MACHINE VIBRATION STANDARDS: OK, GOOD, BETTER & BEST

Part 1 – What causes vibration and why do we care about it?

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Part 1: Why do we care about machine vibration levels? What causes vibration?

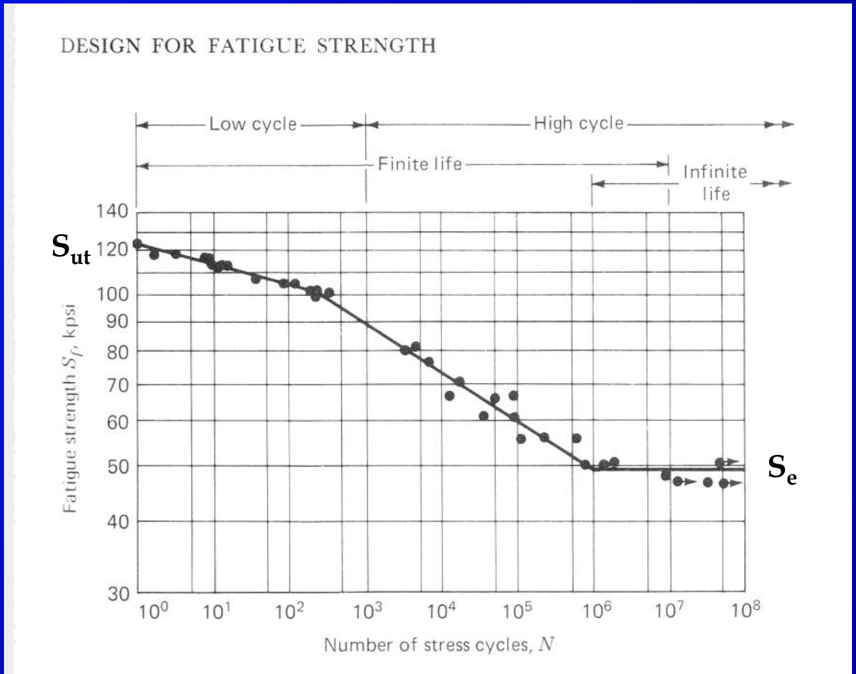
- A machine's vibration level "reflects" the amount of dynamic forces present in the machine.
- A machine is designed to withstand a certain level of dynamic force or dynamic stresses. Once this level is exceeded, expected machine life decreases and reliability suffers.
- **Total Forces = Static Forces + Dynamic Forces**.
- Examples of **static forces** in rotating machinery: weight or gravity, belt tension, pre-loads due to misalignment or improper installation, etc.
- Examples of **dynamic forces** in rotating machinery: unbalance, effects of looseness, a portion of the effects of misalignment, etc.

How vibration effects a material's strength (S-N diagram).

- The diagram below is known as a S-N diagram for materials. It shows the relationship between a material's strength (S) versus the number of loading cycles (N) it is subjected to.
- For most structural materials such as steel, iron, titanium, aluminum, etc, a material's strength (S) decreases with the number of loading cycles (N) until a limiting number of cycles (10^6 cycles @ 50 kpsi) known as the endurance limit (S_e) or fatigue limit is reached.
- Depending on the type of material used, the original design strength can be reduced by ½ to ¼ simply due to fatigue (from diagram ,120 kpsi → 50 kpsi).

- 3,600 rpm → 4.6 hrs to limit.
- 1,800 rpm → 9.25 hrs to limit.
- 900 rpm → 18.52 hrs to limit.

- Think of bending a paper clip. How many times can you bend it by 1/2" or so until it breaks?



S-N Diagram[1]

An example of conservative machine design for fatigue.

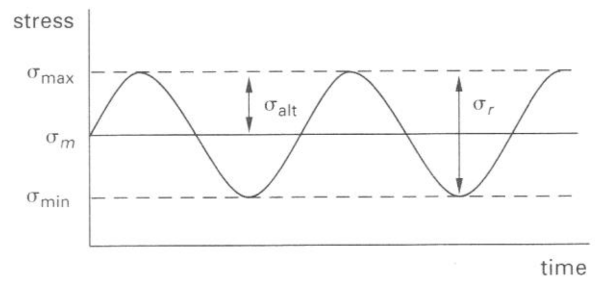


Figure 50.6 *Sinusoidal Fluctuating Stresses*

Fluctuating Stresses[2]

The *mean stress* is

Static Stress

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}$$

The *alternating stress* is half of the *range stress.*

Dynamic Stress

$$\sigma_r = \sigma_{\max} - \sigma_{\min}$$

$$\sigma_{\text{alt}} = \tfrac{1}{2}\sigma_r = \left(\tfrac{1}{2}\right)(\sigma_{\max} - \sigma_{\min})$$

-Higher vibration levels <u>reflect</u> higher alternating (dynamic) stresses.

-As either the mean (static) or alternating (dynamic) stresses rise, the <u>real</u> factor of safety in the machine design drops.

- So, for a <u>designed</u> factor of safety (FS) such as 3 and a known endurance strength (S_e), we must keep our <u>real</u> mean & alternating stresses inside the Soderburg Line or other design limits to achieve our design life.

$$\text{FS} = \frac{S_e}{\sigma_{\text{eq}}} = \frac{S_e}{\sigma_{\text{alt}} + \left(\frac{S_e}{S_{yt}}\right)\sigma_m}$$

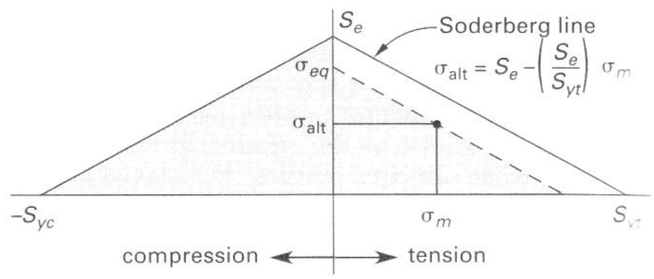
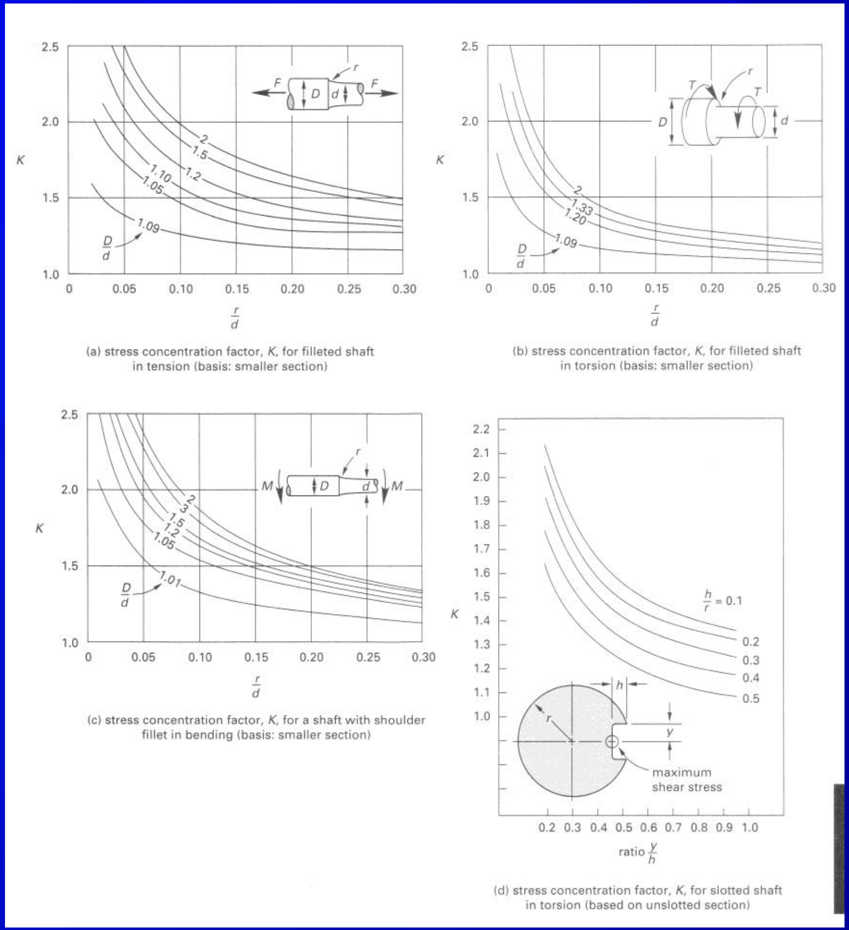


Figure 50.7 *Soderberg Line and Equivalent Stress*

Soderburg Line[2]

Additional factors effecting a material's endurance strength.

- In addition to the amount of fluctuating stress a machine is subjected to, other factors exist that effect it's life such as:
- **Stress Concentration Factors**: Discontinuities or irregularities in the design or geometry of a part that cause an amplification or rise in localized stresses (see plot at right for examples).
- **Surface finish**: Generally, the more smooth a material's surface is finished or polished, the less it's strength is reduced.
- **Corrosion**: Corrosion has particularly nasty effects on a material's strength in that unlike the other factors mentioned above, corrosion tends to **continually** reduce a material's endurance strength overtime until failure inevitably occurs. There is no fatigue limit for a part subjected to corrosion. Minimize corrosion![1]



Calculation of common stress concentration factors[2]

Two examples of shaft failure by fatigue (bending stress with corrosion):

- This is what fatigue failure looks like on a shaft subjected to both bending stress and corrosion.
- In both cases over half of the shaft area had already been lost due to fatigue (crack propagation) before final failure occurred.

Example of shaft failure by fatigue (torsion with stress concentration @ keyway):

- Note how the crack started at the keyway and propagated out from there. Ultimate failure of the shaft occurred after roughly 25% of the shaft area had been lost.

How bearing life is effected by both dynamic loading & machine speed.

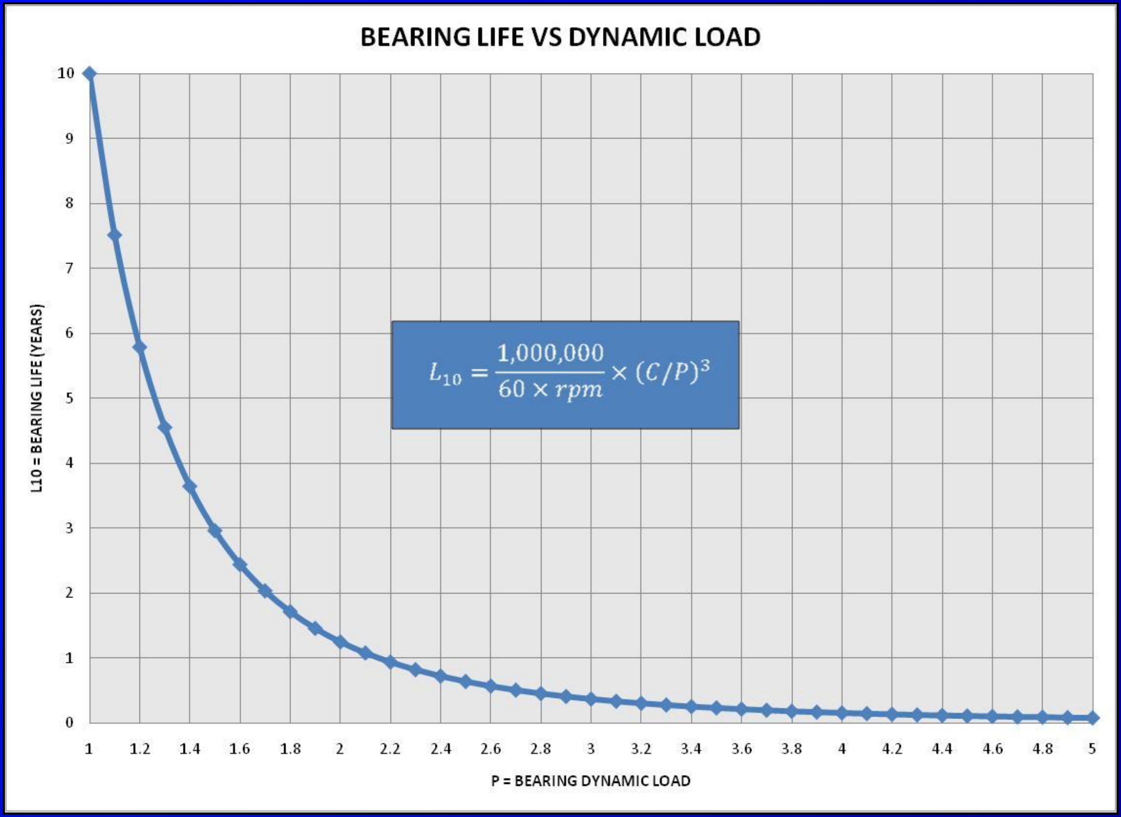
From the SKF products catalog[3], we learn that a given bearing's life expressed in hours of continuous operation can be estimated as:

$$L_{10} = \frac{1{,}000{,}000}{60 \times rpm} \times (C/P)^3$$

C = A bearing's basic dynamic load rating (found in catalog).

P = Equivalent dynamic bearing load.

rpm = machine speed (rpm)



Two examples of common bearing failures:

Outer race fault (spalling) on a spherical roller bearing.

Inner race fault (spalling) on a triple race spherical roller bearing.

Besides the dynamic forces present, what other factors effect vibration levels?

- The dynamic forces present in a machine are only one of many factors that effect the amount of vibration measured at a machine.

- The amount of vibration measured at a machine depends on at least the following factors:

1) Amount of dynamic force (F_o).
2) System mass (m).
3) Stiffness of mechanical system (k).
4) Damping in mechanical system (c).
5) How (if at all) do the frequency(s) of the driving dynamic forces <u>interact</u> with any system natural frequencies?

The equation of motion for a damped single degree of motion system driven by a harmonic force is as follows in two forms[4]

Inertial Force

Spring Force

$$m\ddot{x} + c\dot{x} + kx = F_o \cos \omega t$$

Damping Force

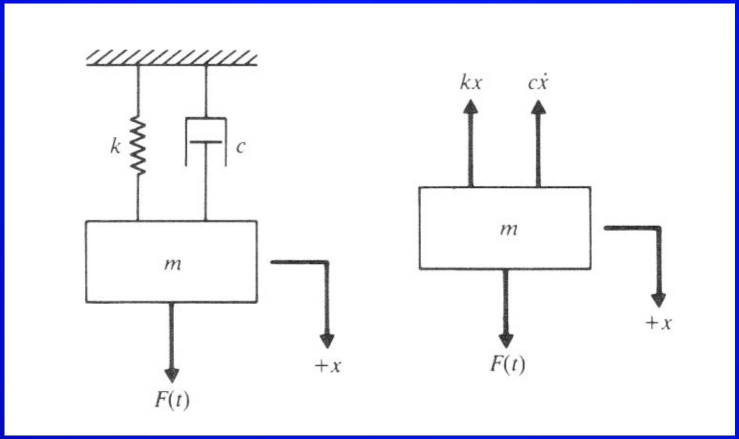
Dynamic Force

$$\ddot{x} = (F_o \cos \omega t - c\dot{x} - kx)/m$$

Same equation solved for acceleration.

Force diagram & the effects of system natural frequencies on vibration levels

Force diagram of a damped single degree of freedom mechanical system driven by a harmonic force[4].

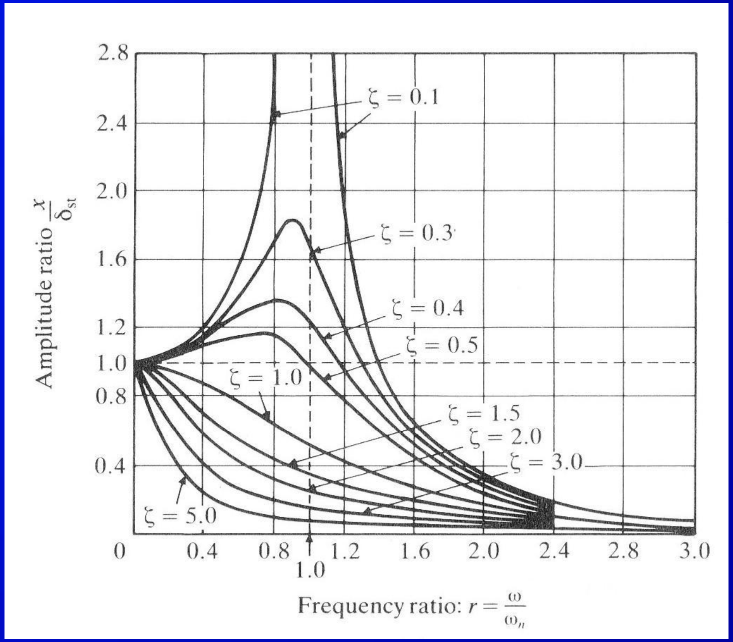


$$m\ddot{x} + c\dot{x} + kx = F_o \cos \omega t$$

ω = frequency of vibration (rad/sec) = $2\pi f$
ω_n = system natural frequency (rad/sec) = $2\pi f_n$
ξ = damping ratio = damping/critical damping

$\omega_n = \sqrt{k/m}$ = Undamped natural frequency

Transmissibility diagram showing the effect of a resonance on vibration levels[4]. Resonance acts as a mechanical amplifier of vibration.



$\omega_d = \omega_n\sqrt{1-\xi^2}$ = Damped natural frequency

The effect of system natural frequencies on vibration levels

If we let $r = \frac{\omega}{\omega_n}$ then the response of a damped mechanical system under a harmonic force is:

$$x(t) = X \sin(\omega t - \varphi) = Harmonic\ motion$$

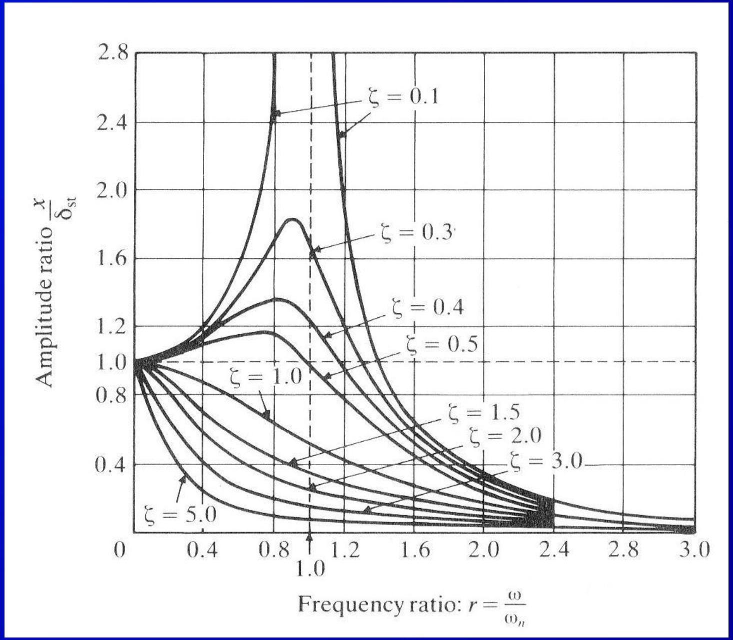
ξ = Damping Ratio = Damping / Critical Damping

X = Maximum displacement

F_o = Static Force

k = System stiffness

$$X = \frac{F_o/k}{\sqrt{(1-r^2)^2+(2\xi r)^2}}$$



How higher vibration levels tend to increase maintenance costs ($):

Higher vibration levels reflect the presence of higher dynamic forces & stresses on machinery.

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Dynamic forces & stresses on machinery that exceed design levels result in reduced machine life.

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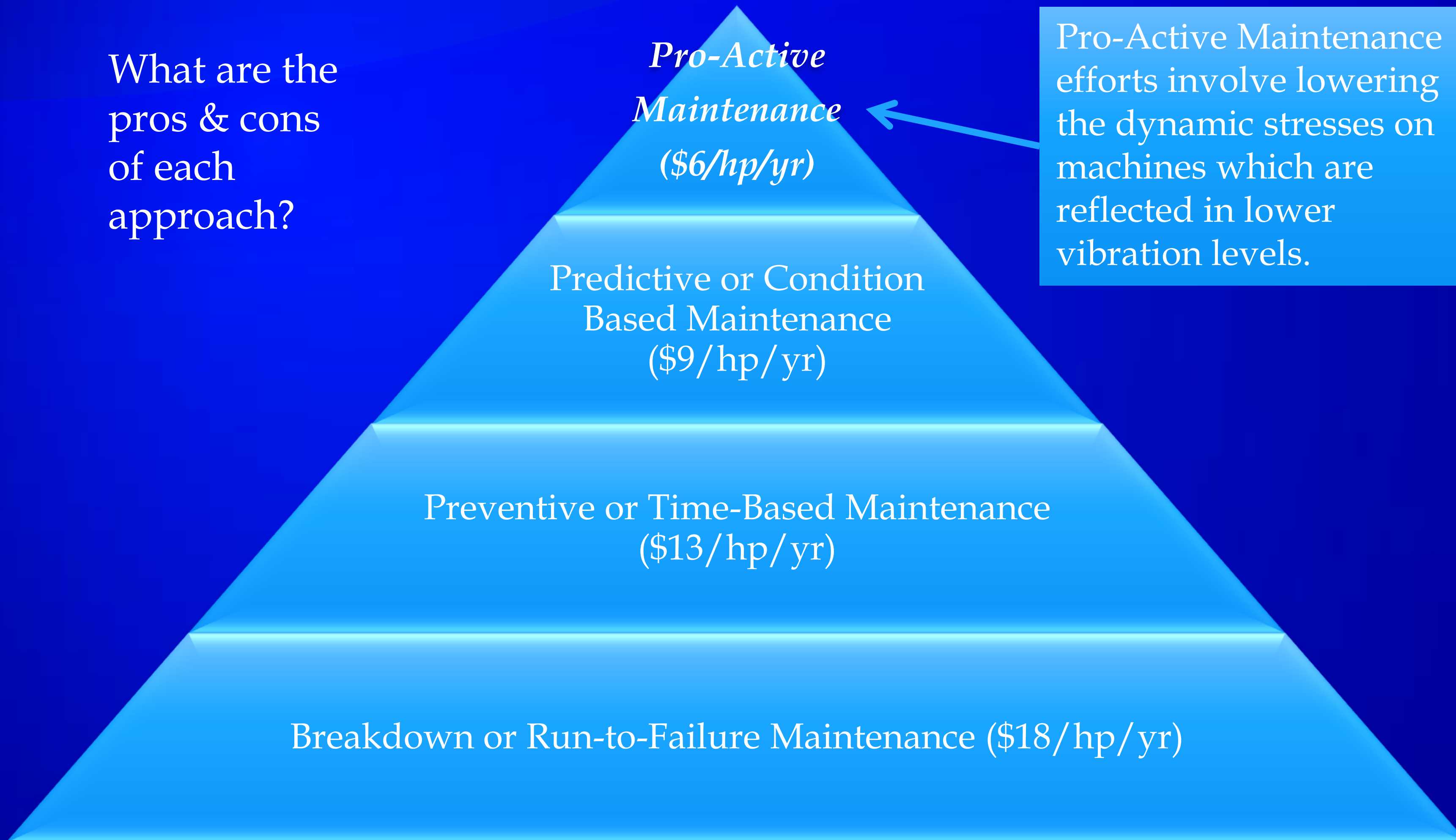
Shorter machine life results in repair & replacement costs ($) occurring more frequently overtime and thus causing much higher total operating costs over a given time frame (5-10 yrs, etc).

- Another particularly nasty quality commonly associated with machines exhibiting high vibration levels is ***their tendency to fail unexpectedly*** resulting in the following additional costs to the plant:

1) A potential loss of plant production as a result of unscheduled machine failure that interrupts a process.
2) A real possibility of machine failure occurring at a time when repair resources (labor or materials) are not available.
3) Machine damage is typically more extensive & costly to repair if the machine is allowed to run to failure.

A related discussion involving the relative costs of implementing different maintenance philosophies[5]:

What are the pros & cons of each approach?



Pro-Active Maintenance efforts involve lowering the dynamic stresses on machines which are reflected in lower vibration levels.

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2) Lindeburg, Michael   Mechanical Engineering Reference Manual, Tenth Edition, Chapter 50, Failure Theories, Professional Publications, Inc, CA, 1998

3) SKF Bearings & Mounted Products Catalog, Publication 100-700, p. 16, SKF USA, PA, 2002

4) Rao, Singiresu   Mechanical Vibrations, Second Edition, Chapter 3, Harmonically Excited Vibration, Addison-Wesley Co, MA, 1990

5) Piotrowski, John   "Pro-Active Maintenance For Pumps", Pumps & Systems, February 2001