Belt Vibration with Case Histories

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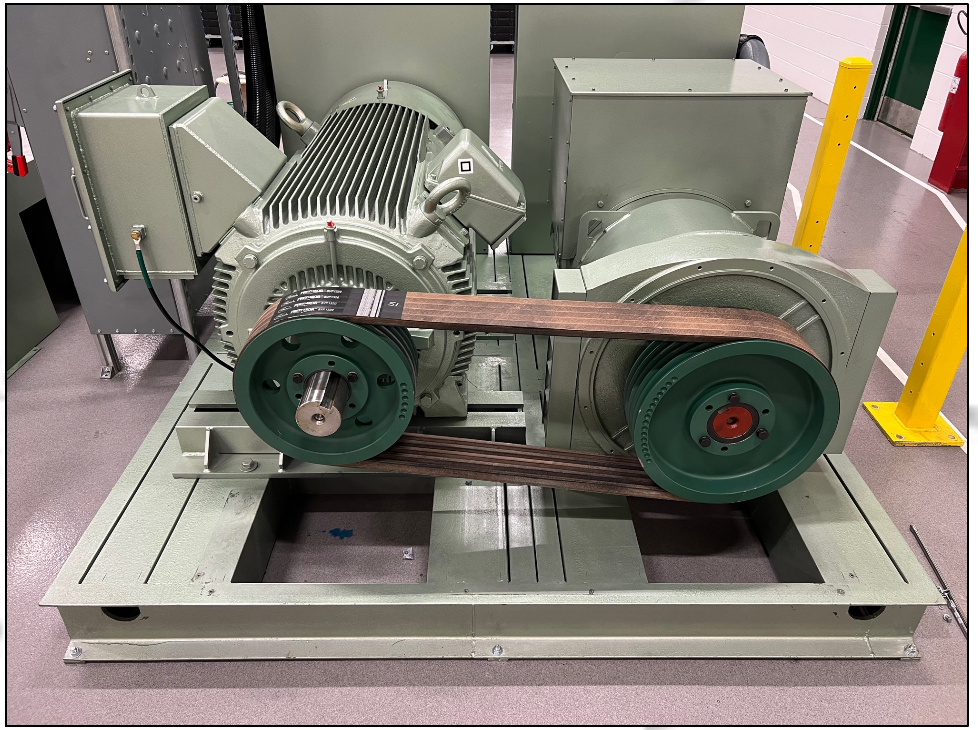
Examples Of Belt Drives

Motor-Generator Set



Cooling Tower Fan

Air Handling Unit (Fan)

Belt Drives

- Belt drives are used as an alternative to direct-drives for rotating equipment.
- These drives are relatively cheap and offer flexible machine speeds and ratios, etc.
- They also allow machine designers flexibility to fit machines in smaller spaces (ie: vertically, horizontally, etc) than those allowed by direct drives which can be a factor for machines like AHU fans that must fit in a small enclosure.
- Knowledge on how to install and maintain belt drives is not that difficult and generally understood by most maintenance personnel.

Belt Drive Design

- Engineers and machine designers try to design belt drives to attain a desired driven machine speed, but also to do this while maintaining a “proper” drive ratio.
- A <u>proper drive ratio</u> in machine design is considered one that allows for a relatively high ”arc of contact” around each sheave in the belt drive.
- Retaining a high “arc of contact” is important because it improves the <u>efficiency</u> of the belt drive by minimizing friction and reducing slip.
- Per machine design, an “ideal” drive ratio is 1:1 while those greater than 3:1 should be avoided.

The following formula is commonly used to size belt length for ”best drive efficiency”:

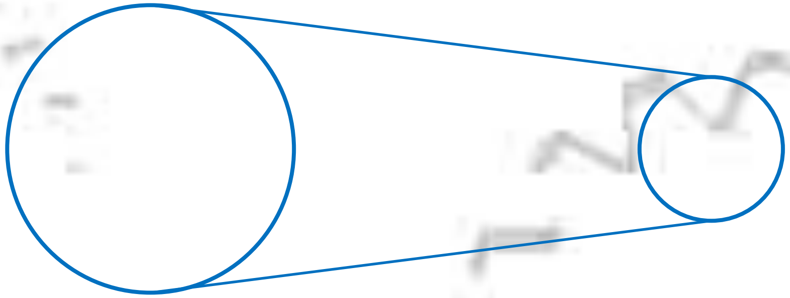
$$\boldsymbol{Belt\ Length = 1.6 * (3.5 * D + d)}$$

Where D = Diameter of largest sheave and d = Diameter of smallest sheave.

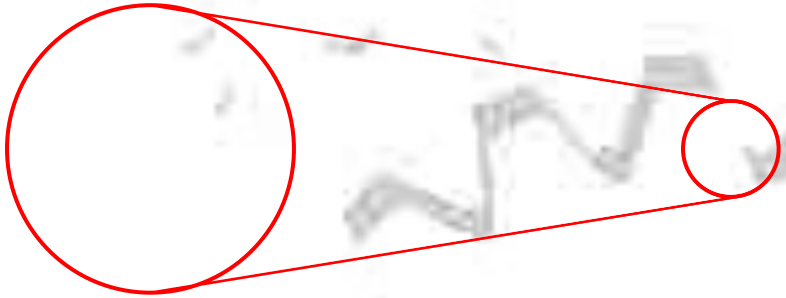
- *We will see in a later case study that while this formula may maximize the drive efficiency, <u>it unfortunately doesn’t take into account the vibration aspects of this design</u>.*

Belt Drive Ratios

”Ideal” Drive Ratio (1:1)
Same arc of contact at each sheave



Good Drive Ratio (2:1)
Large arc of contact



Bad Drive Ratio (3:1)
Arc of contact too small

Belt Speed

- For any piece of rotating equipment, knowing and not guessing its shaft speed is fundamental to analysis of its vibration.
- Therefore, knowing and not guessing the belt speed (frequency) is important to evaluating vibration of a belt-driven machine.
- The **first** thing to understand about the belt speed is that it will always be slower than the speed of either the driving or driven machine.
- *The simple reason for this is the diameter of the belt is always much greater than the diameter of either sheave within the drive.*
- Larger diameter sheaves turn at slower rpms while smaller diameter sheaves turn at faster rpms given a constant velocity belt operating on them (no slipping). As stated above, the diameter of the belt is much larger than the diameter of either of the sheaves it operates on, thus, it must have a much slower speed.

Belt Speed

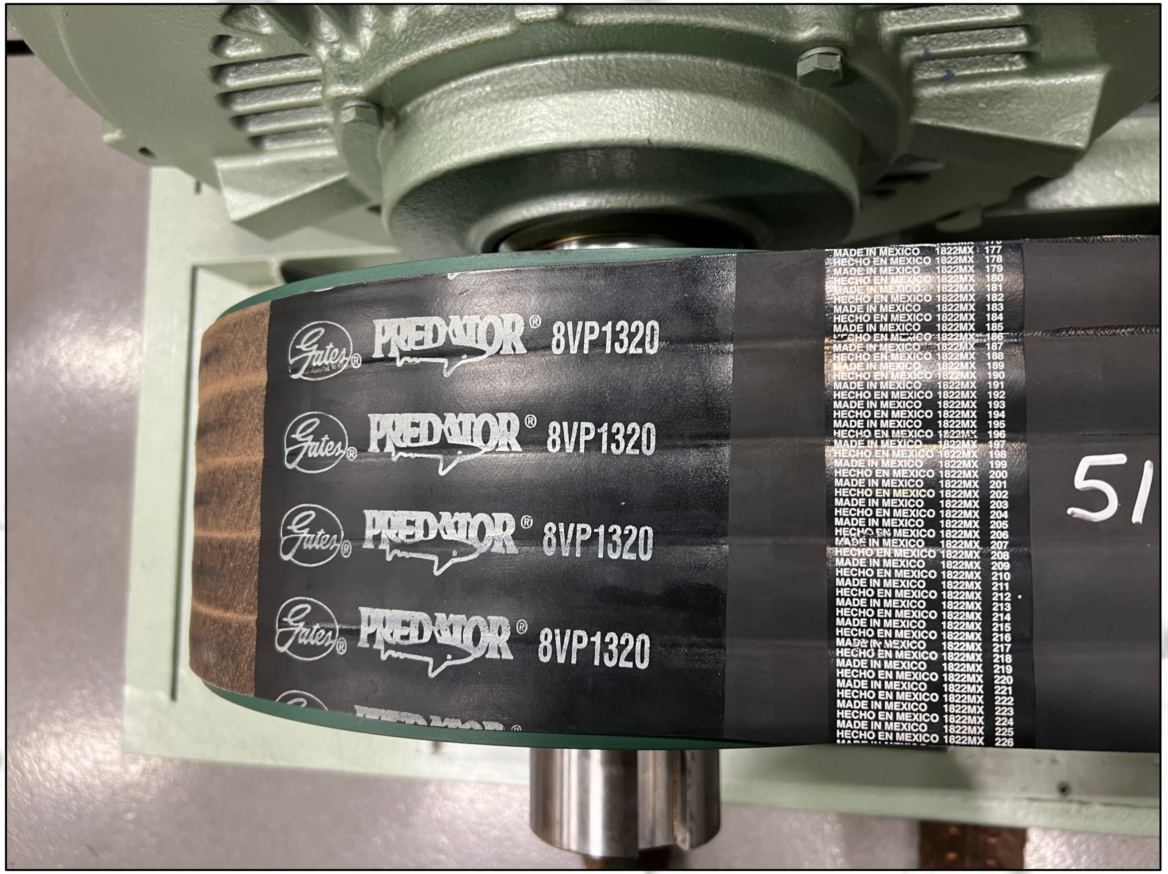
- Knowing that the belt speed will always be lower or slower than the speed of either sheave it operates on, we can say that the belt speed itself will always be **sub-synchronous** (below 1x rpm) to either sheave speed.
- The exact formula for determining the belt speed is as follows:

$$\textbf{Belt Speed (frequency, cpm)} = \frac{\pi * Sheave\ Diameter * RPM}{Belt\ Length}$$

Where the diameter and rpm must refer to the same sheave.

The units used for sheave diameter and belt length must be the same.

Example Of How To Determine Belt Length



- As an example of how to find the length of a belt, the picture at left is of a V-Belt drive from a motor-generator set.
- The following information can be obtained from this photo:
- Belt OEM: Gates
- Belt Model Name: Predator
- Belt Cross Section: 8VP (power band design)
- Effective Belt Length: 132.0 inches
- The effective belt length refers to the length (diameter) of the belt measured at the location where it actually runs (not exactly at the outside diameter).

Belt Length

- The belt length can be **estimated** using the simple formula below:

$$\textbf{Belt Length Estimate} \approx 2 * S + \frac{\pi * D1}{2} + \frac{\pi * D2}{2}$$

S = Distance between shaft centers

D1 = Diameter of sheave 1

D2 = Diameter of sheave 2.

- This formula works pretty good when the two sheave diameters are similar but not so good when they are quite different.
- The **exact** formula involves the use of trigonometric functions and can be found on pages 166, 167 & 168 of "The Simplified Handbook Of Vibration Analysis" by Mr. Arthur Crawford (excellent reference).

Belt Length (Estimate Example)

- Motor sheave diameter, D1 = 16”
- Generator sheave diameter, D2 = 19”
- Center to center shaft distance, S = 38”

Belt Length Estimate ≈ $\mathbf{2 * S + \frac{\pi * D1}{2} + \frac{\pi * D2}{2}}$ = 2*(38) + $\mathbf{\frac{\pi * 16}{2} + \frac{\pi * 19}{2}}$ = 131”

This example is the Gates Predator 8VP 1320 belt shown in the earlier slide. It’s actual length is 132” per spec, thus, our estimate of 131” versus an actual of 132” was within 1% (not bad).

This estimate worked out well due to the fact the two sheave diameters were fairly similar. If we had a 2x or greater difference between sheave diameters, we would still be within 10% or so in our estimate, but not the 1% accuracy shown here.

Belt Speed (From Estimated Belt Length)

- So given our estimate for belt length of 131”, and given our motor operates at ~ 1,800 rpm (4-pole motor not on VFD) with a motor sheave diameter of 16”, what is our belt speed?

Belt Speed (frequency, cpm) = $\frac{\pi * Sheave\ Diameter * RPM}{Belt\ Length} = \frac{\pi * 16” * 1800}{131”}$ = 691 cpm

- The motor in this example operates at 1,800 rpm and the generator it drives operates at 1513 rpm (50 Hz power) while our belt operates (rotates) at 691 rpm. See how the belt speed is much slower than either of the shaft speeds it operates with?

Belt Speed (Strobe-Light)

- Another way to determine the belt speed is by simply using a strobelight.
- It helps to "pre-tune" your strobe at a flash rate slightly below the speeds of either of the shafts and then slowly move **down** from there. You will have found the correct belt speed when the belt is frozen or moving very slowly. Remember the sheave you're measuring the speed near will be rotating when you've "frozen" the belt as it operates at a much higher rpm than the belt.
- This "strobelight" method of determining your belt speed relies of course on having a belt guard designed to allow observation of the belt and sheaves during operation.
- Too often the OEM or plant settles for a belt guard that allows little if any observation of the belt or sheaves during operation - this is unfortunate.
- Using expanded metal on the sides of a belt guard is a proven design that allows observation of the sheaves and belts during operation but still complies with all OSHA regulations.
- Another tip to good belt guard design is don't have it painted with a bright color like yellow, white or unpainted aluminum or stainless as using a strobe-light against such a bright background like this can be challenging.

Worn or Damaged Belts

- If your belt guard is designed well, detecting worn or damaged belts is relatively easy – just look at them. If they are worn, you will see them flopping all around and potentially making an excessive amount of noise during full speed operation.
- **Vibration analysis** can detect worn or damaged belts by noting excessive vibration at many multiples of the belt speed.
- Vibration at <u>even</u> multiples of the belt speed are most common due to the belts being "released" twice per revolution (two sheaves). This quick release of the belts by the two sheaves is analogous to performing an impact test on them exactly twice per revolution.
- It is also common as belts wear to see the belt strand frequency (resonance frequency) to be excited more than usual as you are again essentially performing an impact test on the belts twice per revolution.
- Essentially when your belts wear you have the beginning of a "negative feedback loop" in your drive. Belt wear leads to more vibration which excites your belt into a state of resonance which adds more vibration which overtime wears the belts more, etc – the worst is yet to come.

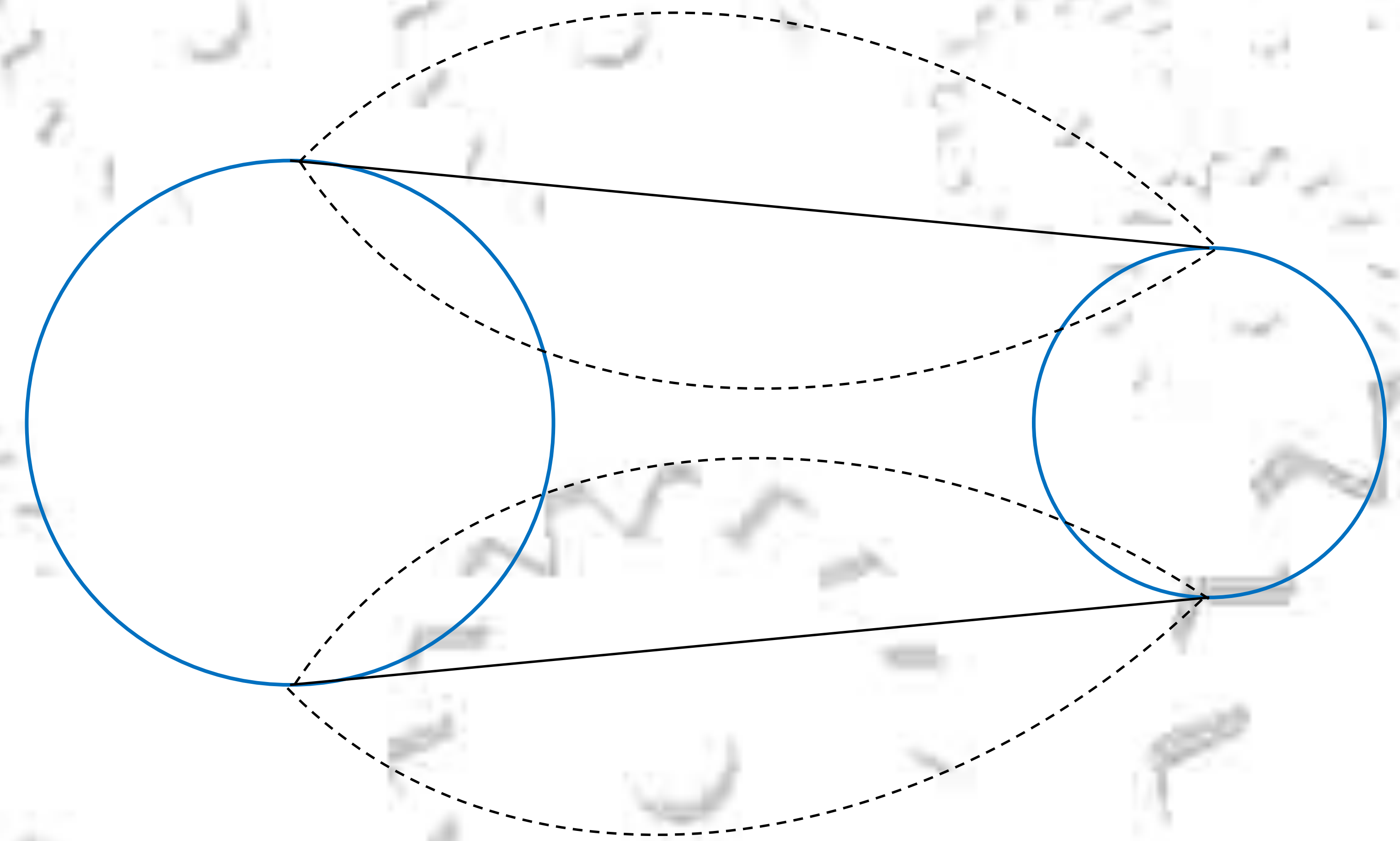
Worn or Damaged Belts

- When installing new belts it is always preferred to install a "**matched set**" and not one or two new belts on say a three or four groove belt drive. By using a matched set, you ensure (to the best of your ability) that all the belts were made at the same time and to the same specification (similar length and stiffness).
- Be aware that the belts in your drive are not the only wearing component - ***the sheaves on your belt drive wear also.***
- As the sheaves wear, they progressively make it easier for your belts to slip requiring more tension to keep them tight. More tension means higher loading and shorter bearing life. For V-belt sheaves, be aware that the belts are not designed to be making contact with the bottom of the sheave grooves. If you see a shiny surface at the bottom of your sheaves, it's past time to change them.
- It has been suggested to replace your sheaves at every second or third belt change.
- When installing new sheaves, **ensure they have been balanced for service** at the correct rpm of the machine. At least an ISO G2.5 balance tolerance should be required at the appropriate operating sheave speeds.

Belt Strand Frequency (Resonance)

- In addition to knowing the belt length and belt speed, it is quite helpful to measure the **belt strand frequency** or **belt resonance frequency**.
- This belt strand frequency is simply the **first bending mode** of your drive belts and is analogous to the frequency or pitch a guitar string sounds out at when it is plucked.
- ***It turns out to be quite important to measure this belt strand frequency because too often machine designers unfortunately aren't taking this into consideration.***
- Like any other resonances say of the machine, its base or supporting structure, if we have a dynamic force within about 10 to 20% of the belt strand frequency, it will be excited into a state of resonance resulting in significantly higher vibration levels on both machines (driver & driven) and as an added bonus shorter belt life.
- Belt resonance problems are more common than you think in part because machine designers don't seem to be taking them into account.

Belt Strand Frequency (Resonance)



Measuring Belt Strand Frequency (Resonance)

- Measuring the belt strand frequency (resonance) is relatively easy once the machine is down, locked out and the belt guarding removed:

1) Place your vibration sensor on either the motor or driven machine's sheave-end bearing in the direction of the belts.
2) Place your analyzer in "Peak-hold" mode, set it up to take 50 or more averages.
3) Before you begin plucking the belts, it helps to look at your analyzers display to see what vibration exists before you begin your plucking. Having an assistant to pluck the belts as you monitor the analyzer screen is best.
4) Begin "plucking" the belts at or near their mid-point.
5) Only after you begin plucking the belts, the belt strand frequency(s) and perhaps other natural frequencies will appear where they did not appear prior to you plucking the belts.
6) **You do not have to pluck the belts hard**, in fact, if you pluck them hard it may deteriorate the accuracy of your measurement and you run the increasing risk of also exciting structural resonances as well.
7) The tall peak or peaks you will see appear on your analyzer screen only when you pluck the belts will be your belt strand frequency(s).

- If any of these belt strand frequencies are within 10 to 20% of the speed of either the driving or driven machine, they are being excited and are a problem.
- **SEE MEASURING BELT STRAND FREQUENCY VIDEO**

Solving Belt Strand Frequency Problems

- Solving a belt strand frequency problem can be easy or difficult depending on how poorly your drive has been designed.
- Like any other natural frequency, the belt strand frequency can be moved up or down by simply increasing or decreasing its stiffness.
- We increase the stiffness of the belts by tightening them – this increases the belt strand frequency.
- We decrease the stiffness of the belts by loosening them – this decreases the belt strand frequency.
- The motor base designs of most belt drives allow for relatively easy tightening and loosening of the belts by movement of the motor position toward or away from the driven machine.
- **Whether you should tighten or loosen the belts depends on whether your belt strand frequency is slightly above or below the exciting speed in question. If the belt strand frequency ends up being pretty much on top of one of the shaft speeds (yes this happens) loosen the belts.**
- As an engineer, I view the belts as a sacrificial machine component. In other words, I would rather shorten my belt life a bit by loosening them than compromise the life of my sheave-end bearings and potentially the shafts by tightening the belts excessively - this is my opinion.

Solving Belt Strand Frequency Problems

If tightening or loosening the belts isn't enough to solve a belt strand problem, you can try either of the potential solutions:

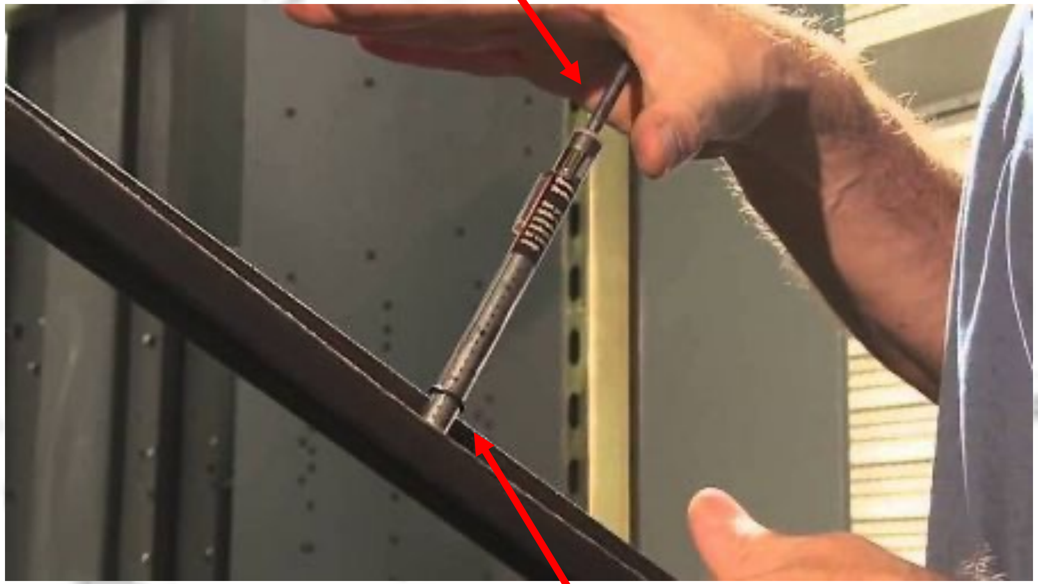
1) **Change the belt length** by one or two sizes (larger or smaller depending on whether you want to lower or raise the belt strand frequency). Most motor bases designed for belt drives will accommodate a small belt length change. For equal tensioning, a shorter belt has a higher natural frequency and a longer belt has a lower natural frequency.
2) **Change the belt design or type**. It is possible that a small change in the cross-sectional area of the belts may not require sheave changes. Check with your belt and sheave supplier on your options here.
3) If a multiple belt drive is in use, **remove one of the belts** to require a higher tension and thus a higher belt strand frequency.
4) If all else fails, **an idler pulley can be installed** to change the stiffness of the belts, but I have personally never had to resort to this extreme.

Proper Belt Tensioning

- What is the right tension our belts should be set to? Until it “feels right”?
- It may surprise you to know that most belt manufacturers offer recommendations on proper tension given a center-to-center shaft distance, belt type, smallest sheave diameter, and belt service type.
- Either a spring-loaded tension tester or a sonic belt tension tester can be used to accurately measure and set the appropriate belt tension.
- A small range of appropriate tensions are suggested for a given set of belts. I prefer to set belts to the lower end of this recommended range.

Belt Tension Tester (Spring-Loaded Device)

Belt tension setpoint (lbs)
Lookup in belt OEM table



Belt deflection setpoint (inches)
Lookup in belt OEM table

Belt Tension Tester (Sonic Device)

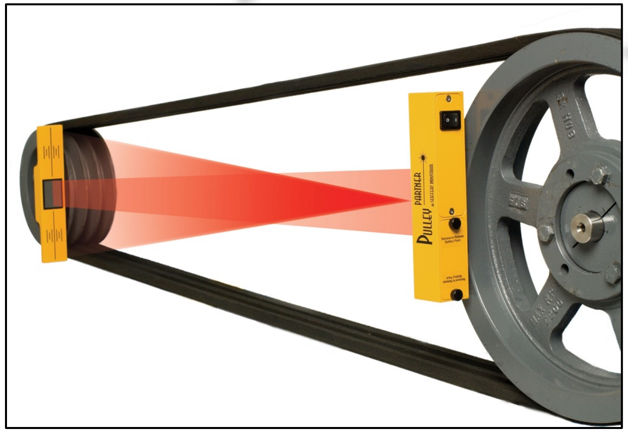
Belt tension sensor (acoustic)
Use table and/or software to lookup frequency

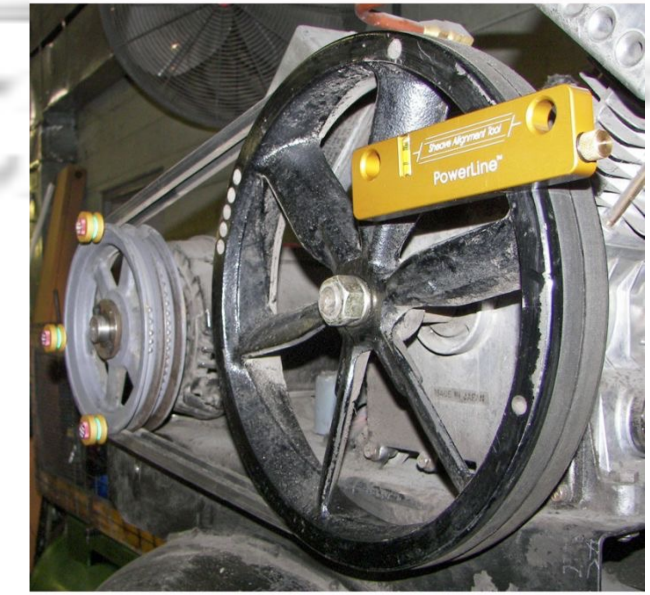
Pluck belt with sensor held nearby and measure belt strand frequency. Adjust belt tension until within recommended range.

Sheave Alignment

- Sheave alignment using a string was common in years past, but today laser sheave alignment tools are clearly the tool of choice.
- These laser sheave alignment tools are quite easy to use and can accomplish a better tolerance.
- There are many manufacturers of laser sheave alignment tools today.
- The primary difference between them appears to be whether they mount to the outside surface of the sheaves or within the belt grooves of the sheaves.
- For most belt drives, attaining a sheave alignment within 1/16” is considered excellent while alignment within 1/8” might be acceptable. A longer center-to-center shaft distance allows a more forgiving tolerance.
- **Vibration analysis** can detect sheave alignment problems by noting higher than normal axial (thrust) vibration at the sheave-end bearings with the dominant frequency of vibration being 1x rpm of either sheave.

Laser Sheave Alignment Tools

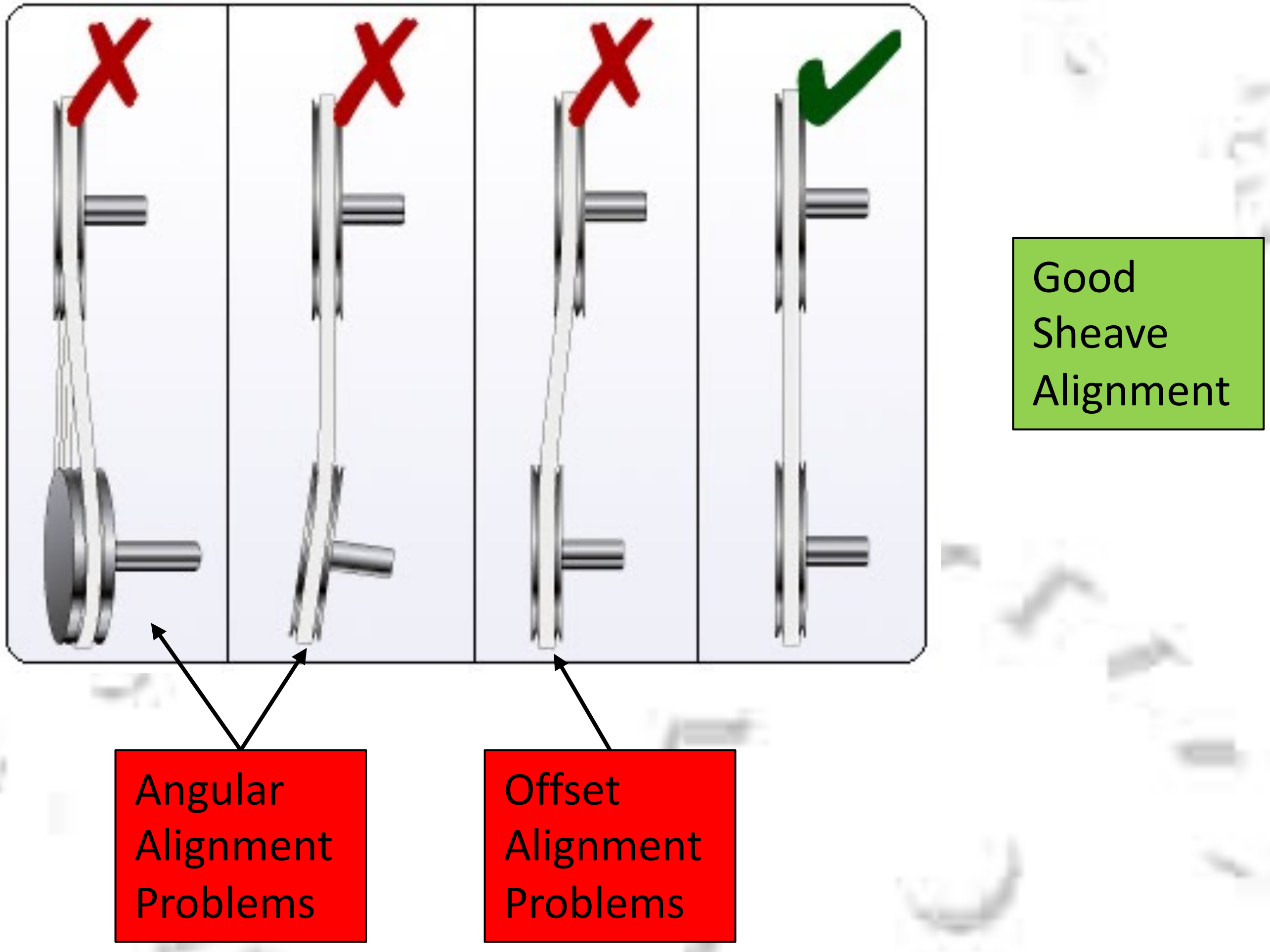




Mounts to outer sheave surface
Must account for potential differences in sheave thickness.

Mounts inside belt grooves (where the belts operate)

Sheave Alignment

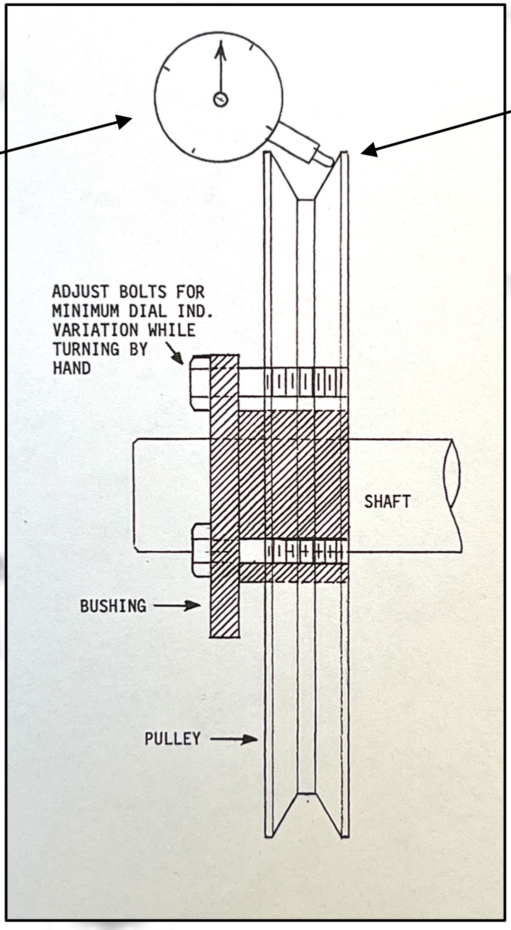


Measuring Sheave Run-Out (Eccentricity)

- An additional check that should be performed on belt sheaves is to measure their run-out using a dial indicator with a magnetic base.
- This simple check will identify **eccentricity** of the sheave and/or shaft that if left unresolved will result in elevated vibration at the running speed of the eccentric sheave and shorter belt & bearing life.
- Most plants consider acceptable eccentricity or run-out of a sheave at 2 thous or less (TIR 4 thous or less).
- Vibration analysis can detect an eccentric sheave by looking for elevated vibration at 1x rpm of the eccentric sheave along with a highly directional or linear orbit.
- This type of highly directional vibration produces phase differences (horizontal versus vertical) near 0 or 180 deg and not the near 90 deg normally expected.

Measuring Sheave Run-Out (Eccentricity)

Dial indicator mounted to motor or fan bearing or base.



Dial indicator measurement made perpendicular to working surface of sheave groove (where the belts operate).

Loose Sheaves Or Bushings

- A final problem common to belt drives are loose sheaves or bushings.
- What I'm suggesting is either the sheave is loose on the bushing or the bushing is loose on the shaft or both.
- Vibration analysis can detect this problem in the same manner as any other type of looseness: higher than normal vibration at 1x rpm of the loose sheave or higher than normal vibration at multiples of 1x rpm of the loose sheave. Vibration at 1/2x rpm multiples are also possible. These vibration symptoms will be greatest at the sheave-end bearings and dissipate as you move to the opposite sheave-end bearing.
- If your belt guard is designed correctly, you can sometimes confirm a loose sheave or bushing by using a strobe-light tuned slightly off of the speed of the loose sheave (5 to 10 rpm off).

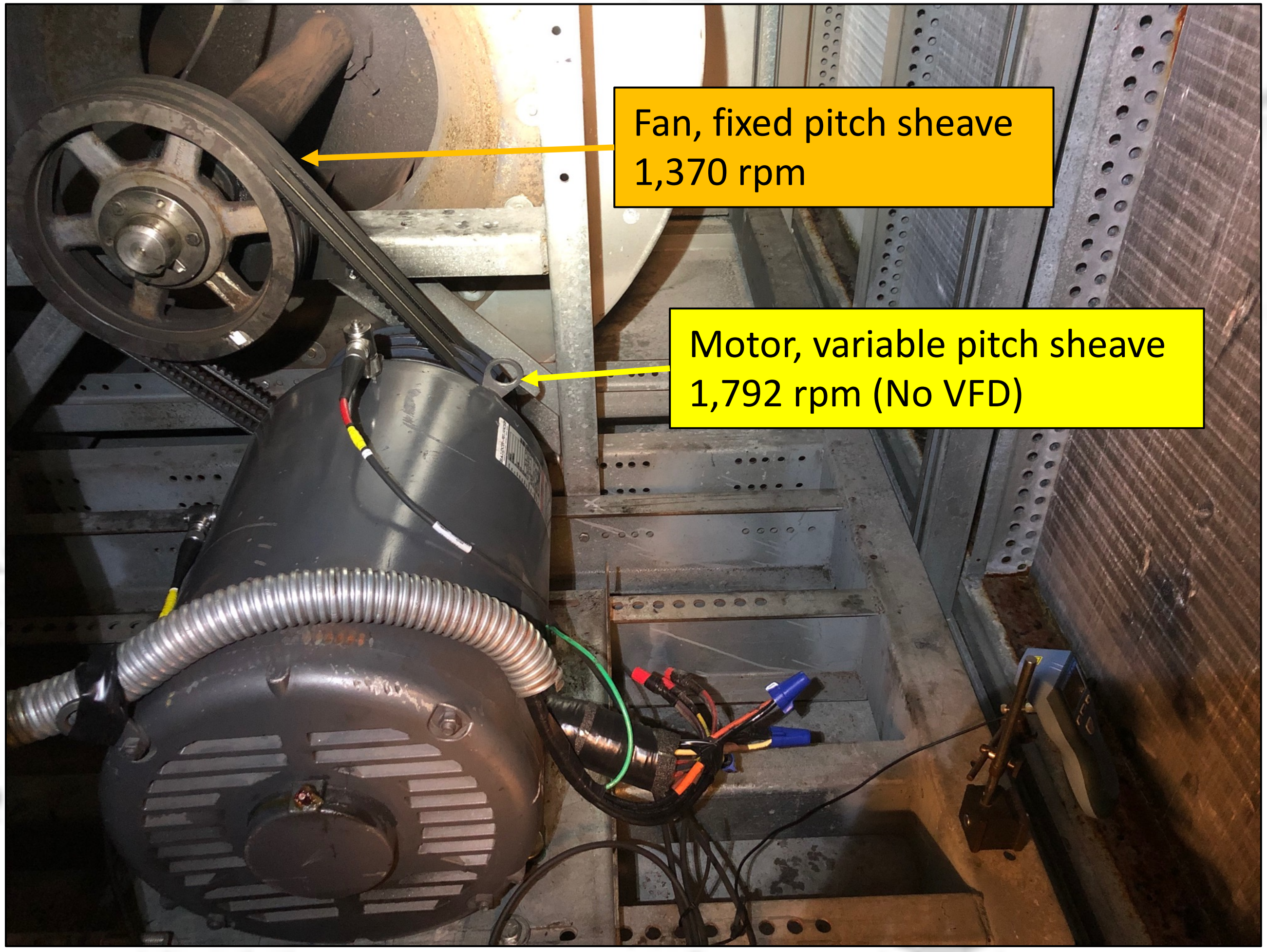
Case History 1

Excessive Vibration Of Hospital Fan

Case History 1 – Excessive Vibration Of Hospital Fan

- Persistent high vibration was reported at a critical AHU fan in a hospital.
- The AHU fan consisted of a center-hung, belt-driven fan operating on pillow-block bearings and driven by a small 4-pole motor. The motor did not operate on a VFD. The entire motor-fan system operated on a fabricated steel base supported by spring isolators.
- The motor speed was measured via strobe-light at 1,792 rpm while the fan speed was measured at 1,370 rpm. (1.308:1 ratio).
- A fixed pitch sheave was found on the fan shaft while a variable pitch sheave was found on the motor shaft.

Case History 1 – Excessive Vibration Of Hospital Fan



Case History 1 – Excessive Vibration Of Hospital Fan

- Vibration sensors were placed on the motor & fan bearings and initial vibration measurements were made to determine the dominant frequency(s) of vibration present.
- These initial vibration measurements found high vibration occurring at the motor speed of 1,792 rpm with very low vibration at the slower fan speed of 1,370 rpm. This was our first indication that the motor and not the fan was to blame for the majority of the excessive vibration present.
- These initial findings came as a surprise to hospital maintenance staff who were prepared to change the fan bearings and then have the fan cleaned & balanced.
- This is an example of how predictive maintenance not only gives us early warning of machine problems but also helps to **avoid unnecessary maintenance & associated expenses** that wouldn't improve anything.

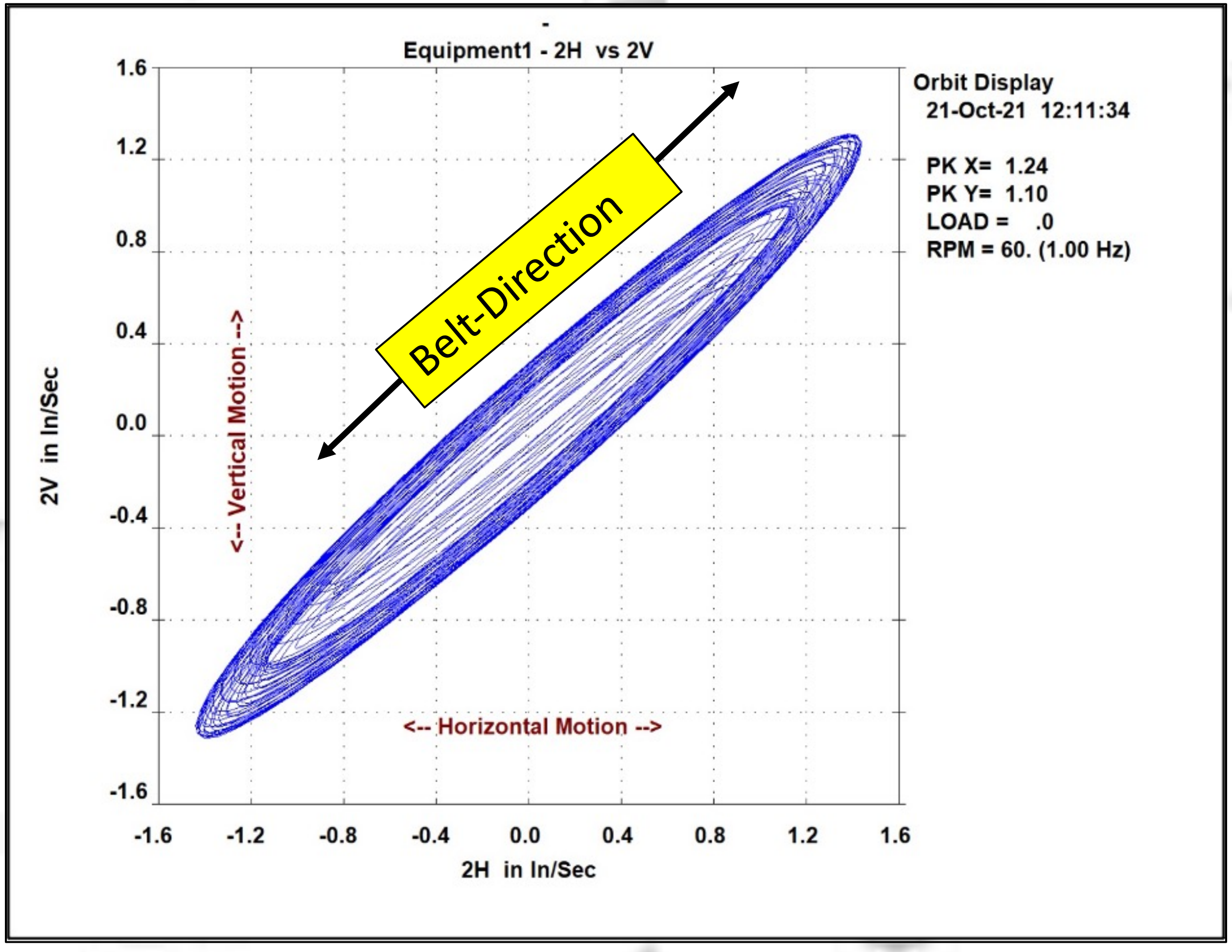
Case History 1 – Excessive Vibration Of Hospital Fan

- Motor, Sheave-End Bearing, Vertical Measurement, OA @ 1.45 ips-pk, Motor 1x rpm @ 1.19 ips-pk.
- Fan, Sheave-End Bearing, Vertical Measurement, OA @ 1.18 ips-pk, Motor 1x rpm @ 1.02 ips-pk.
- Fan, Opposite Sheave-End Bearing, Vertical Measurement, OA @ 0.82 ips-pk, Motor 1x rpm @ 0.44 ips-pk.

Case History 1 – Excessive Vibration Of Hospital Fan

- Once we knew that dominant vibration was occurring at the motor and not the fan speed, special orbit vibration data was collected at the motor, sheave-end bearing.
- This orbit data showed **highly directional motion** occurring at the motor speed. **The direction of motion was in-line with the belts.**
- Phase measurements were collected at the motor speed (1,792 cpm) at the motor sheave-end bearing. These phase measurements showed essentially a zero degree phase difference between horizontal & vertical measurements at the motor sheave-end bearing.
- Under normal circumstances, the phase difference between horizontal & vertical measurements should be ~ 90 deg and not ~ 0 deg.

Case History 1 – Excessive Vibration Of Hospital Fan



- Highly directional orbit seen at motor, sheave-end bearing.
- Dominant motion in-line with belts.

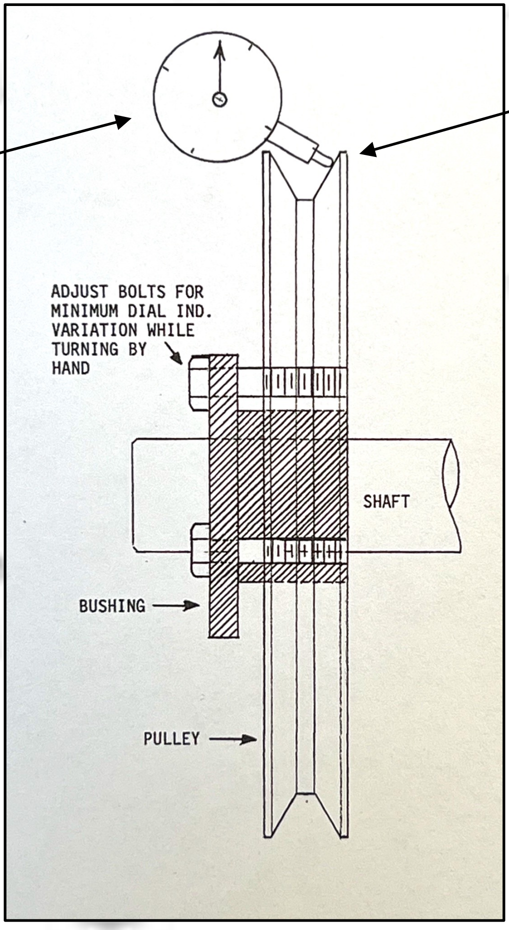
Point	Description	Motor 1x Pk (ips-pk)	Motor 1x Phase (deg)
2H	Motor, Sheave-End, Horizontal	1.25	254
2V	Motor, Sheave-End, Vertical	1.03	252

Case History 1 – Excessive Vibration Of Hospital Fan

- Given the vibration data gathered, next a dial indicator was setup to measure the run-out at both the motor & fan sheaves.
- A magnetic base was mounted to the motor frame and fan frame and run-out was measured at the corresponding sheaves at or as close as possible to the location where the belts ran at each sheave (see prior slide).
- Run-out (1/2 TIR) of ~ 4 thous was measured at the fan sheave.
- Run-out (1/2 TIR) of ~ 16 thous was measured at the motor sheave.
- A run-out tolerance of < 3 thous is accepted by most plants. By this standard both the fan & motor sheave were out of spec with the motor sheave being way out.
- Given that the motor sheave was a variable pitch type and not a fixed pitch type, our results were not surprising. **Variable pitch sheaves are basically a mistake.** Don't use them unless you have no choice.
- The reason for this is the near impossibility of getting the run-out and groove widths consistent between grooves and even within a groove.

Measuring Sheave Run-Out (Eccentricity)

Dial indicator mounted to motor or fan bearing or base.



Dial indicator measurement made perpendicular to working surface of sheave groove (where the belts operate).

Case History 1 – Excessive Vibration Of Hospital Fan

- Sheave run-out results in an eccentric sheave condition which causes the exact vibration symptoms we had measured namely:
  1) High vibration at the speed of the eccentric sheave (in our case the motor speed).
  2) Very directional vibration in the direction of the belts.
  3) Phase differences (horizontal versus vertical at the sheave-end bearings) at the speed of the eccentric sheave nowhere near 90 deg but instead at or near 0 or 180 deg (these phase differences are simply a reflection or indication of the directional vibration seen in the orbit).
- Groove width differences result in some belts being tight while others are relatively loose. It can also result in belts being tight throughout a portion of their rotation then loose throughout the rest (similar indications to run-out, eccentricity).
- Variable pitch sheaves seem inherently plagued by the groove width variations mentioned above and thus their existence on your belt drive alone will almost certainly result in higher than normal vibration at the speed of the variable pitch sheave and as an added bonus, shorter belt life.

Case History 1 – Excessive Vibration Of Hospital Fan

- Recommendations were made as follows:
    1) Replace the existing variable pitch motor sheave with one of fixed pitch but equal diameter.
    2) Ensure the new motor sheave has been balanced for 2,000 rpm service to an ISO G2.5 or better tolerance.
    3) Ensure the new fixed pitch motor sheave has run-out of less than 3 thous.
    4) Replace the existing belts with a new matched set.

Case History 2

Balance Needed At Large Hospital Fan?

Case History 2 – Balance Needed At Large Hospital Fan?

- High vibration was reported at a large fan in operation at a hospital.
- The fan operated on two pillow-block bearings and was belt-driven by a 4-pole motor operating on a VFD.
- The fan operates on a steel frame structure inside the ducting while the motor operates outside the ducting on an adjustable, fabricated steel base.
- Balance of the fan was requested by the customer to resolve the vibration problem.
- Upon arrival, both the motor & fan shaft speeds were measured using a strobe-light. The VFD frequency of the motor was also noted.
- Initial motor speed was 740 rpm (VFD Frequency 25 Hz) and initial fan speed was 308 rpm (2.4:1 ratio).
- On-site inspections noted a fixed pitch fan sheave and a variable pitch motor sheave.
- On-site inspections also noted the keyway on the fan shaft ran the entire length of the fan shaft.

Case History 2 – Balance Needed At Large Hospital Fan?

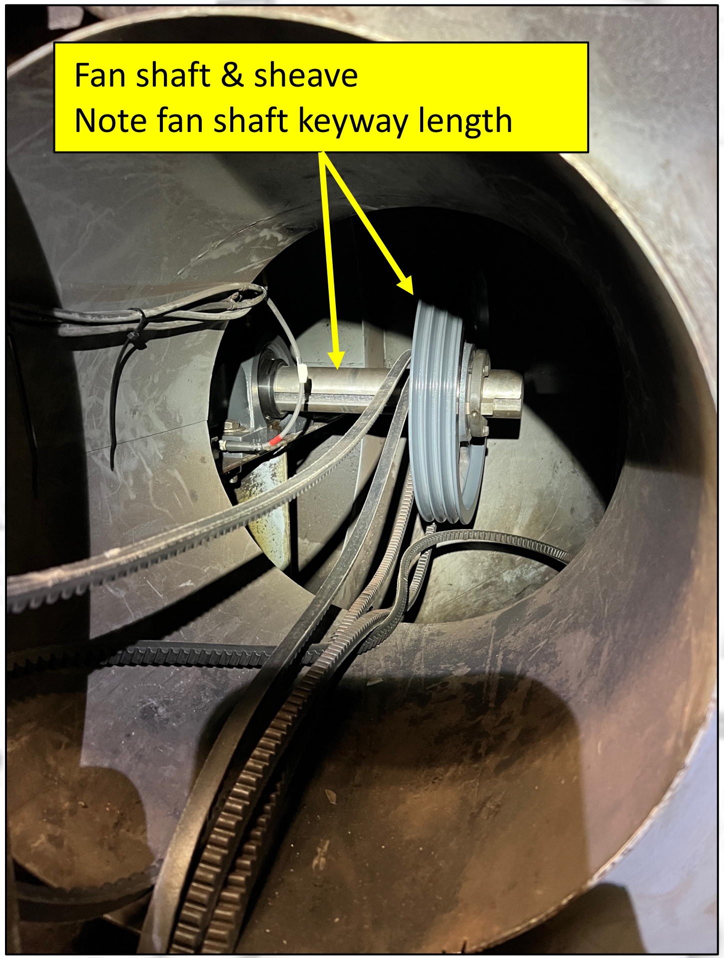
- Vibration sensors were mounted to both fan bearings and to the motor. A laser tach was used to monitor the fan speed and serve as a phase reference for our anticipated fan balance.
- Initial vibration data was collected and showed **low vibration at the fan speed** (< 0.10 ips-pk) at all points with corresponding **high vibration at the motor speed** (> 0.50 ips-pk) at all points. In addition, clear motor bearing defect frequencies were seen in the motor data only. At this point it was clear that a fan balance would have little effect at eliminating our fan vibration problem, so our focus shifted from the fan to the motor.
- A close inspection of the motor and its base ensued. This inspection identified the following problems:

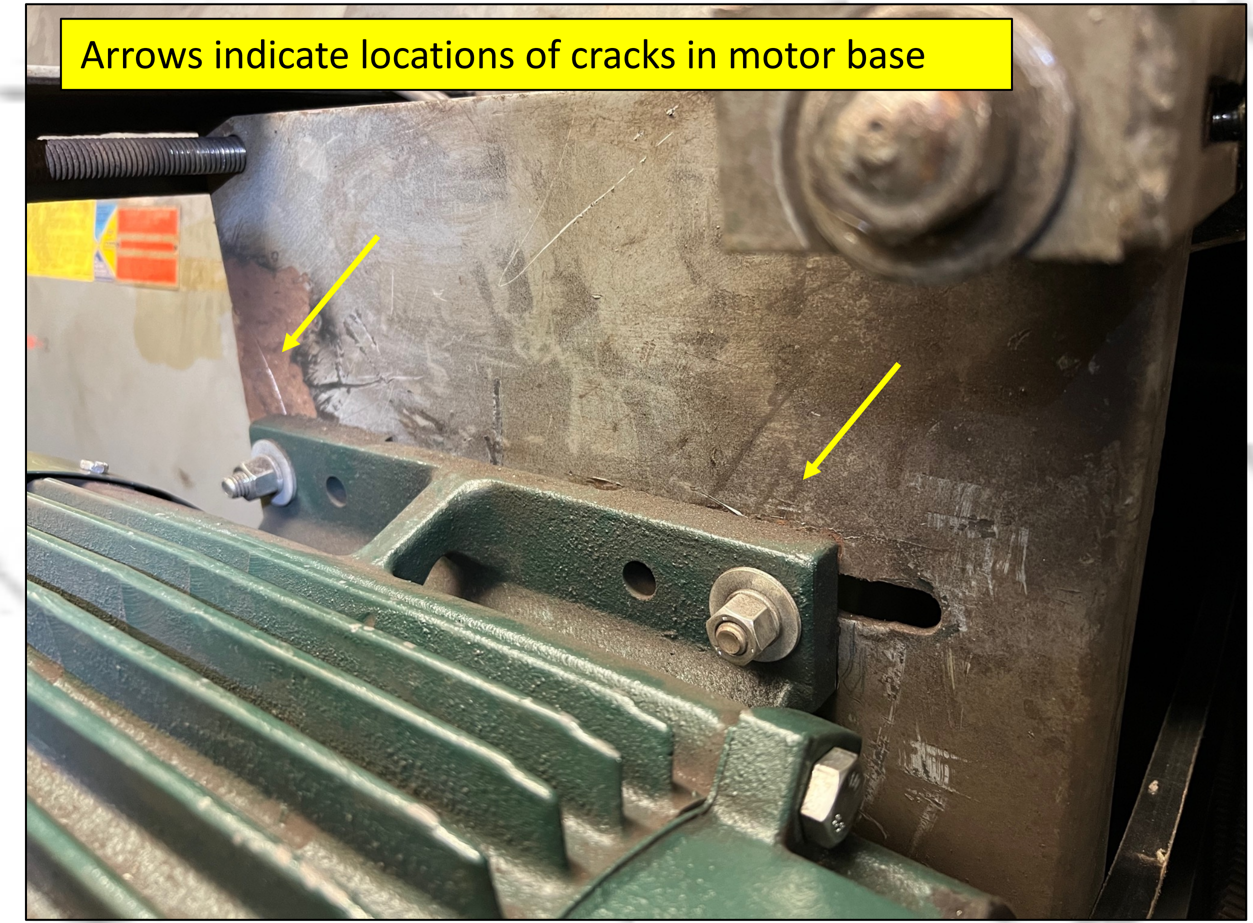
  1) Multiple cracks were identified within the motor base. A few of these cracks had clearly been welded up in the past and had cracked again.

  2) A variable pitch sheave existed at the motor. Run-out in excess of 15 thous was measured at this motor sheave using a dial indicator. This run-out varied from groove to groove and seemed more of a case of groove width variations than run-out. This particular problem of groove width variations is unfortunately common with variable pitch sheaves.

Case History 2 – Balance Needed At Large Hospital Fan?

On-site photos of large hospital fan

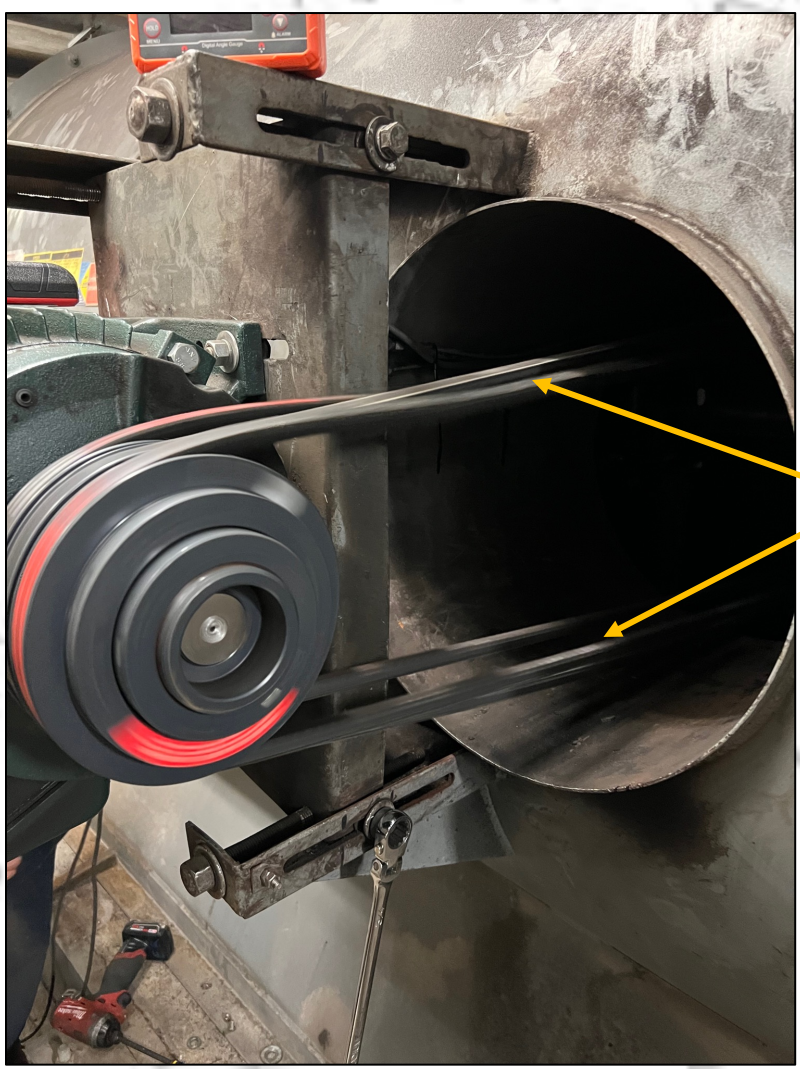




Case History 2 – Balance Needed At Large Hospital Fan?

- Further inspection of the belts both during operation and during coast-down noted the following:
  1) During operation the belts flopped around quite a bit with some belts moving much more than others (3-belt drive).
  2) During coast-down of the drive when the fan & motor sheaves were turning slowly, the variations in belt tension between the three belts was evident as well as movement of the belts in and out of the belt grooves throughout rotation of the motor sheave (ie: the belts moved to a slightly different pitch diameter depending on the rotation angle of the motor sheave).
- Both observations above were further evidence of imperfections at the variable pitch motor sheave causing trouble.

Case History 2 – Balance Needed At Large Hospital Fan?



Note how middle belt appears to have a different tension from those at the outside.

On-site videos of belt trouble and motor base cracks

Case History 2 – Balance Needed At Large Hospital Fan?

- The motor bearings were changed on-site and follow-up vibration was taken that confirmed the elimination of that problem, but the continuation of elevated vibration at the motor speed.
- The following recommendations were made to eliminate the remaining vibration problems:
  1) Replace the existing variable pitch sheave with one of identical, fixed pitch diameter and balanced to a ISO G2.5 tolerance or better for service at 2,000 rpm.
  2) Replace the existing motor base with one of equal dimensions but try to have one fabricated of slightly thicker steel. Thicker construction will make cracking of the base more difficult in the future.
  3) Down the road when the fan bearings are already being changed, consider replacement of the existing fan shaft with one only having a keyway at either end of the shaft and not along its entire length.

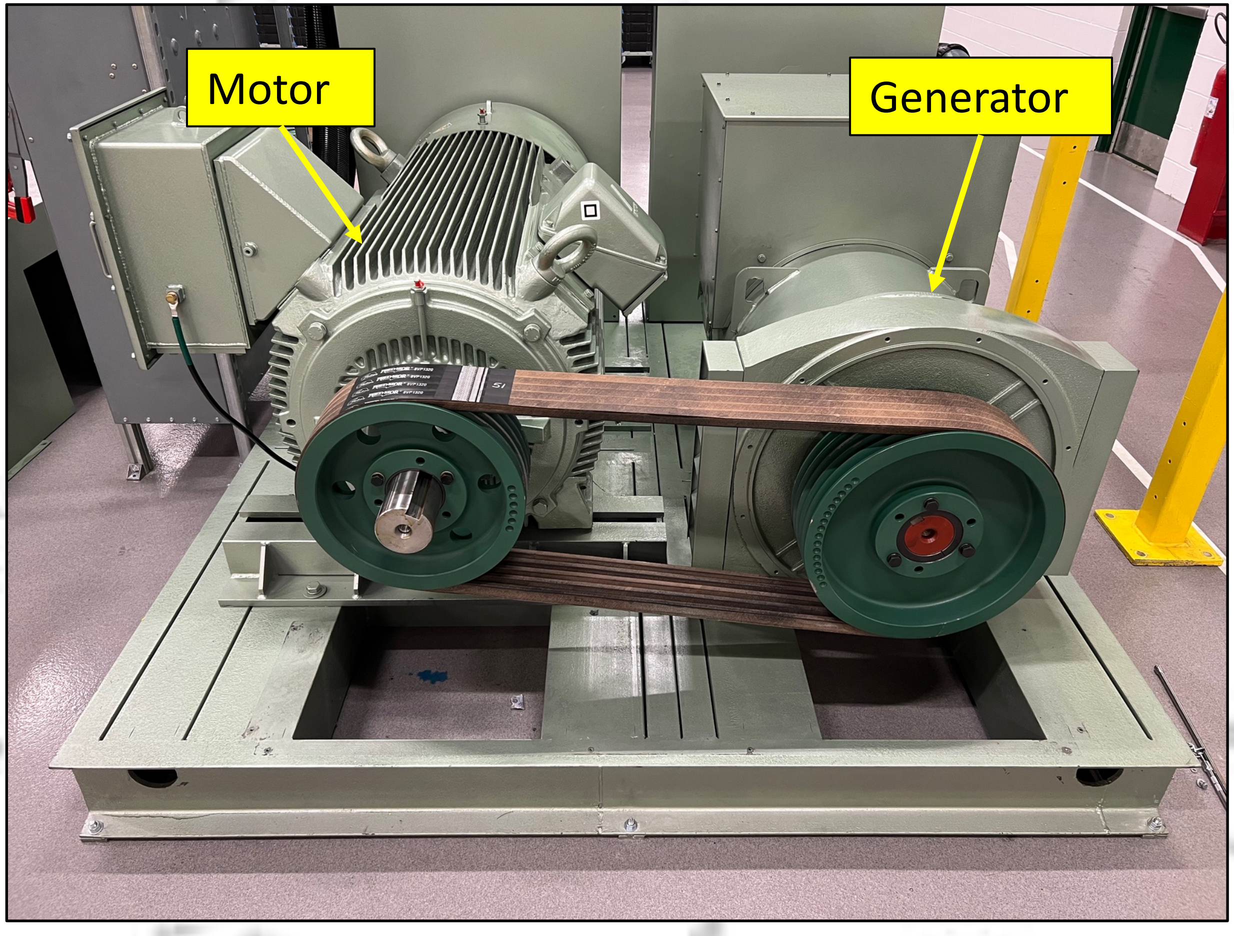
Case History 3

Critical Motor Generator Set Begins Service with High Vibration

Case History 3 - Critical Motor Generator Set Begins Service with High Vibration

- A new motor generator set was installed at a manufacturing facility.
- Following installation, initial operation of the machine noted high vibration levels.
- The motor generator set consisted of a 4-pole motor operating at ~ 1,800 rpm (no VFD) driving a 50 Hz, 4-pole generator at ~ 1,500 rpm thru a belt drive.
- Both motor and generator were bolted to a fabricated steel base which in turn was bolted to a concrete floor (no isolation and no grouted, rigid base).
- The motor sheave diameter was measured on-site at ~ 16" while the generator sheave diameter was measured at ~ 19". The center-to-center shaft distance was measured at ~ 38".
- From these three measurements above and knowing the shaft speeds of the motor & generator, we were able to estimate the belt speed at ~ 688 rpm and a 2x belt speed frequency of ~ 1,376 cpm.

Case History 3 - Critical Motor Generator Set Begins Service with High Vibration



- On-site photo of motor-generator set.
- Motor is at left while generator is at right.
- Note the fabricated steel base bolted to the floor.
- Note the grooves cut or designed into the steel base.

Case History 3 - Critical Motor Generator Set Begins Service with High Vibration

- Vibration route data was collected along both the motor & generator during no-load operation.
- This initial vibration data confirmed the high vibration levels reported with no measurement on either machine meeting relevant Acceptance tolerances and over half the measurements exceeding either Alert or Alarm levels for a machine of this type.
- The highest vibration levels at each bearing occurred in the horizontal direction.
- Having no vibration specs provided by the customer or M-G set OEM, I used the Technical Associates Of Charlotte vibration tolerances.
- I prefer use of the **Technical Associates vibration specs** when none are provided by the OEM or customer for the following reasons:
    1) They are machine specific; they take into account the fact that vibration levels for a motor-generator set like this are and should be different from those of a Roots Style Blower, Steam Turbine, Vertical Pump, etc.
    2) They are based on real vibration measurements and machine histories from many machines of the types listed.

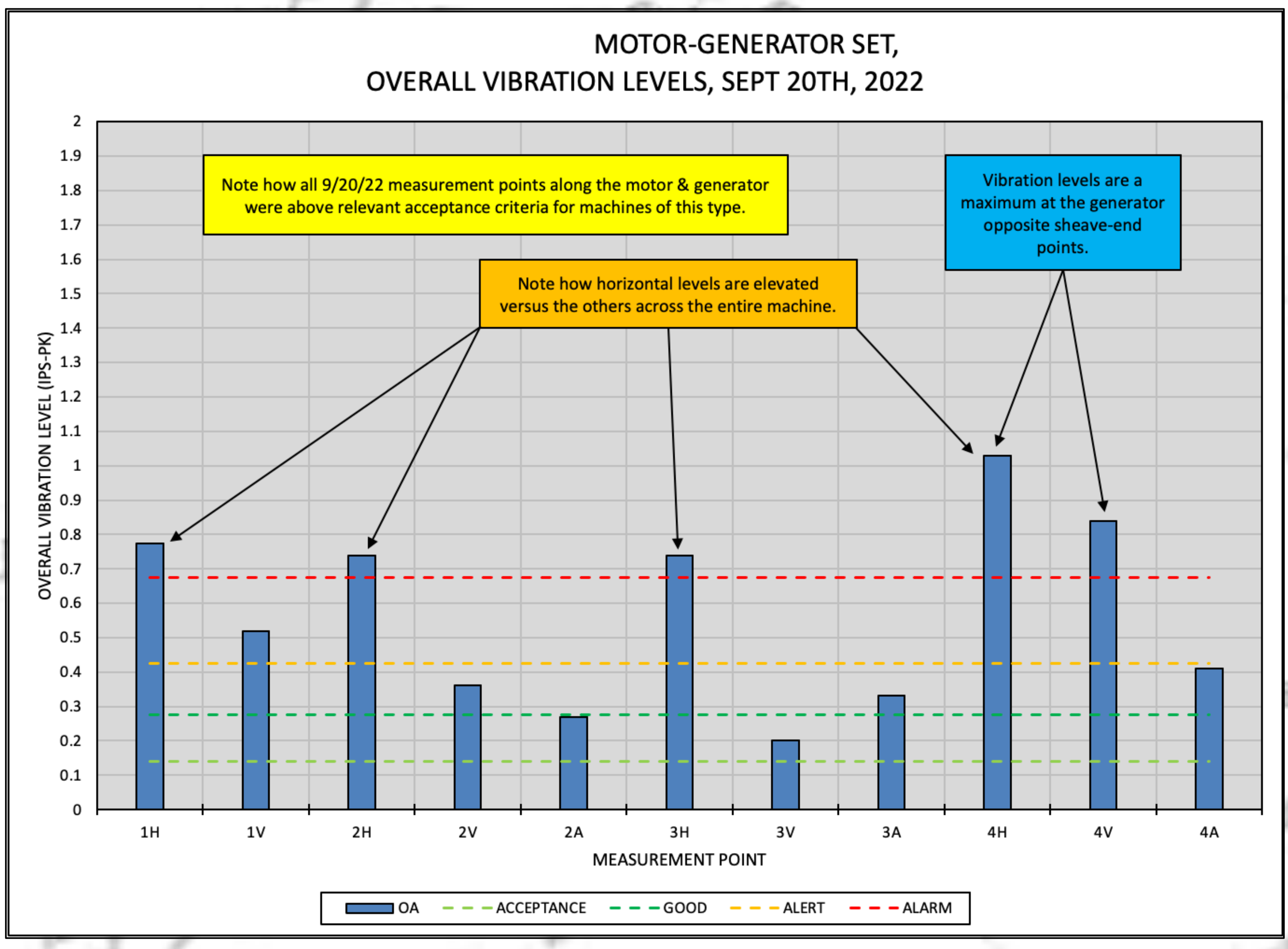
Case History 3 - Critical Motor Generator Set Begins Service with High Vibration

Overall vibration levels (velocity, ips-pk) measured along the motor-generator set. The TA vibration tolerances for a machine of this type are shown in the columns at right.

SYMBOL	DESCRIPTION
1H	MOTOR, OPPOSITE SHEAVE-END, HORIZONTAL
1V	MOTOR, OPPOSITE SHEAVE-END, VERTICAL
2H	MOTOR, SHEAVE-END, HORIZONTAL
2V	MOTOR, SHEAVE-END, VERTICAL
2A	MOTOR, SHEAVE-END, AXIAL
3H	GENERATOR, SHEAVE-END, HORIZONTAL
3V	GENERATOR, SHEAVE-END, VERTICAL
3A	GENERATOR, SHEAVE-END, AXIAL
4H	GENERATOR, OPPOSITE SHEAVE-END, HORIZONTAL
4V	GENERATOR, OPPOSITE SHEAVE-END, VERTICAL
4A	GENERATOR, OPPOSITE SHEAVE-END, AXIAL

SYMBOL	OA VIBRATION (IPS-PK)	TA VIBRATION CRITERIA (IPS-PK)				
		ACCEPTANCE	GOOD	FAIR	ALERT	ALARM
1H	0.773	0.14	0.275	0.275-0.425	0.425	0.675
1V	0.52	0.14	0.275	0.275-0.425	0.425	0.675
2H	0.739	0.14	0.275	0.275-0.425	0.425	0.675
2V	0.362	0.14	0.275	0.275-0.425	0.425	0.675
2A	0.27	0.14	0.275	0.275-0.425	0.425	0.675
3H	0.738	0.14	0.275	0.275-0.425	0.425	0.675
3V	0.201	0.14	0.275	0.275-0.425	0.425	0.675
3A	0.331	0.14	0.275	0.275-0.425	0.425	0.675
4H	1.028	0.14	0.275	0.275-0.425	0.425	0.675
4V	0.84	0.14	0.275	0.275-0.425	0.425	0.675
4A	0.409	0.14	0.275	0.275-0.425	0.425	0.675
AVERAGE:	0.565					
MEDIAN:	0.520					
MAX:	1.028					

Case History 3 - Critical Motor Generator Set Begins Service with High Vibration

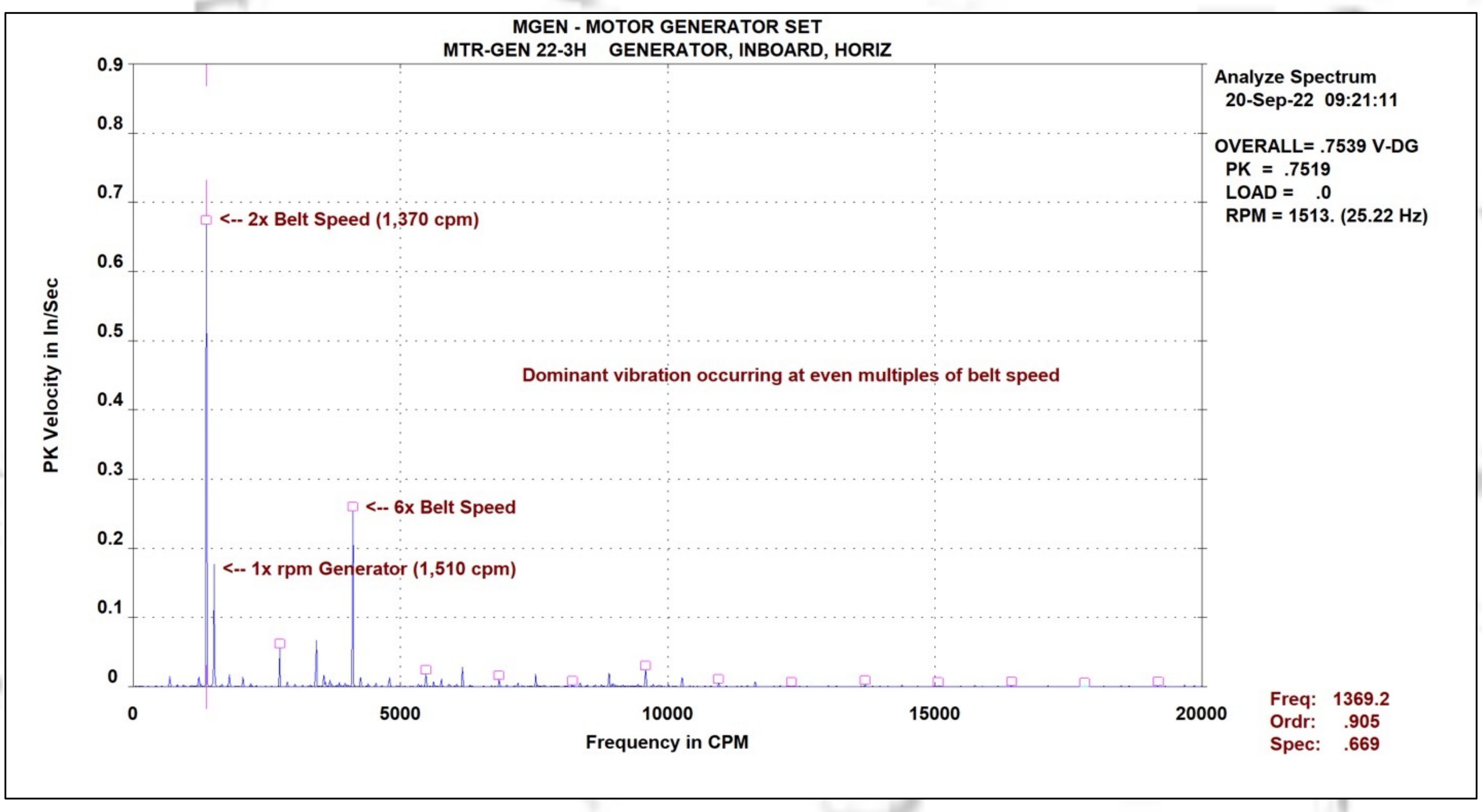


From the overall levels alone we could see our **horizontal** (belt-direction) vibration was highest across both motor & generator.

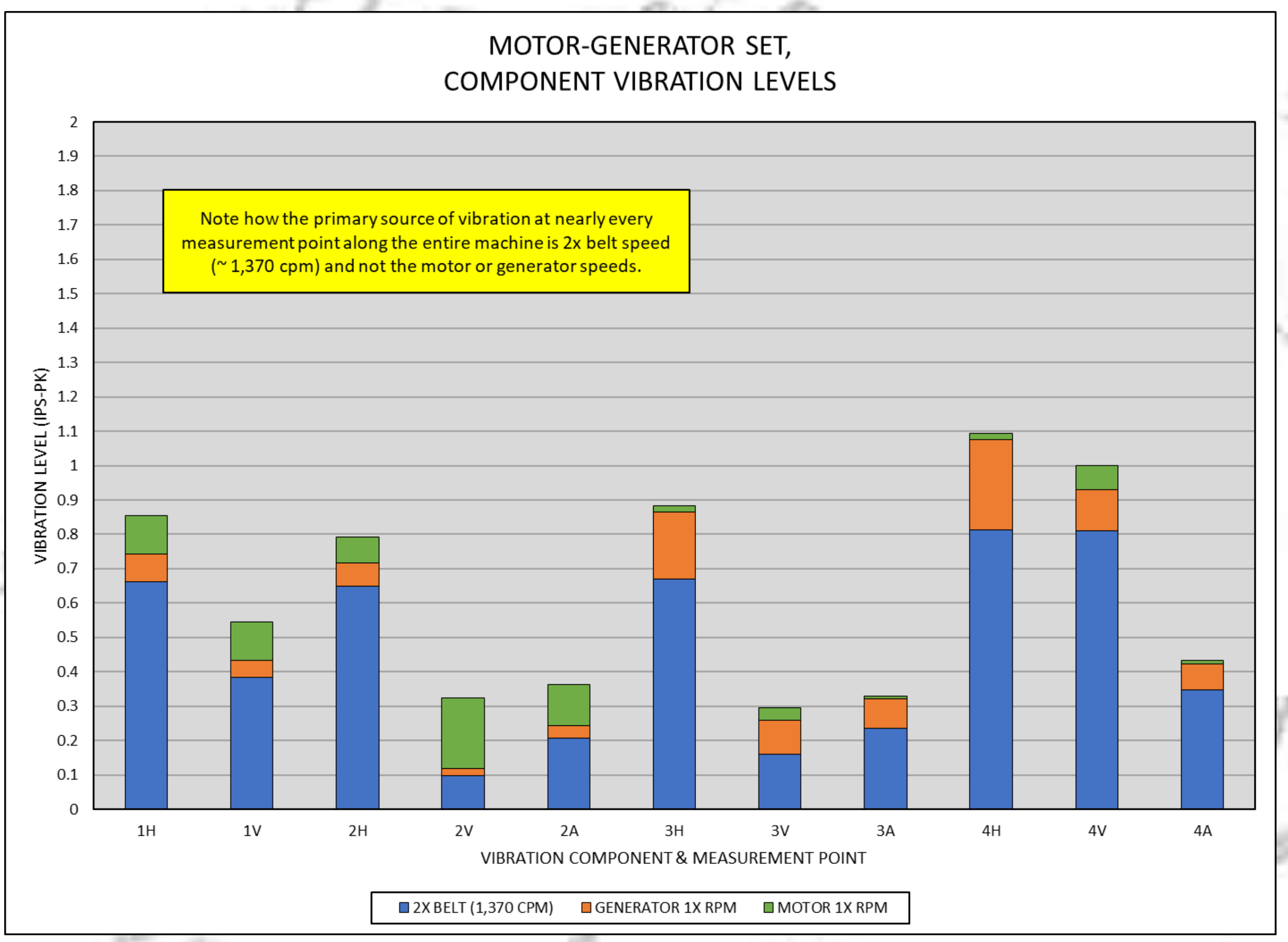
Case History 3 - Critical Motor Generator Set Begins Service with High Vibration

- Vibration spectral data from the points of highest vibration noted dominant vibration occurring not at the motor speed of ~ 1,800 cpm or the generator speed of ~ 1,500 rpm but instead at ~ 1,370 cpm.
- We recalled our belt speed was estimated at 688 rpm giving us 2x belt speed at ~ 1,376 cpm which is essentially a perfect match with the dominant vibration frequency seen.
- But why was vibration at 2x belt speed so high especially on a new machine with a new set of belts installed?

Case History 3 - Critical Motor Generator Set Begins Service with High Vibration



Case History 3 - Critical Motor Generator Set Begins Service with High Vibration



Case History 3 - Critical Motor Generator Set Begins Service with High Vibration

- The motor generator set was locked out and impact testing was performed on both the motor, generator and belts.
- Impact testing of the motor & generator identified horizontal natural frequencies at 1,313 & 1,463 cpm – both of these natural frequencies are within the resonance range of 2x belt speed (1,370 cpm).
- The horizontal natural frequency of 1,313 cpm is only 4.6% away from 2x belt speed.
- The horizontal natural frequency of 1,463 cpm is only 6.3% away from 2x belt speed.

Case History 3 - Critical Motor Generator Set Begins Service with High Vibration

- Impact testing performed on the belts found a belt strand frequency (resonance) at 1,440 cpm which is only 4.7% away from 2x belt speed and easily within the resonance zone.
- From damping measurements made from the belt impact testing, an amplification factor of > 30x was estimated for the 1,440 cpm belt natural frequency!
- This belt impact testing was performed by placing a vibration sensor on the motor in the belt direction and plucking the belts by hand with the analyzer collecting spectral data in the Peak Hold mode.
- When performing Peak Hold impact testing it is important to take about 50 averages and look at the data before impacting as well as during impacting. You want to make sure the natural frequencies you identify were not there until you impacted the machine.

Case History 3 - Critical Motor Generator Set Begins Service with High Vibration

- Given the existence of natural frequencies at the belts, motor & generator easily within the resonance range, it was no wonder this brand new machine was beginning its service with severe vibration levels!
- To avoid a resonance condition we must do at least one of the following:

1) Move the forcing function at least 10 to 15% away from the natural frequencies (in our case, move 2x belt speed).
2) Add stiffness or mass to the machine or structure to move the natural frequencies away from the forcing function (in our case tighten or loosen the belts and stiffen or add mass to the structure).
3) Add damping to reduce the severity of the resonance (not an easy option in our case).

Case History 3 - Critical Motor Generator Set Begins Service with High Vibration

- Motion amplified video was shot of the motor-generator set during operation both with and without the belt guarding in place. My observations from this MA video was as follows:

1) Dominant motion (vibration) of both the motor & generator is occurring at 2x belt speed and not at either the motor or generator speed or any other vibration frequency.
2) The dominant horizontal motion of the motor & generator is **out of phase** motion. When the motor is moving in one direction horizontally, the generator is moving in the opposite direction. This type of motion is in keeping with resonance of the belts being the primary cause.
3) Clear looseness between the machine base and concrete floor exists at the motor side of the machine base. Specifically the center anchor bolt at the motor side is very loose from the floor.
4) Unexpected flexure of the machine base itself was noted at the "slotted" locations. Specifically flexure was noted at the motor end and between the motor and generator. Why are these slots here at all? They have the effect of reducing the horizontal stiffness of the motor & generator – was this the intention of the OEM?
5) The anchor bolt at the machine base, generator side, opposite sheave-end is also loose from the floor.
6) The generator side of the machine base appears to be rocking in the horizontal direction.
7) The motor opposite sheave-end base is loose from the machine base below.

MA Videos of Motor-Generator Set

Video#	Belt Guard On/Off?	View Description
1	Belt Guard On	Motor & Generator, End View
2	Belt Guard On	Motor Corner View
3	Belt Guard On	Motor Side View
4	Belt Guard On	Rear Corner View (Motor Side)
5	Belt Guard On	Rear Corner View (Generator Side)
6	Belt Guard On	Generator Corner View
7	Belt Guard On	Motor Corner View Zoom
8	Belt Guard On	Generator Side View Zoom
9	Belt Guard Off	Motor & Generator, End View
10	Belt Guard Off	Generator Corner View
11	Belt Guard Off	Motor & Generator, End View

Conclusions

1) The vibration levels at the newly installed motor-generator set are excessive by any reasonable measure. Maximum overall vibration levels exceeding 1 ips-pk were measured with half of the measurement points in excess of 0.5 ips-pk. Expected levels for a newly commissioned machine of this type are certainly < 0.2 ips-pk with relevant specs suggesting < 0.14 ips-pk being possible for new equipment.
2) Dominant vibration across both motor & generator is occurring at 2x belt speed (1,370 cpm) and multiples thereof meaning the primary cause of vibration at this machine has to do with the belts and not with the motor or generator.
3) A very common cause of high vibration at 2x belt speed and multiples is sheave alignment trouble. On-site inspection of the belts noted a difference in belt tension from the inside to the outside of the belts – this is also an indication of belt alignment trouble.
4) Impact testing of the belts discovered a belt natural frequency at 1,440 cpm which is well within the resonance range with 2x belt speed of 1,375 rpm (within 5%). An amplification factor of > 30x was measured from the belt impact data. What this means is in its current condition, the belts "want to vibrate" at 2x belt speed, and any degree of alignment trouble or other belt problems will result in excessive vibration at 2x belt speed – this is what we observe across this machine.

Conclusions (cont):

1) Impact testing of the motor & generator identified natural frequencies at 1,313 cpm and 1,463 cpm both of which are easily within the resonance range of both 2x belt speed and the belt natural frequency at 1,440 cpm. Amplification factors of 20 to 30x were measured at these two natural frequencies. We have a mechanical system in the belts, machines and base that currently want to vibrate at frequencies very near 2x belt speed.

2) Looseness between the machine base and floor was identified at specific locations including the motor side, center anchor bolt and generator side, opposite sheave-end anchor bolt (see MA videos for exact locations of this looseness). Looseness between the motor, opposite sheave-end base and machine base was also noted.

3) Flexure of the machine base itself at the "slotted" locations was noted in the videos at many points but especially at the motor side **and between the motor & generator**. I am puzzled as to why these slots exist on this base at all.

Recommendations

1) Using a sheave laser alignment tool, measure the alignment of the motor and generator sheaves and bring into tolerance as needed. For a span of this length, a tolerance of < 1/8" is certainly possible.

2) Consider **<u>reducing</u>** the tension of the belts or changing from the existing belts to those having lower tension. The belt natural frequency is directly related to the belt tension (lower tension → lower natural frequency). Given the fact that this motor operates on a soft start, I see no real need for the high tension, very stout set of belts in place. All things being equal, I would rather have lower belt life than shorter bearing or shaft life. If the belt tension could be lowered enough, resonance of the belts could be avoided as the natural frequency might be lowered 10% or more below 2x belt speed.

3) Another option would be to go with a **<u>slightly longer set of belts</u>** (longer belts, lower natural frequency), or belts of a different design. *I say reduce and not increase the belt tension because both the generator speed at 1,500 rpm and the motor speed at 1,800 rpm are waiting just above the current belt natural frequency of 1,440 cpm and will excite it into resonance if the tension is increased. Don't tighten the belts or go with a "tougher" set of belts – this is the path of destruction.*

Recommendations (cont):

4) At least double the existing number of anchor bolts and at least double the existing diameter of the anchor bolts themselves. The size of the anchor bolts currently in place is in my view entirely too small for this large of a machine.

5) Consider installation of firm elastomeric pads between the anchor bolt locations to reduce deflection of the machine base and raise its stiffness.

6) Can additional anchor bolts be added near the center of the base between the motor and generator? MA video suggests considerable motion of the base is occurring there.

7) Consult with the motor-generator OEM as to the purpose of the slots along the base; **these are not normal**. They must have a reason for including slots in the base design.

8) Tighten up the loose motor base at the opposite sheave end (see MA videos).

References

The following excellent references were used to research this presentation:

1) “The Simplified Handbook Of Vibration Analysis”, Volume 2, Arthur R. Crawford, Computational Systems Incorporated (CSI), 1992.
2) “Machinery Vibration, Measurement And Analysis”, Victor Wowk, McGraw-Hill, 1991.
3) “ISO Category 3 (Analysis 2)” Class Book, Mr. James E. Berry, Technical Associates Of Charlotte, 2010.
4) “IRD Mechanalysis, Vibration Technology 1”, Columbus, OH, 1988.
5) “Practical Solutions To Machinery And Maintenance Vibration Problems”, Ralph T. Buscarello, Update International, 1991.

THE END