Vibration versus Bearing Life

Machinery professionals intuitively know that by doing alignment and balancing jobs to tighter tolerances, and by reducing internal clearances in machinery, that vibration levels will be reduced with a corresponding increase in machinery reliability. However, it is often difficult to justify what needs to be done.

Alignment and balancing jobs are often skipped or postponed because everyone is in a hurry to get the process back up and running. Entire vibration programs are scrapped because no one can document how much, if any, payback is occurring.

Reliability and replacement costs for rolling element bearings are major concerns in most plants. By examining the additional forces that mechanical problems exert on a bearing, we can estimate the bearing's useful life reduction.

For those involved in predictive maintenance activities, especially vibration monitoring and analysis, two questions have always been present.

- What is the correlation between changes in vibration level and the corresponding impact on bearing life?
- What is the value in knowing this correlation if there is one?

There is a direct correlation between vibration level changes and bearing longevity! A simplified definition for vibration can be phrased as follows.

Machine Vibration: A Dynamic Response to a Dynamic Force!

It is critical to note that typically vibration responds to a dynamic force in a linear fashion. Exceptions include machines where structural resonance, shaft criticals, component looseness, etc., occur.

Seven predominant factors impact rolling element bearing life:

- RPM of the shaft
- Design load rating of the bearing (as defined by the manufacturer)
- Type of rolling element bearing (ball or other rolling element type-cylindrical roller, spherical roller, needle roller, tapered roller)
- Actual load (force) applied to the bearing
- Lubricant ability
- Contamination level
- Operating temperature.

BASIC BEARING LIFE EQUATION

Examining the basic bearing life equation we find that speed, load and the type of bearing are factors:

L_{10h} = (16667 / rpm) x (C / P)^r

Where:

- L_{10h} = 90th percentile of life in hours (the point at which only 10 percent of bearings in identical applications fail); Note: average life = 5 x L_{10h}
- Rpm = Rotational speed of the bearing
- C = Published catalog load rating
- P = Effective load (actual force applied to the bearing)
- r = 3 for ball bearings
- r = 3 1/3 for other types of rolling element bearings

First, let's investigate the impact of rotational speed on bearing life. Reviewing the basic bearing life equation:

L_{10h} = (16667 / rpm) x (C / P)^r

The impact of increasing speed is obvious. Doubling the rotational speed (while maintaining a constant load) = L_{10h} / 2 = 1/2 the original life.

Rule: *Bearing life is inversely proportional to speed changes.*
(1 / speed change ratio)

Examples:

2 x rpm = 1/2 life
3 x rpm = 1/3 life
1.25 x rpm = 0.8 life

Next, we need to investigate the impact of load on bearing life. Reviewing the basic bearing life equation again: L_{10h} = (16667 / rpm) x (C / P)^r. The impact of increasing load (force) is pronounced. Doubling load (while maintaining a constant speed) = L_{10h} / 8 or 1/8 life (1/2)^3 for ball bearings.

Rule: *Increased load results in an inversely exponential reduction in life!*

TABLE 1

IMPACT OF INCREASED LOAD ON BEARING LIFE

	Percentage Life Decrease	
% Load Increase	Ball Bearings	Other Rolling Element Bearing Types[1]
5	14	15
10	25	27
15	34	37
20	42	46
25	49	52
50	70	74
75	81	85
100	87	90

[1] Other rolling element bearing types include cylindrical, spherical, tapered and needle bearings.

To calculate the impact on bearing life for other percentages of load change, the following formulae may be used:

Ball Bearings:

- % Bearing Life Decrease = $(1 - (1 / (1 + (\% \text{ Load Increase} / 100)))^3) \times 100$

Other Rolling Element Bearing Types:

- % Bearing Life Decrease = $(1 - (1 / (1 + (\% \text{ Load Increase} / 100)))^{3\,1/3}) \times 100$

VIBRATION FORCES

Since we now know:

1. Vibration is a dynamic response to a dynamic force, and
2. An increase in force is extremely detrimental to bearing life,

then, we also know that an increase in vibration (which results from an increase in forces) produces a corresponding decrease in bearing life which can be calculated. Also, if we know the source of the vibration and can reduce or eliminate this force, then a subsequent increase in bearing life can be expected.

Rule: *Excessive vibration = excessive force = a dramatic reduction in bearing life!*

Table 2 lists the most common forces applied to rolling element bearings.

TABLE 2

FORCES AND SOURCES OF VIBRATION

Force Source	Type of Force	Reducible
Unbalance	Dynamic	Yes
Shaft Misalignment	Dynamic & Static	Yes
Belt / Drive Tension	Static	Yes, if Excessive Tension is Present
Looseness	Dynamic	Yes, if Excessive Looseness is Present
Rotor Weight	Static	No, Not Normally
Gear Reaction	Dynamic & Static	No
Process Forces	Dynamic & Static	No, Not Normally

Of these seven different forces, only the first four can normally be addressed by the maintenance department. The other three are machine design related and are not normally reducible. In order to classify the severity of each of the four force sources which maintenance practices can reduce or eliminate, we must understand the nature of the forces which are created.

UNBALANCED FORCES

Unbalance is one of the primary sources of machine vibration. The force produced due to unbalance can be calculated using either of the following formulae:

$F_{lbs.}$ = 1.770 x (rpm / 1000)^2 x U oz. In.

or

$F_{lbs.}$ = 0.062 x (rpm / 1000)^2 x U gm. In.

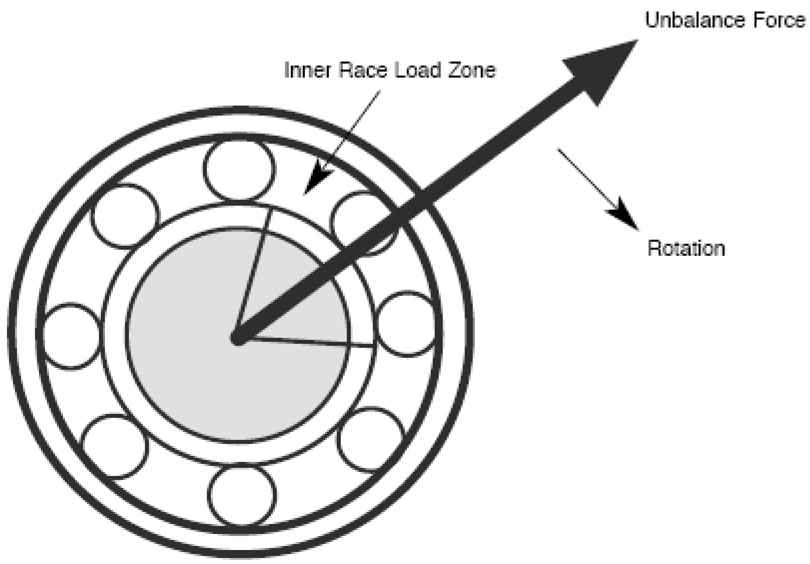
Where:

1 oz. in. = 1 oz. of mass @ 1 in. of radius from centerline of rotation
1 gm. in. = 1 gm. of mass @ 1 in. of radius from centerline of rotation

Example:

1 oz. of unbalance @ 36 in. of radius (72 in. dia.) on a 2000 rpm blower produces 255 lbs. of radial force.

Because unbalance is a rotating load, the bearing's inner race is zone loaded. This is a different type of loading compared to most of the other force sources.



Because unbalance is a “rotating load or force”, the following conversion must be made to use this force in the bearing life equation:

$P = F_{lbs.} \times f_m$

Where:

$F_{lbs.}$ = Force due to unbalance
f_m = Factor of 1.0 to 1.5 according to the ratio of static force compared to the unbalance force on the bearing (When this ratio is 1.0 then the factor is 1.333)

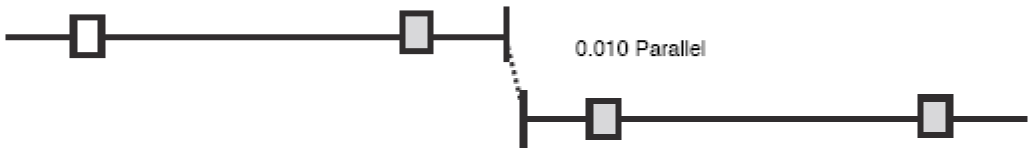
Rule: *Unbalance is up to 50 percent more destructive to bearing life than other vibration sources producing equal vibration levels.*

MISALIGNMENT FORCES

Calculating the forces due to shaft misalignment is a far more difficult task than this text needs to address. However it is worthy to note that the following simple rule always applies when misalignment is present.

Rule: *Any parallel or angular misalignment produces radial and axial forces.*

The following misalignment situation illustrates the severe nature of static misalignment forces. (The dynamic forces are the ones that produce vibration.) Note that the static forces due to misalignment are similar to U-joint systems which are misaligned identically.



Torque = Force x Distance

or

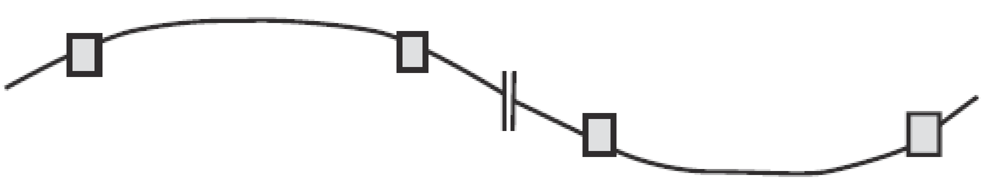
Force = Torque / Distance (essentially the same as cranking force)

Example:

For a 20 hp drive with 0.010 in. parallel misalignment: (assuming absolute shaft rigidity)
20 hp @ 1750 rpm = 1000 in. lbs. of torque
Force = Torque / Distance
Force = 1000 in. lbs. / 0.010 in. = 100,000 lbs.

We know that 100,000 lbs. of radial force would be instantly destructive to most 20 hp. drives. But we did assume absolute shaft rigidity which is a poor assumption because there are no absolutely rigid shafts or structures in machines.

ACTUAL MECHANICAL RESPONSE SHOWING SHAFT DEFLECTION (EXAGGERATED)



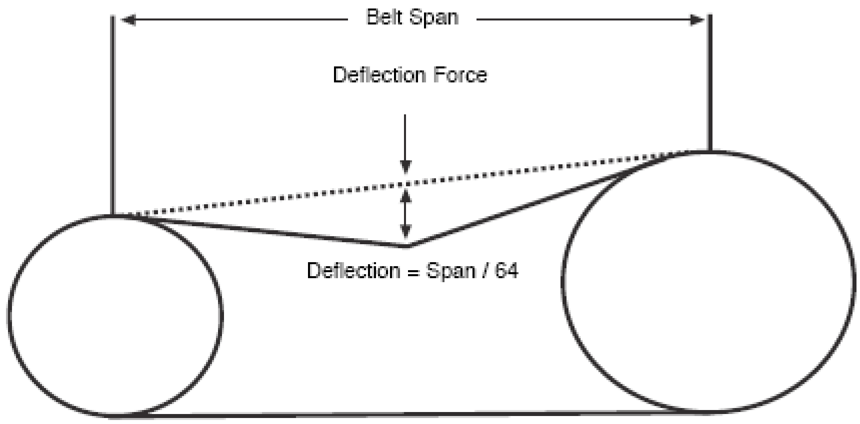
Assuming absolute shaft rigidity is really quite silly, isn't it? It is simply important to realize that misalignment produces forces which negatively impact bearing life as well.

V-BELT TENSION FORCES

A typical v-belt drive is tensioned using the force-deflection method to measure the relative tension of the belts. A belt is deflected for a distance of 1 / 64th of its span and the force to obtain this deflection is measured.

Using this general rule, the shaft force per belt applied at the sheave due to belt tension, equals 32 x the deflection forces. It should be noticed that horsepower does not enter into the equation at all. Belts should be tensioned so that they do not slip during startup or operation.

However most maintenance personnel simply apply their thumb or, at best, the deflection force values found in the belt manufacturer's handbook. Because of this, over designed drives produce excessive belt tension and shaft force regardless of the horsepower requirements. It must be noted that the overall shaft force does not change at all due to changes in horsepower levels and changes only slightly with increased speed (due to centrifugal forces in the belts).



Rule: *Shaft force = deflection force x 32 x number of belts.*

Table 3 provides some typical force values for v-belt drives.

TABLE 3

V-BELT TENSION FORCES

Manufacturers' Recommended V-belt Tension Levels

Belt	Deflecton. Force-lbs.[2]		Shaft Forces-lbs.	
Cross Sect.	Plain	Notched	Plain	Notched
A	3.5	4.5	112	144
B	5.1	6.5	163	208
C	12.0	14.0	384	448
D	25.0	26.0	800	832
3V	4.0	5.0	128	160
5V	10.5	13.0	336	416
8V	28.0	32.0	896	1024

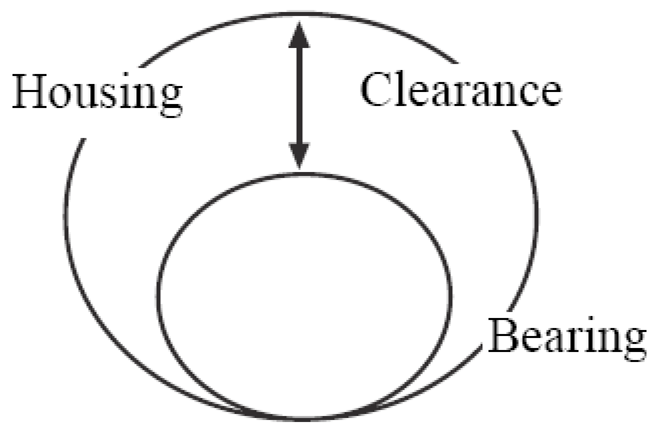
[2]Approximate average for all sheave sizes and manufacturers

It is obvious that v-belts produce a significant amount of force especially when using larger belt cross sections and multiple belts on the drive. Flat, synchronous, Poly-V and round belts also require significant levels of tension in order to operate.

Since belt tension is a static phenomenon, it creates little or no machine vibration. Since it is a force though, changes in tension can affect a machine's response to other vibration sources and a bearing's wear rate and noise level. These changes are minor and are poor indicators of the overall tension of the drive.

LOOSENESS FORCES

It is difficult to define the forces due to looseness of machine components. However, a simple case does demonstrate the possible magnitude of forces that could occur.



Looseness of a shaft within a bearing or a bearing within a housing can produce an unbalance equivalent to:

U = Clearance / 2 x rotor weight in grams or ounces

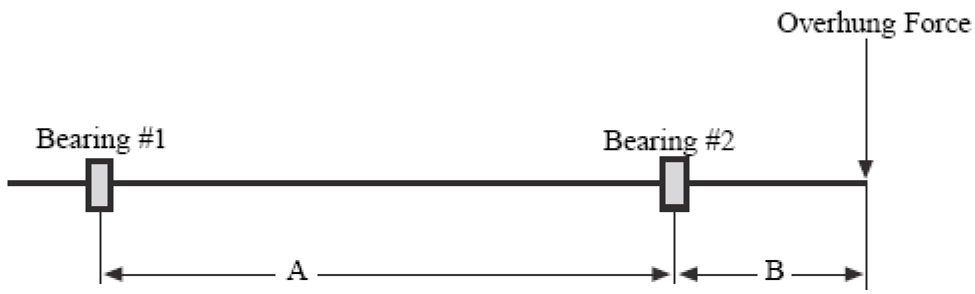
If a rotor weighing 100 lbs. or 1600 ounces were placed in supports where each allowed 0.020 in. of clearance with the shaft or the bearing, the subsequent unbalance would be equivalent to 16 oz. in. If the rotor turns 1800 rpm, the final unbalance force would be equal to 92 lbs. of force. Looseness also produces other force components which will not be addressed here.

MECHANICAL ADVANTAGE

Finally, seldom do unbalance, misalignment or belt tension produce forces in plane with the bearings themselves. These forces usually act at other positions along the shaft. Because of this, the actual force applied to the bearing as a result of mechanical advantage must be computed.

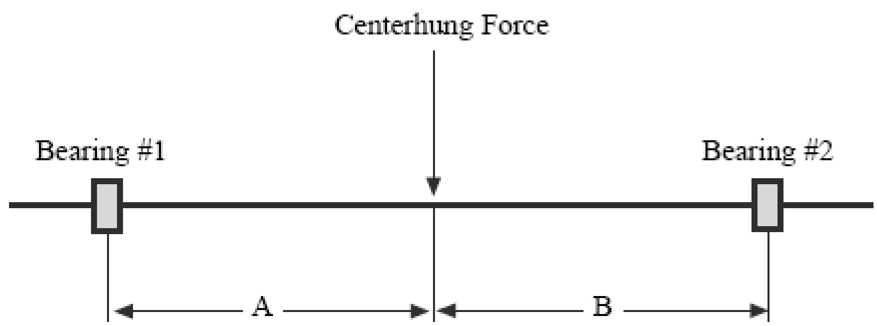
Overhung Forces:

Load at Bearing # 1 = Force x B / A
Load at Bearing # 2 = Force x (A + B) / A



Centerhung Forces:

Load at Bearing #1 = Force x B / (A + B)
Load at Bearing # 2 = Force x A / (A + B)



SUMMARY

Reducing the forces caused by unbalance, looseness and misalignment will result in lower vibration levels for machines. Reducing excessive belt tension will also reduce machine forces but will not produce an appreciable reduction in vibration level. The vibrations themselves have only a minor impact on bearing life but the forces which cause these vibrations, as has been shown, have a major impact on the actual bearing's longevity.

Table 4 details in graphic form the increase in bearing life which can be expected by addressing machinery problems and, by so doing, reducing both vibration levels and operating forces.

If the dynamic force component is not the major constituent of the total force acting on the bearing, then use the following formula:

% Reduction = % Vibration Reduction x Vibration Related Force / Total Bearing Force

To calculate the impact on bearing life for other percentages of vibration reduction, the following formulae may be used:

Ball Bearings:

$$\% \text{ Life Increase} = ((1 / (1 - (\% \text{ Load Reduction} / 100)))^{3} - 1) \times 100$$

Other Rolling Element Bearing Types:

$$\% \text{ Life Increase} = ((1 / (1 - (\% \text{ Load Reduction} / 100)))^{3\ 1/3} - 1) \times 100$$

APPLICATIONS

A predictive maintenance technician or manager may use Table 4 and the information contained in this article in a variety of ways.

TABLE 4

IMPACT OF VIBRATION REDUCTION ON BEARING LIFE

(Assuming dynamic load is the major force component)

	Percentage Increase in Bearing Life	
% Reduction in Vibration	Ball Bearing Types	Other Rolling Element Bearing
5	17	19
10	37	42
15	63	72
20	95	110
25	137	161
30	192	228
40	363	449
50	700	908

Reports:

Balancing the Plant XXX Blower achieved a 20 percent reduction in overall machine vibration. This corresponds to a 95 percent increase in blower bearing life and a corresponding reduction in maintenance costs.

Annual Program Justification:

The PDM program's record portrays an average reduction in plant-wide machinery vibration levels of five percent. This corresponds to a 17 percent increase in plant machinery life and a similar reduction in maintenance costs. Average maintenance costs for rotating machinery approached $550,000. This corresponds to an additional realized savings of $93,500 / year, which can be directly attributed to the predictive maintenance program. As the program continues to isolate problems and allow further reduction in average vibration levels, additional savings will follow.

Establishing Tolerances:

The rotor averaged a vibration level of 0.25 ips pk. for the past 2 years and bearing replacements were required each 6 months. The main component of the vibration is unbalance of the rotor and the rotor weight is nominal. Currently the rotor is balanced to a tolerance of ISO G6.3 or 2 oz. in. per plane. By adjusting this balance tolerance to ISO G3.2 or to 1 oz. in. per plane, the bearing life should be extended by 700 percent. Since the vibration should be cut in half as a result of the improved balance tolerance, I also suggest reducing the program alarm level for the machine to 0.13 ips pk. as soon as the new balancing tolerance is achieved.

As you can see, this data is not only pertinent to the day-to-day operation of a predictive maintenance program, but is invaluable as a gauge of program effectiveness, as a mechanism for establishing tolerances and as a yardstick for judging proper applications of corrective actions.

Once machine forces are corrected to minimum levels, the other three factors affecting bearing life (lubricant ability, contamination level and operating temperature) may be adjusted as well to achieve further improvements.

SECONDARY BENEFITS

In addition to improving reliability and reducing the cost of maintenance of machines, several more benefits are obtained by reducing vibration levels:

- Reduced Noise Levels
- Reduced Operating Costs (Utilities)
- Improved Operating Safety
- Improved Maintenance Technician Morale
- Increased Life for Related Machine Components (seals, housings, shafts, impellers, windings, etc.)
- Reducing vibration levels on machines by correcting common machine problems or applying tighter tolerances does indeed dramatically improve bearing life and reduce maintenance and operating costs.

—Article written by L. Douglas Berry in 12/95 issue of Reliability Magazine

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