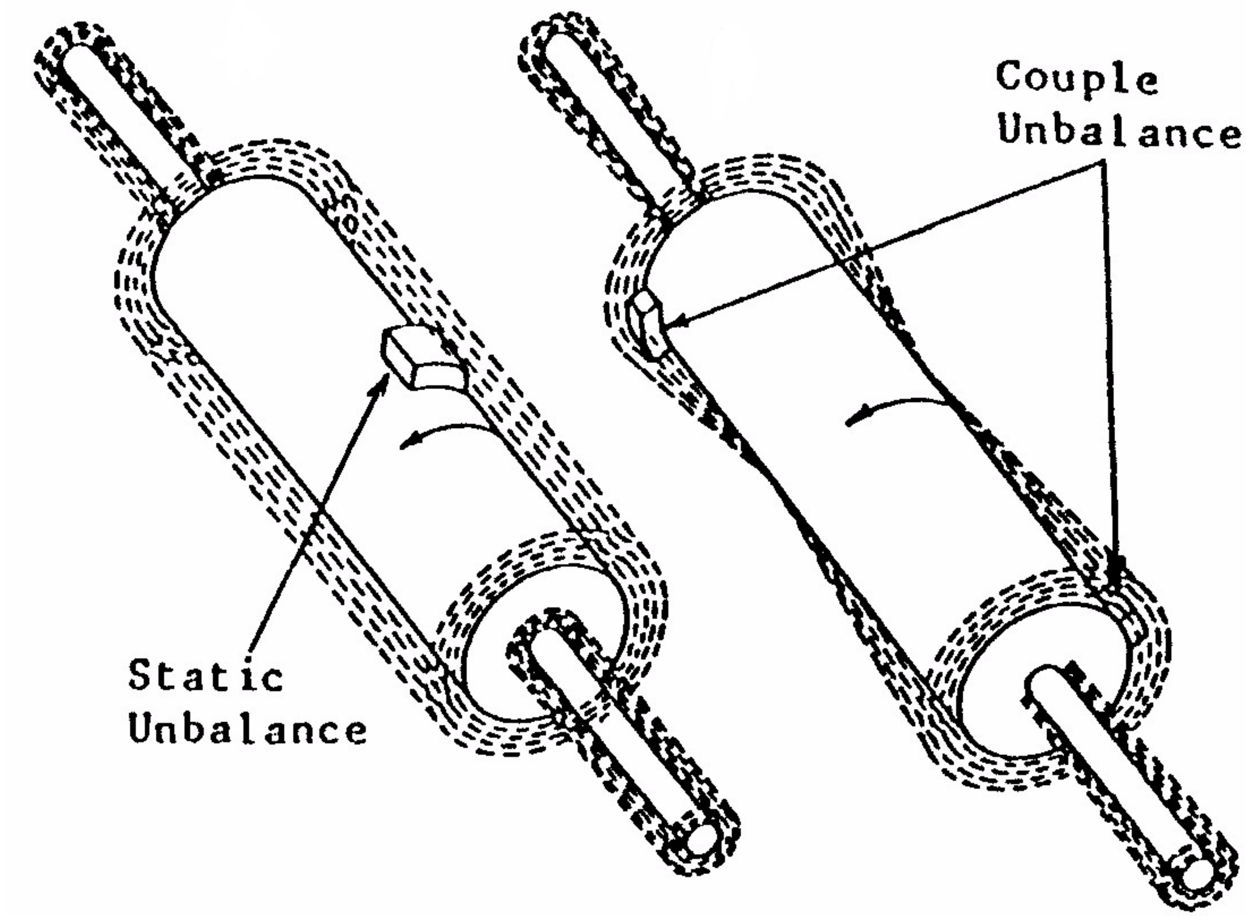
a) in phase - static unbalance

- all points vibrate in the same direction at the same time

b) out of phase - couple unbalance

- points at opposite ends vibrate in opposite directions

# Unbalance




Effect of Unbalance on Free Rotor Motion

# Unbalance

## Rotor Motions

c) quasi - static unbalance (static & couple)

- apex of vibration is moved away from centre of gravity

d) dynamic unbalance - complex

# Runout vs Unbalance

- Runout is the linear radial displacement of the outside surface of the rotor
- Zero runout does not indicate a balanced rotor
  - Because of voids, density changes etc.

# Unbalance

## Effects of Rotational Speed

- at low speeds

  high spot (maximum displacement of shaft) at same location as unbalance

- at increased speeds

  the high spot will lag behind the unbalance location

# Effects of Rotational Speed on Unbalance

- at first critical speed (first resonance)

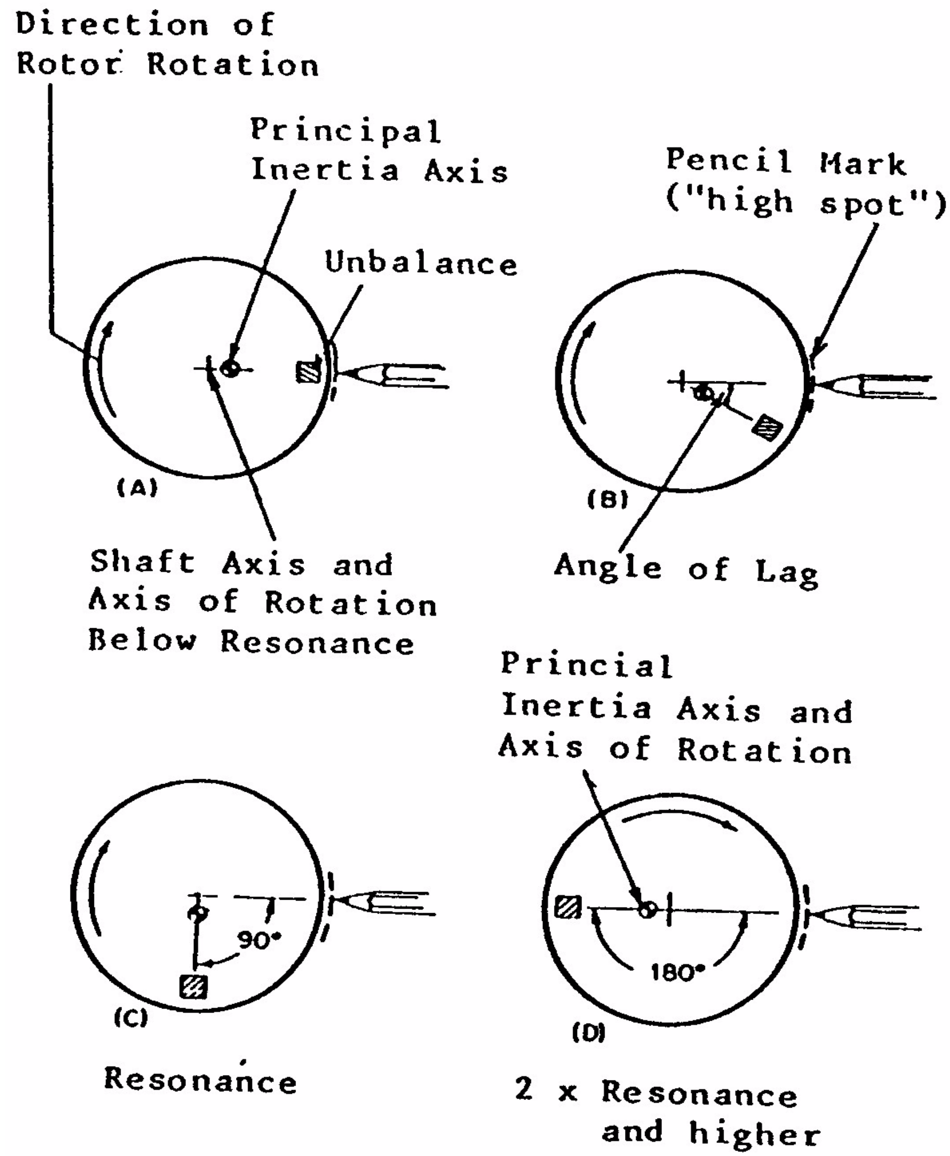
  lag reaches 90°

- at 2nd critical and above

  lag reaches 180°

# Effects of Rotational Speed on Unbalance

Angle of Lag and migration of Axis of Rotation

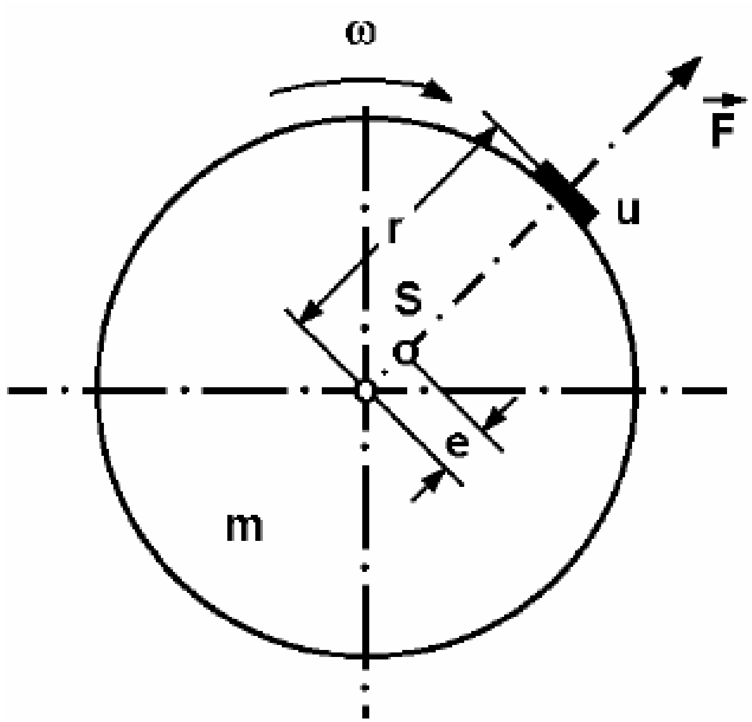


# Unbalance

## Correlating Center of Gravity Displacement with Unbalance

- important relationship when correcting for unbalance, setting balancing procedures, and tolerance selection.
- disc shaped rotor - simple
- long rotors - need to make assumptions

# Unbalance




A rotating disc with an unbalance mass **u** at radius **r**, has its centre of gravity **S** displaced by a value **e**, creating a centrifugal force F

# Unbalance

## Disc Shaped Rotor Example:

- Weight of disc = 999 oz.
- Unbalance mass added = 1 oz.
- Total weight, W = 1000 oz.
- Weight added 10 inches from center of rotation
- Unbalance force, U = 10 in $\times$ 1 oz = 10 oz in.
- C of G displaced by, e = eccentricity

# Unbalance

Consider the C of G rotating at a distance *e* about the shaft rotational axis.

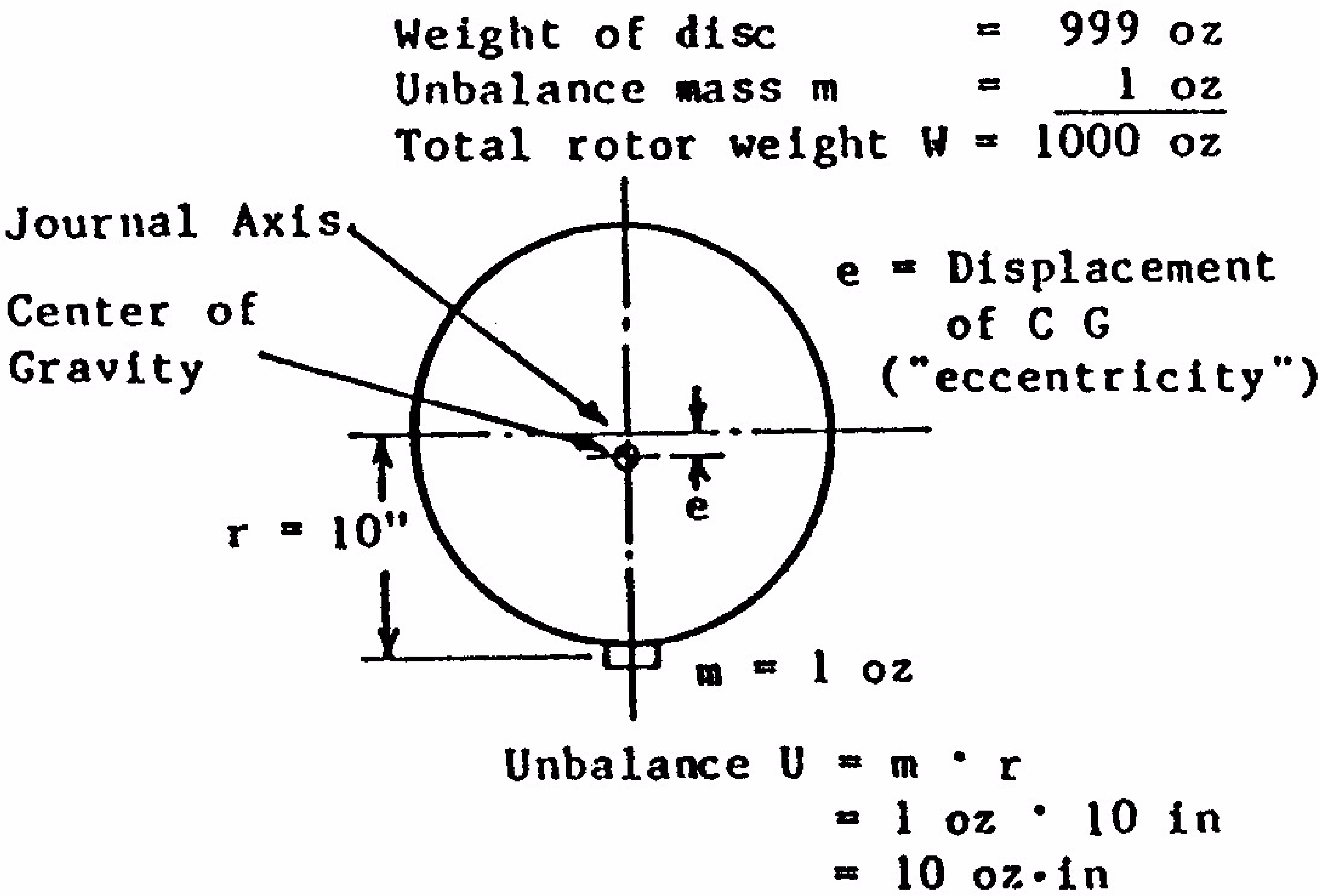
$$U = W \times e$$

$$10 \text{ oz. in} = 1000 \text{ oz.} \times e$$

$$e = \frac{10\ oz.in}{1000\ oz} = 0.01 \text{ in}$$

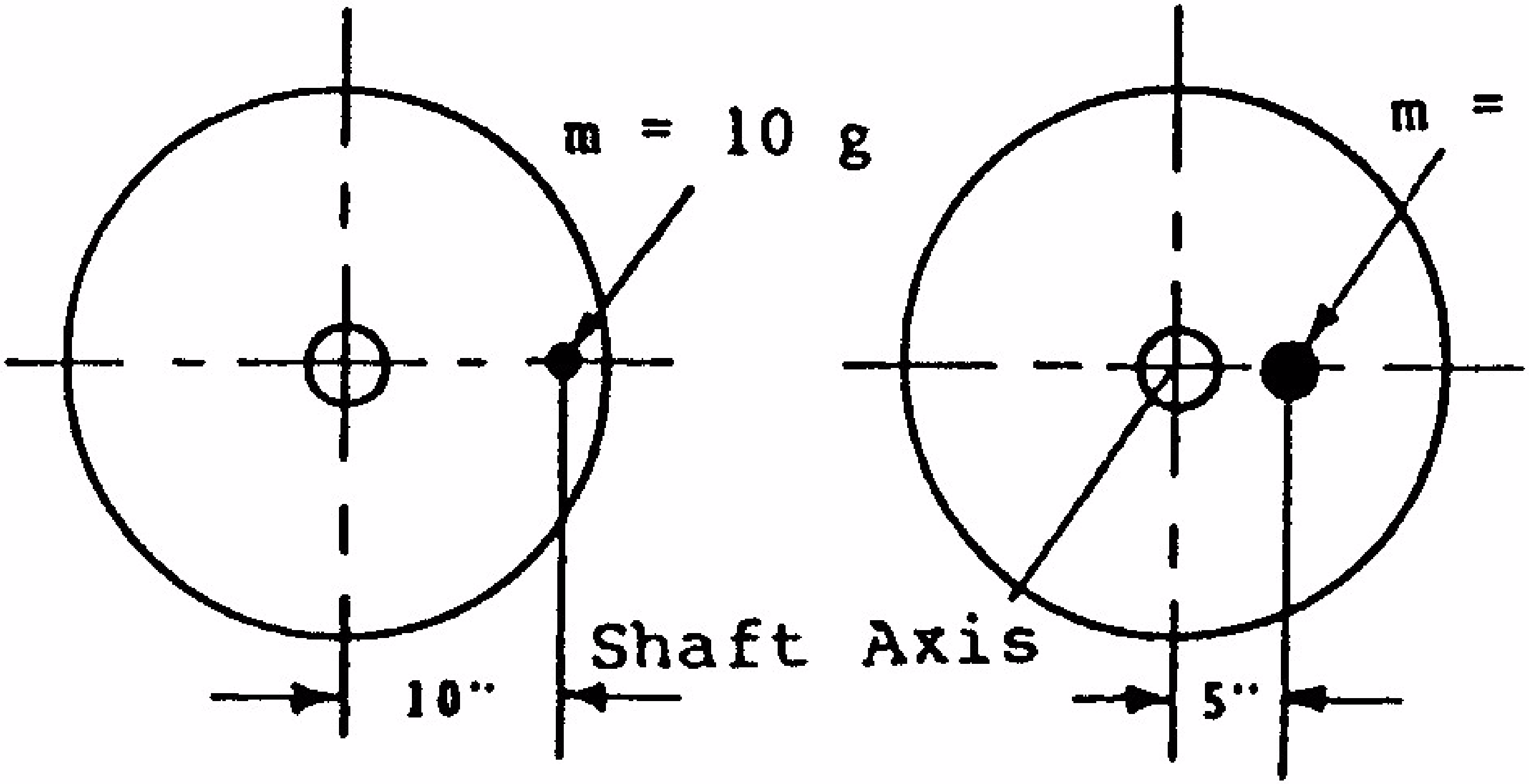
$$e = \frac{U\ \ oz.in}{W\ \ oz.}$$

# Unbalance



Weight of disc = 999 oz
Unbalance mass m = 1 oz
Total rotor weight W = 1000 oz
Journal Axis
Center of Gravity
e = Displacement of C G ("eccentricity")
e
r = 10"
m = 1 oz
Unbalance U = m • r
= 1 oz • 10 in
= 10 oz•in

# Unbalance



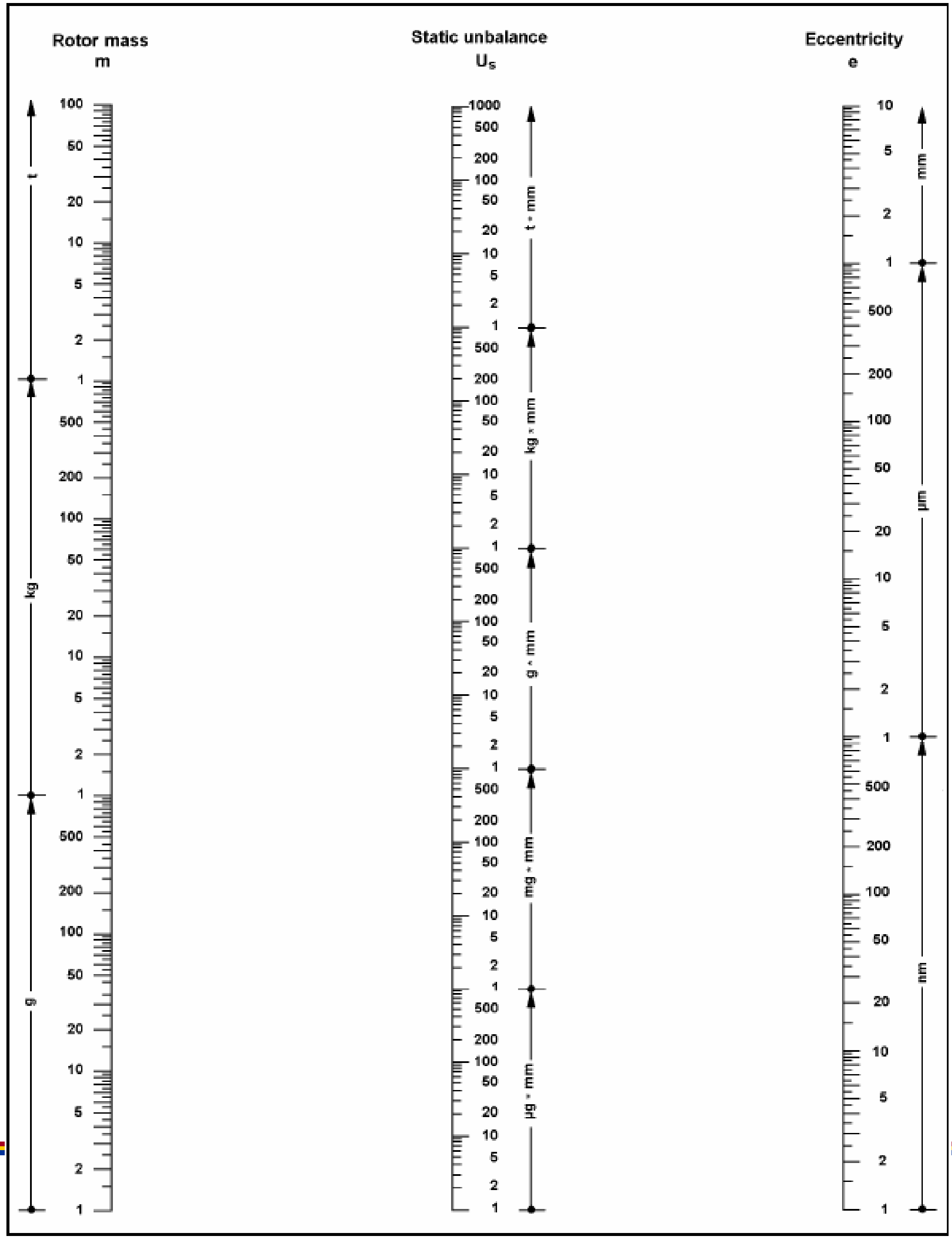
# Unbalance

**Note:**

- displacement, e, is always only 1/2 of the measured relative vibration amplitude.

- for rotors longer than a disc shape,

  e = $\frac{U}{W}$ is true for static unbalance only.


Rotor mass
m
Static unbalance
$U_s$
Eccentricity
e
t
kg
g
t · mm
kg · mm
g · mm
mg · mm
µg · mm
mm
µm
nm

# Unbalance

**Example:**

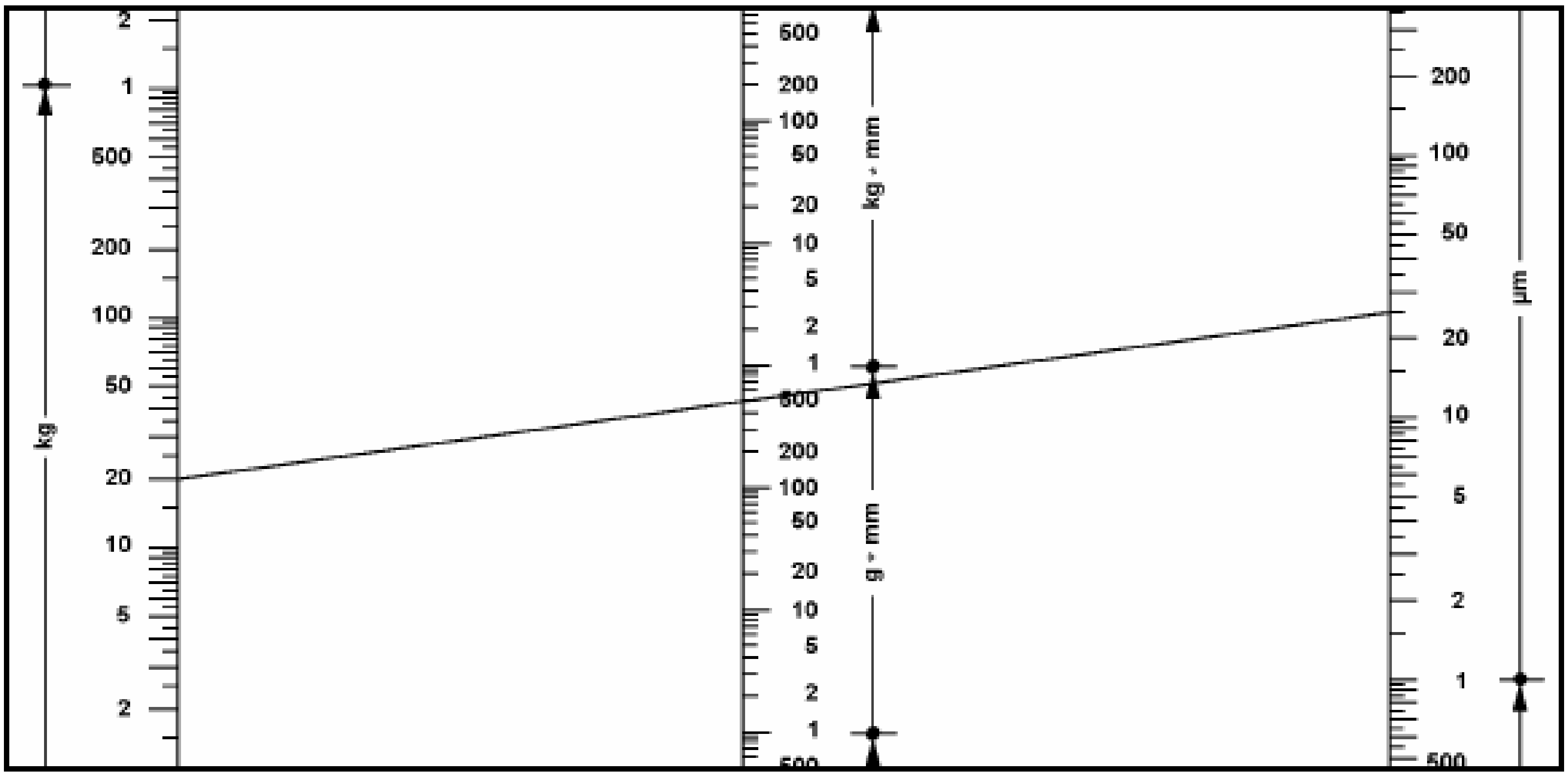
A pulley with mass of 20kg has a static unbalance mass u = 5g added at a radius r = 100mm.

Calculate the magnitude of the center of gravity eccentricity **e**.

**Solution:**

$$e = \frac{u \times r}{m} = \frac{5g \times 100mm}{20kg} = \frac{.005kg \times 0.1m}{20kg} = 0.000025m = 25\mu m$$

# Unbalance



kg
2
1
500
200
100
50
20
10
5
2
kg · mm
500
200
100
50
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5
2
1
g · mm
500
200
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20
10
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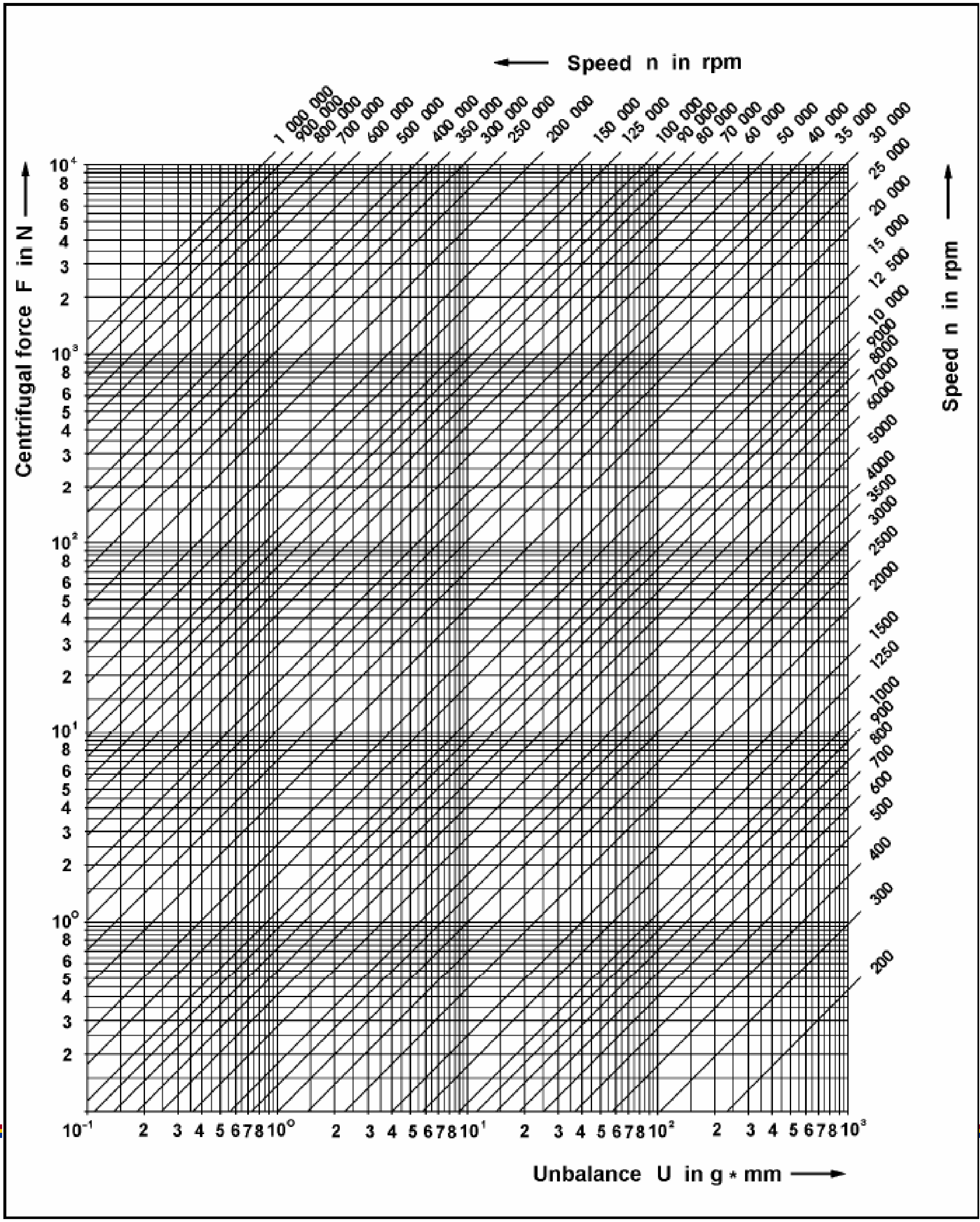
10
5
2
1
500



Speed n in rpm
Centrifugal force F in N
Unbalance U in g * mm

# Unbalance

**Example:**

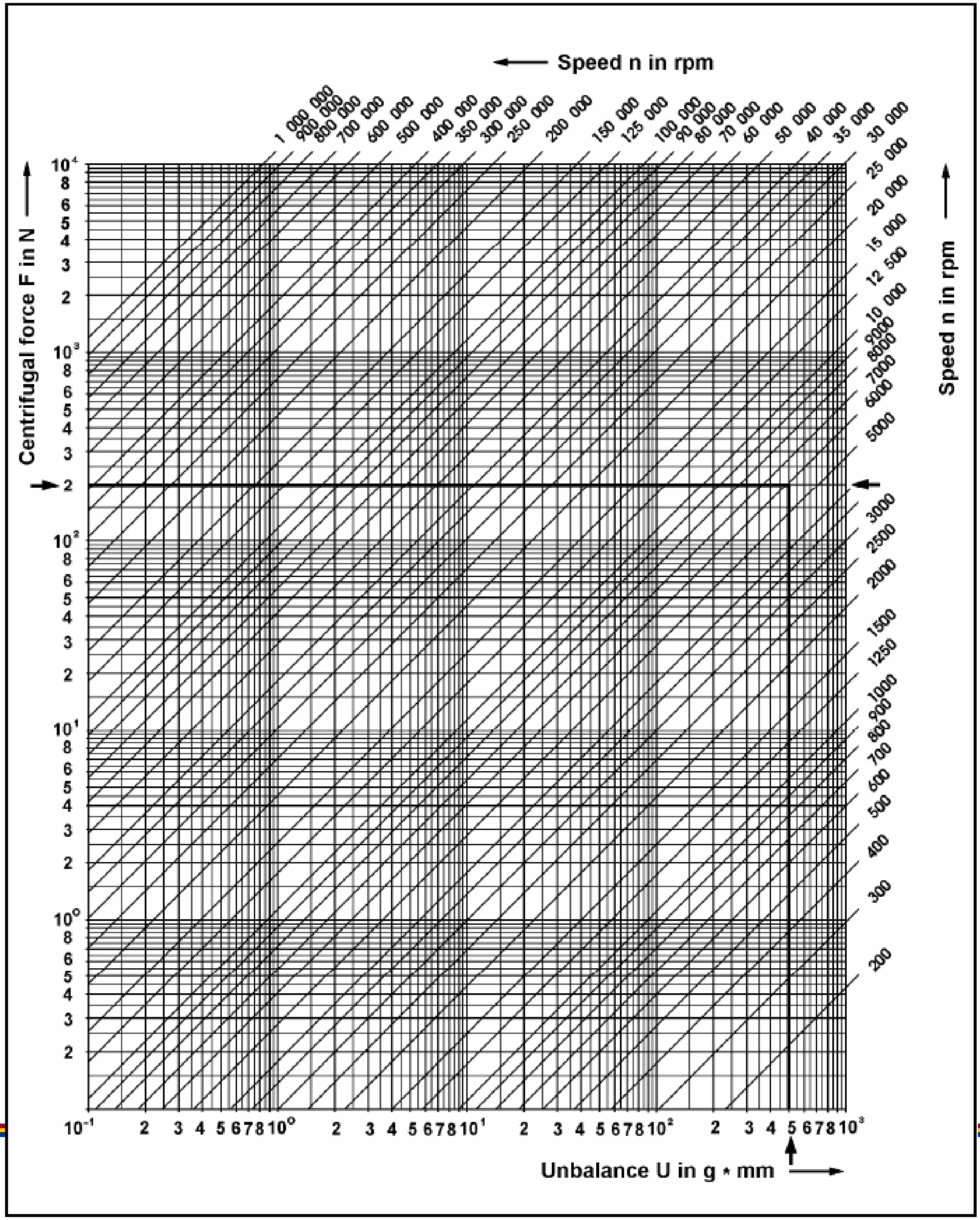
The disc in the previous example with the static unbalance u = 5g at a radius r = 100mm rotates at a speed of n = 6,000rpm (f = 100cps). Calculate the centrifugal force in **Newtons** induced by the unbalance.

**Solution:**

$$F_u = u \times r \times \omega^2$$

$$F_u = 0.005kg \times 0.10m \times \left(2\pi \times 100\right)^2$$

$$F_u = 197N$$


Speed n in rpm
Centrifugal force F in N
Speed n in rpm
Unbalance U in g * mm
1 000 000
900 000
800 000
700 000
600 000
500 000
400 000
350 000
300 000
250 000
200 000
150 000
125 000
100 000
90 000
80 000
70 000
60 000
50 000
40 000
35 000
30 000
25 000
20 000
15 000
12 500
10 000
9000
8000
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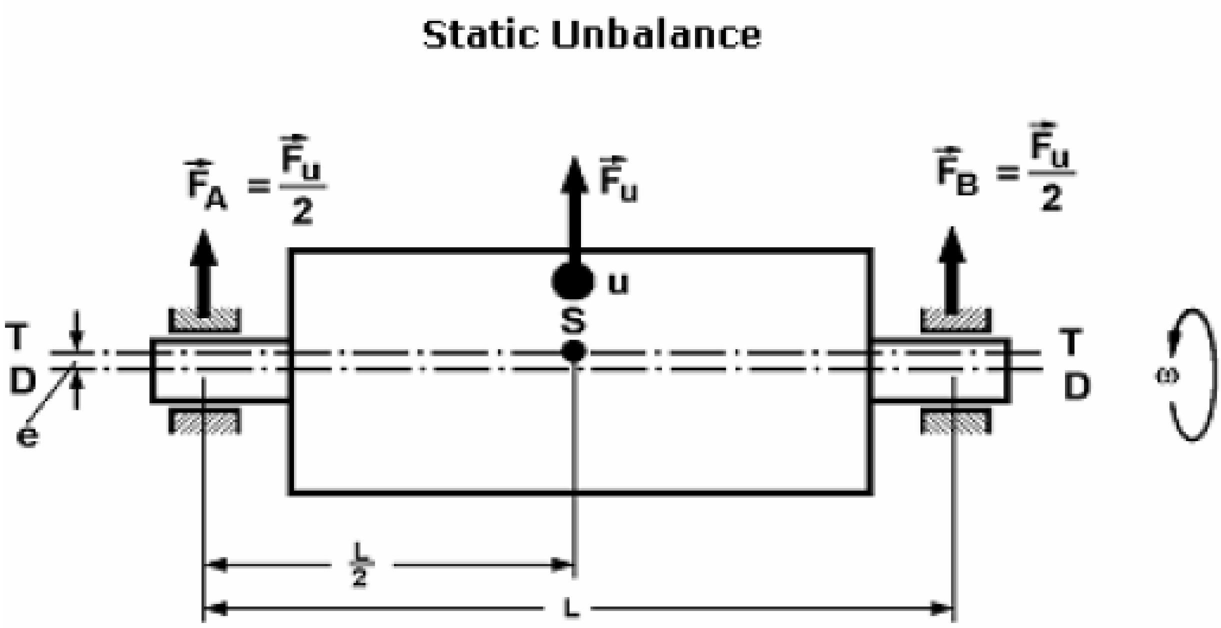
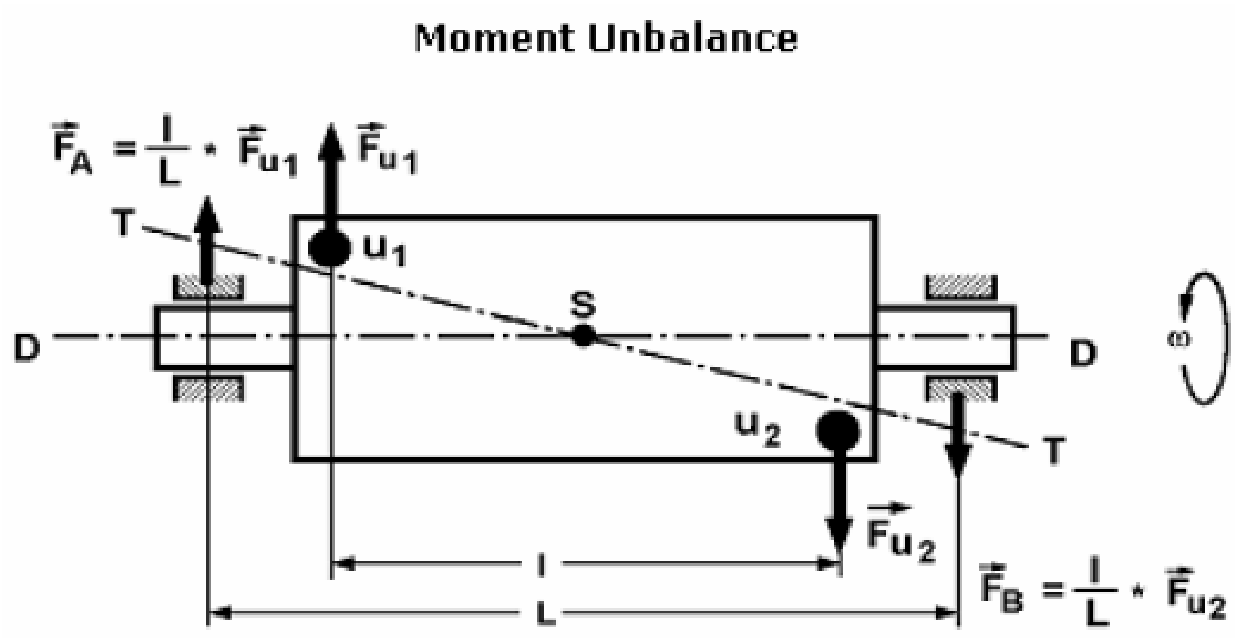
3000
2500
2000
1500
1250
1000
900
800
700
600
500
400
300
200

# Unbalance




Centrifugal forces and bearing forces – static unbalance

# Unbalance




Centrifugal forces and bearing forces – couple unbalance

# Unbalance

For the case where the unbalance weight is near one end of the rotor:

$$d = \frac{m\,r}{W + m} + \frac{m\,r\,j\,h}{I_x - I_z}$$

d = displacement of principal axis of inertia from shaft axis at the bearing

W = rotor weight

m = Unbalance mass

r = radius of unbalance

h = distance from center of gravity to plane of unbalance

# Unbalance

For the case where the unbalance weight is near one end of the rotor:

$$d = \frac{mr}{W + m} + \frac{mrjh}{I_x - I_z}$$

j = distance from center of gravity to bearing

$I_x$ = moment of inertia around transverse axis

$I_z$ = polar moment of inertia around shaft axis

Since $I_x$ & $I_z$ are not usually known, it is acceptable in most cases to assume that the unbalance causes parallel displacement of the principal axis of inertia.

# Balancing

## Single-plane balancing.

Typical rotors which often require only single-plane balancing, especially in the assembled condition, are:

- Fans, ventilators and air separators,
- grinding discs, die chucks,
- pulleys, flywheels, clutches,
- gears,
- impellers, atomizer discs.

# Horizontal Balancing Machine

# Horizontal Balancing Machine

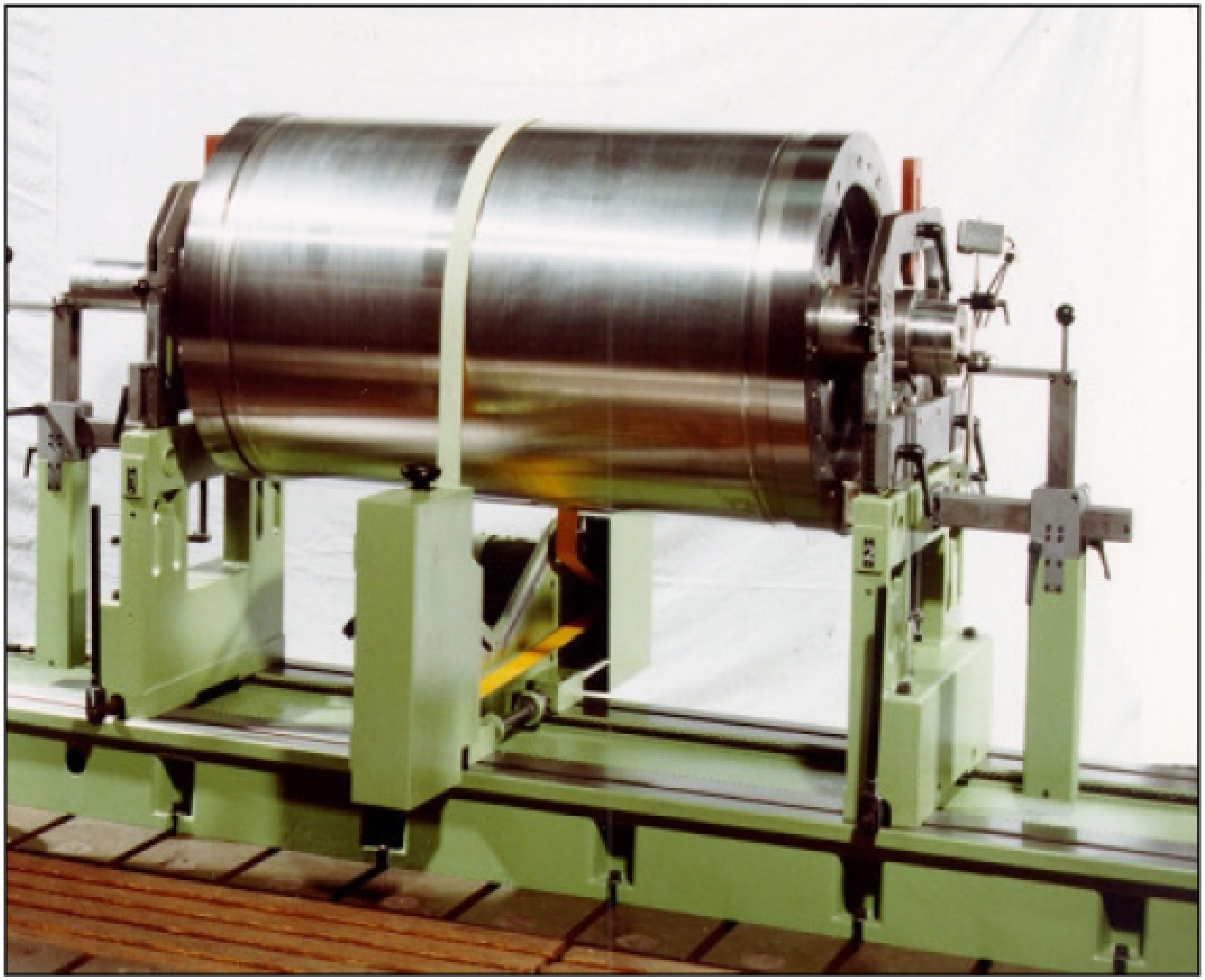
# Balancing

**Two-plane (dynamic) balancing.**

Typical rotors which should be balanced in two planes are:

- Paper machine rolls,
- steam turbine/generator sets,
- electric motor and generator armatures,
- crushing and cutting rotors,
- machine tool spindles,
- grinding rolls,
- fans and blowers with longer distances between the end plates and
- compressor rotors.

# Horizontal Balancing Machine

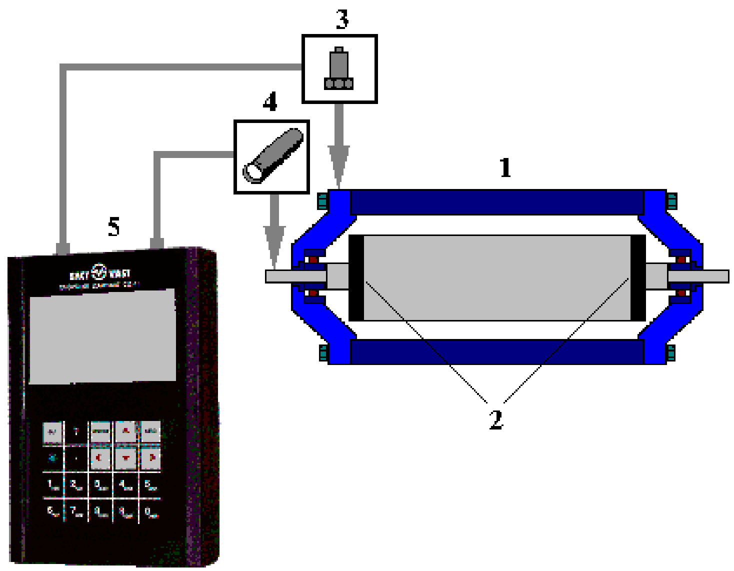


# Horizontal Balancing Machine

# Horizontal Balancing Machine

# Unbalance

## Field Balancing (in situ)




**Advantages:**

- rotor balanced on own bearings
- balanced at normal operating speed
- balanced at normal load
- rotor driver same as normal operation
- no tear down, re-assembly & re-alignment
- in place trim balance not required

# Field Balancing

**Advantages:**

- down time greatly reduced
- generally simple procedures which require only
  - starting and stopping machine (may be time consuming)
  - adding or removing correction weights

# Pre-Balancing Checks

## Before starting balancing

- Determine if mass unbalance is the problem by performing a complete vibration analysis
- If mass unbalance is not the problem, look into and correct other problems: excessive bearing clearance, looseness, resonance, and misalignment, etc
- If mass unbalance is the cause, continue with pre-balancing checks

# Pre-Balancing Checks

- Nature of unbalance problem (do a vibration analysis)
- Determine whether or not the rotor is clean
- Assess rotor stability (structural, thermal)
- Determine critical speeds (star-up/coast-down tests)
- Locate balance weights already in place
- Know details of balance planes or rings

# Measurements

## Sensors for vibration

- Proximity probes – the most direct measure
- Velocity transducers – indirect measure
- Accelerometers – indirect measure

## Sensors for phase

- Strobe light – less accurate phase reading
- Photoelectric sensor –accurate phase reading
- Proximity probe – accurate phase reading

# Field Balancing

## Single Plane Balancing

- dynamic balance conducted in only one plane
- the centrifugal force developed by an unbalance is

$$F_c = \omega^2 \times \frac{U_b}{g}$$

$$U_b = M \times r$$

$U_b$ = Unbalance (oz. in)

M = weight of unbalance (oz.)

r = radius from rotor center to M (in.)

# Field Balancing

## Single Plane Balancing

$\omega = 2 \pi f$

f = frequency (Hz)

g = acceleration due to gravity

$F_c$ = centrifugal force

Note:

The shaft motion induced by an unbalance will be orbital, that is, the shaft center will move in a circular path. The vibration transducer only sees the motion that is parallel with its principal axis of operation.

# Field Balancing

## Single Plane Balancing – Vibration Measurements

The instantaneous vibration amplitude measured by a displacement transducer is,

$$d = \frac{D}{2} \times \sin(\omega t)$$

d = instantaneous displacement

$\omega = 2 \pi f$ ,   f = frequency (Hz) , t = time (sec)

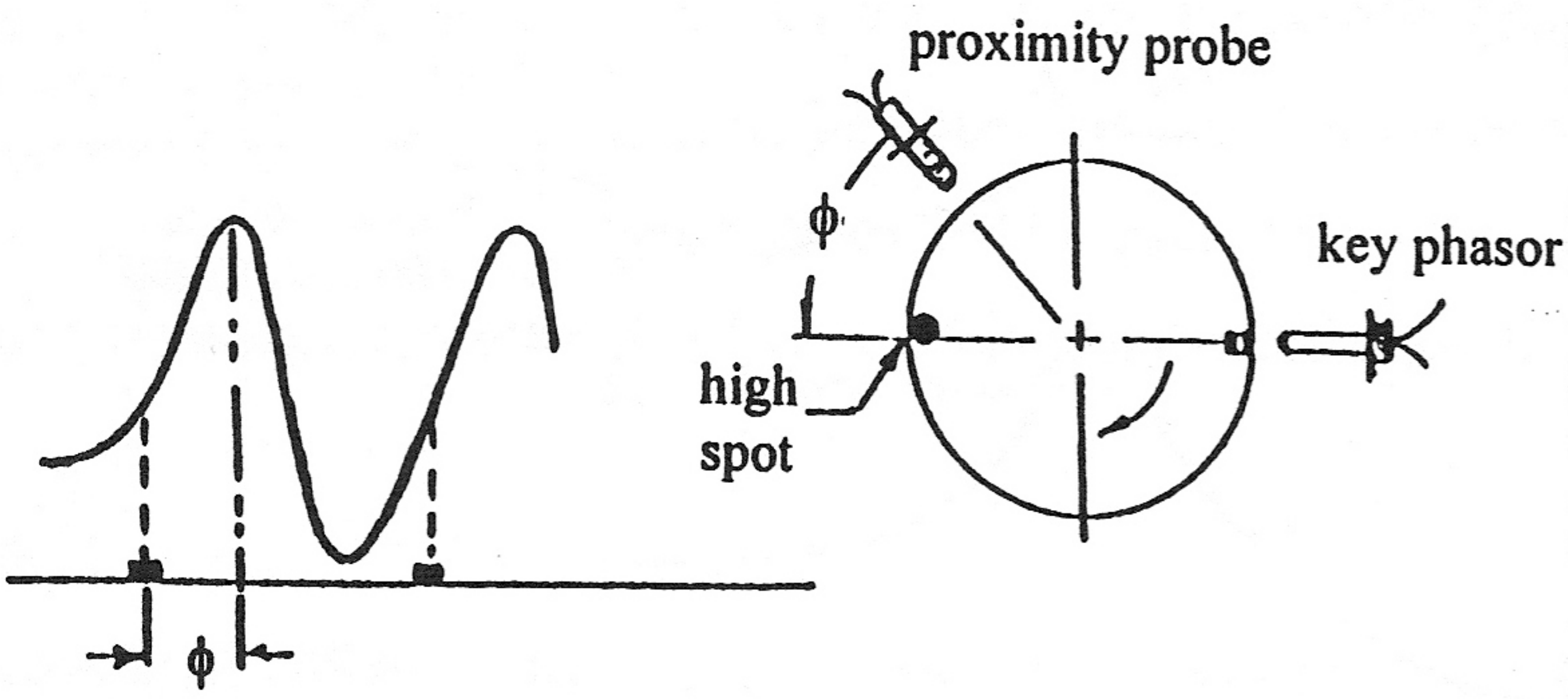
D = Peak-to-Peak displacement

Note: using displacement for balancing simplifies phase measurements and calculation of correction weight placement

# Field Balancing

## Proximity probe measurement

- No electronic phase lag between signals with mechanical phase lag



# Field Balancing

## Single Plane Balancing – Vibration Measurements

The instantaneous vibration amplitude measured by a velocity transducer is,

$$\text{v} = \frac{d}{dt}d = \frac{\omega D}{2} \times \cos(\omega t)$$

v = instantaneous velocity

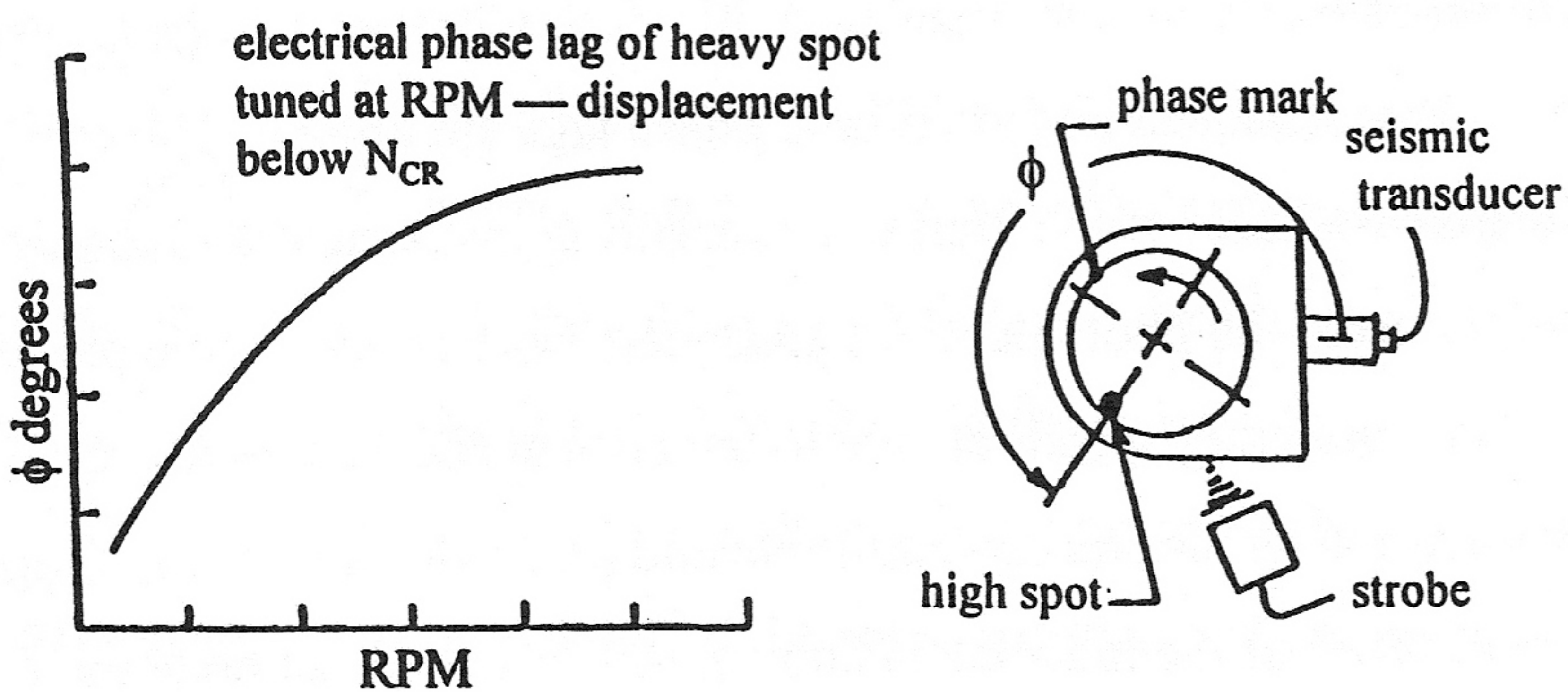
$\omega = 2\pi f$ , f = frequency (Hz) , t = time (sec)

D = Peak-to-Peak displacement

# Field Balancing

## Strobe/velocity measurement

- With both electronic and mechanical phase lags



# Field Balancing

## Single Plane Balancing – Vibration Measurements

The instantaneous vibration amplitude measured by an accelerometer transducer is,

$$a = \frac{d}{dt}v = \frac{-\omega^2 D}{2} \times \sin(\omega t)$$

a = instantaneous acceleration

$\omega = 2\pi f$ , f = frequency (Hz) , t = time (sec)

D = Peak-to-Peak displacement

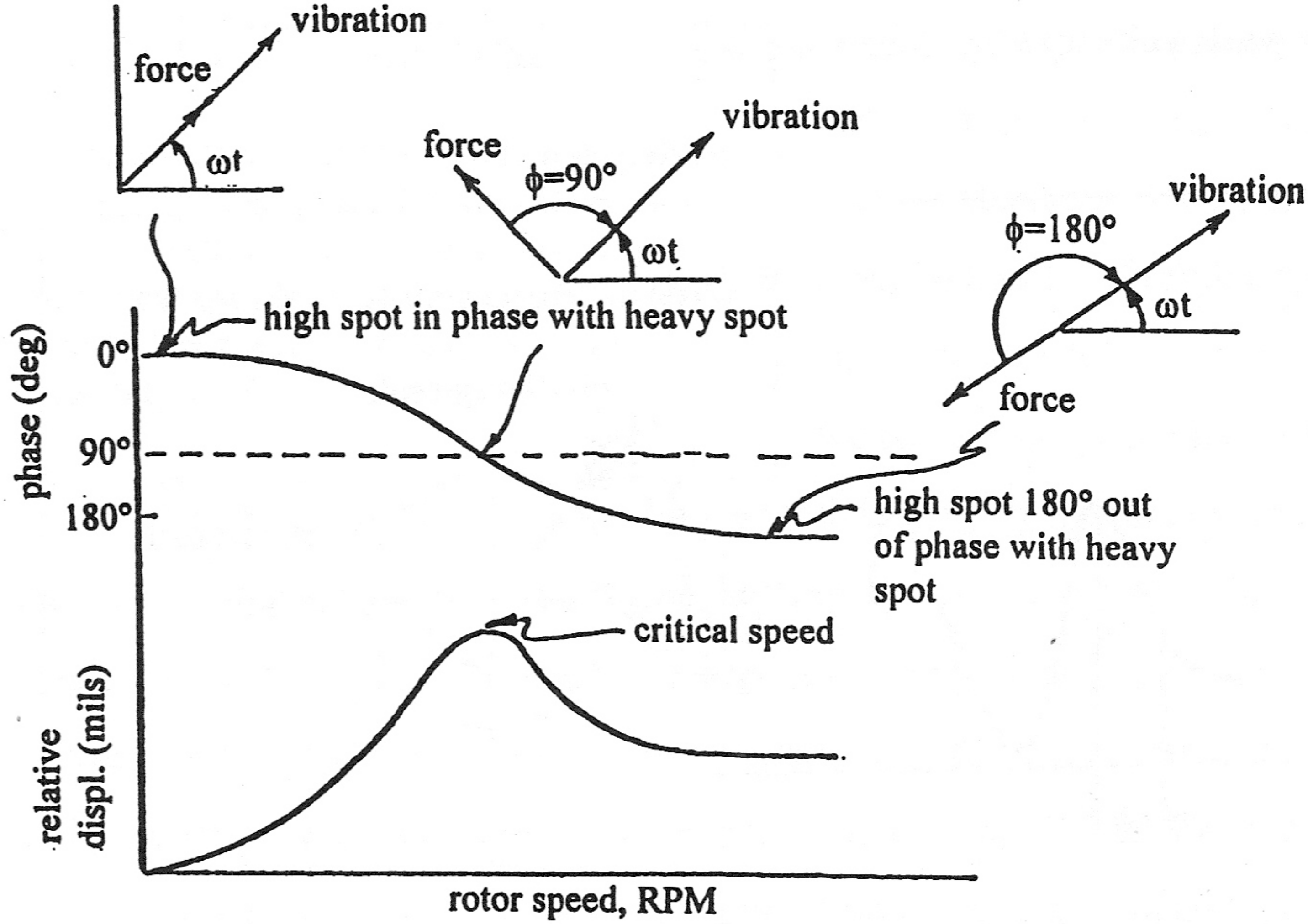
# Mass Unbalance and Phase Relationships

The force by mass unbalance (heavy spot) leads the vibration peak (high spot) by 0º to 180º depending the operating speed

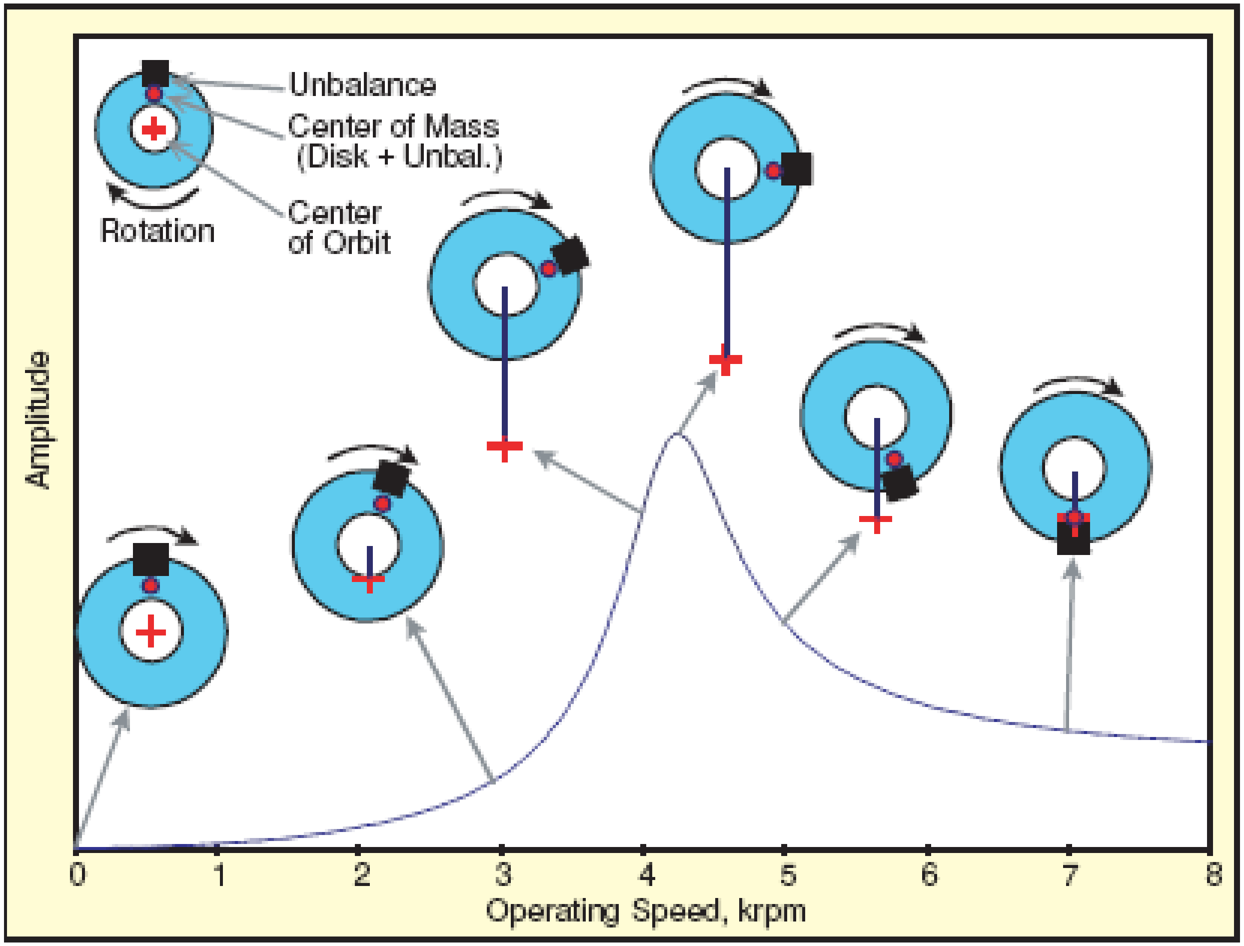
- 0º - 90º : operating speed is less than the first critical speed
- 90º: operating speed is close to the first critical speed
- 90º - 180º: operating speed is beyond to the first critical speed

# Mass Unbalance and Phase Relationships

Heavy/high spot relationship – mechanical phase lag



# Mass Unbalance and Phase Relationships



# Mass Unbalance and Phase Relationships

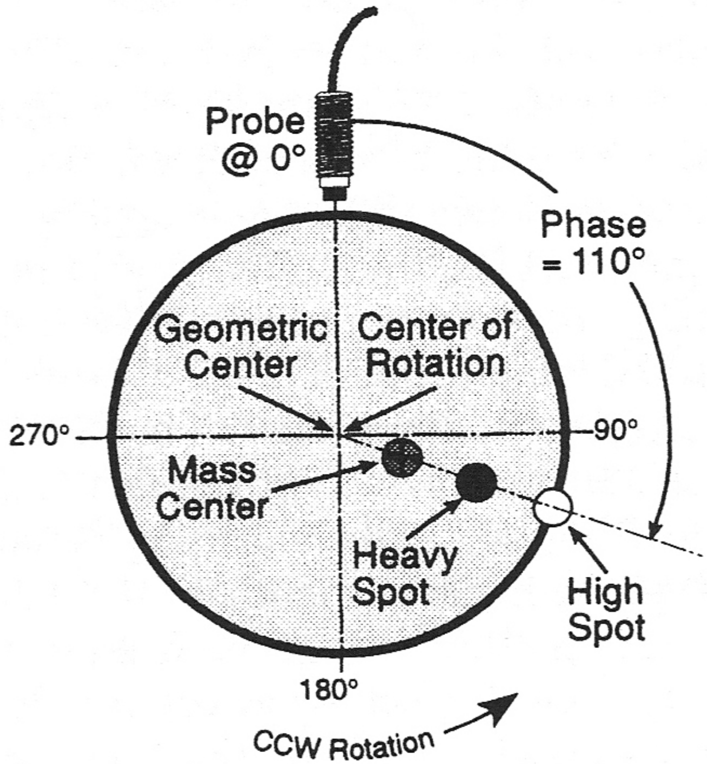



Fig. 3–39 Simple Rotor Operating Well Below The Shaft Critical Speed

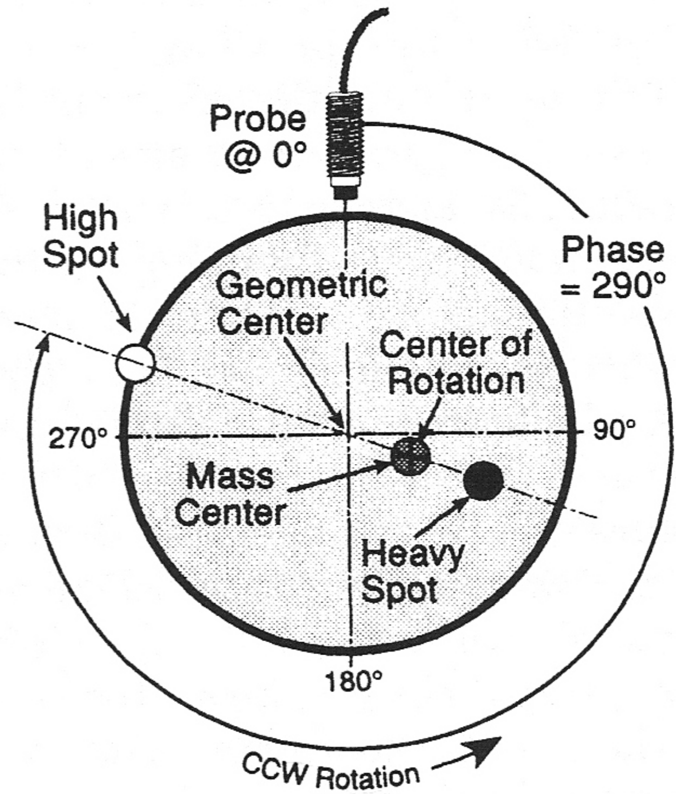



Fig. 3–40 Simple Rotor Operating ' Above The Shaft Critical Speed

# Mass Unbalance and Phase Relationships

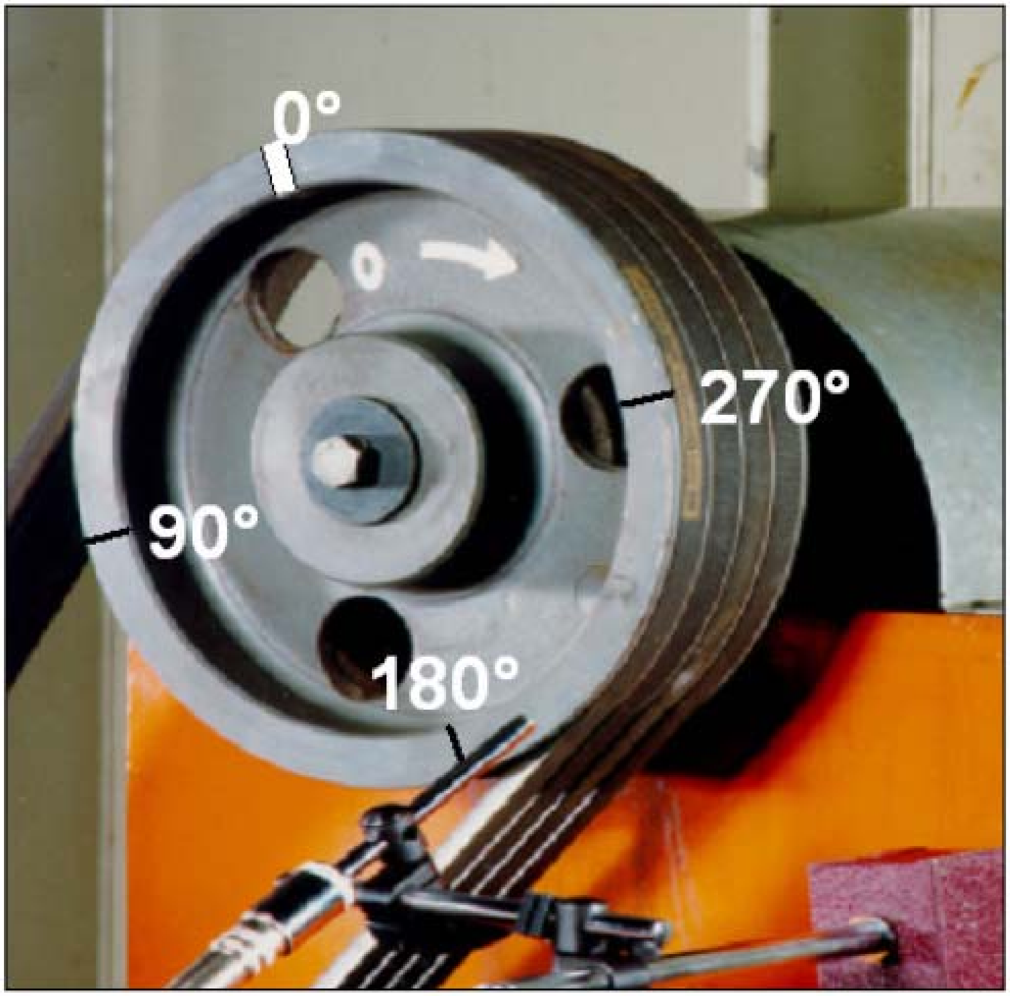



*Figure 3.5: Establishing the angle and speed reference with a photo-electric sensor and a reference mark (reflective tape)*