



STÖBER

Vibrations in Designs Incorporating Gears: Sources, Analysis, and Solutions

In this eBook, we outline how vibration occurs under both normal and compromised operation of motion system machinery incorporating gearboxes for speed reduction. Then we describe what vibration analysis can reveal to end users of these designs.

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Section 1: **The basics of vibration in gear-driven designs**

Whether induced by a continuous forcer source, or discrete physical strikes that propagate by the matter's elasticity (exciting system natural frequencies), machinery vibration is often an unwelcome motion byproduct. It wastes energy, degrades movement accuracy, wears components, makes noise, and can lead to system failure. Abating the pressure pulsations (sound) generated by vibrating motion systems is an entire industry—to protect workers from strain and hearing injuries. Many modern applications are only possible because of advancements in vibration prevention and mitigation.

Yet, vibration cannot be entirely avoided, because the sole purpose of any moving machinery (including today's prevalent motor-driven designs fitted with speed-reducing gearboxes) is to output motion—and that requires degrees of freedom propitious to vibrations.

In other words, opportunities for vibration abound at the electric motor, shaft and coupling motor-gearbox connections, gearbox, power-transmission components downstream, as well as support bearings along the way. Both external forces and interactions between subcomponents cause vibration, and its expression depends on subcomponent masses, damping abilities, and energy-propagation tendencies.

① Normal machine motion excites the natural frequencies of subcomponents and (in the case of plant applications) parts manufactured. These natural

frequencies generate detrimental secondary motion responsible for the system problems already listed, plus inconsistency and lower perceived quality in finished products or output.

The most common prime movers—ac electric motors—are driven under inherently cyclical operation, and are potentially the first originating source of vibration. Downstream, even normal system stops and starts can induce natural-frequency excitation; accelerations and decelerations due to load changes have similar effect. Consider the challenging scenario of a normally operating punch press and the vibratory effects to be mitigated. If a system's speed is increased to boost throughput, required stopping force also increases, and with it relative motion by inherent component non-rigidity—sometimes even requiring dwells to allow for vibration decay.

② Within the power-transmission system, looseness (in the form of play or backlash) allows space for component-on-component strikes and amplified vibratory response. Component backlash (in gears, as well as couplings) opens connected components to slams that propagate through the system, causing secondary movements in shafts and connected components. In gears requiring backlash, heavy loads exaggerate tooth-stiffness irregularities and vary mesh deflections. These can then cause transmission errors and a periodic inertial load supplement—vibratory and eventually destructive.

Another source of vibration propagation is gearbox housings: Costlier rigid housings are generally machined to tight tolerances, but some gearboxes designed for automated assembly sport housings of plates and gaskets bolted together, and exhibit significant vibration.

Section 2: Elements that affect gear-based vibration

Within the actual gearbox itself, gearing type, tooth profile and loading, module, pitchline velocity, pressure angle, and overlap and gear ratios affect

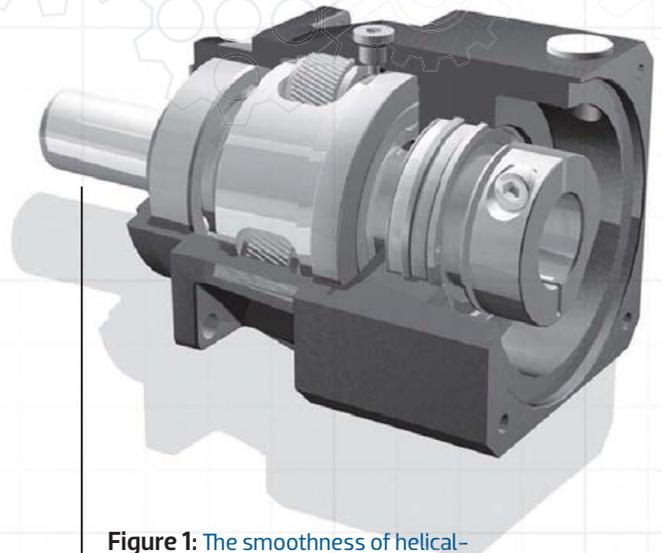


Figure 1: The smoothness of helical-gear transmission reduces vibrations, particularly when compared to spur gears. Shown here is a STOBBER ServoFit gearbox suitable for high-accuracy servo applications requiring minimized vibration.

vibration. The defining factors are tooth engagement and the spring-like behavior of gear teeth under load (as defined by torsional stiffness, beyond the scope of this eBook). Generally speaking, better tooth-contact consistency diminishes the impacts and friction that contribute to vibration. To this end, engineers can change the gear type, improve lubrication, or specify gears with refined geometry and surfaces. For the latter, a gear hardened before cutting (and finished after heat treatment with shaving, grinding, or lapping) exhibits fewer inconsistencies that can cause vibration, and finer finishes result in quieter operation.

Spur gears—common, cost effective, and simple—have the most pronounced tooth strikes conducive to vibration, so often, reliefs are cut into their tooth roots and tips to reduce transmission error and vibration at key loads and roll angles. Then the teeth are crowned—shaped like a set of tuning forks, to create a more oval tooth profile; in moderation, this decreases friction and vibration, and can make for a more pleasant meshing sound. However, over-altering tooth geometry can compromise strength, and compensating with larger



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gears increases pitch line velocities and vibration.

Switching to helical gears is a more common solution to vibration. Used in everything from automobile transmissions to presses, helical gears create a spiral engagement to soften tooth meshing and minimize vibration and noise. More specifically, helical gearing is widely used in myriad high-speed applications because it has the best maximum-to-minimum contact-length ratio.

Gearbox vibrations exist. One common vibration-severity standard is ISO 2372 (BS4675); ISO 8579-2 is specific to gears. The latter outlines acceptable vibration levels for myriad machinery classes, so it requires classification of the design under investigation. Another standard is ANSI/AGMA 6000-B96, which defines allowable vibrations by categorizing individual units largely by pitch line velocity. It outlines specific methods for measuring gearbox vibration, and includes discrete vibration frequency limits. Also considered are system effects on gearbox vibration.

For the audible sound that vibration generates, OSHA stipulates that employees be spared noise levels above 90 dBA (1910.95 occupational noise exposure) or be provided hearing protection. Typical sound levels for enclosed gear units are defined by ANSI/AGMA 6025-D98.

Section 3: **Vibration Analysis in Predictive Maintenance**

Maintaining machine health is traditionally executed through two potentially inefficient approaches—breakdown maintenance (repairing machinery after failure) and preventative maintenance (regularly servicing machinery regardless of its condition). Superior to these approaches is condition-based Predictive Maintenance (PdM), the servicing of equipment only when it exhibits faults that threaten to turn into real problems. Predictive Maintenance programs for electromechanical motion system designs consist of five approaches: Ultrasonic scanning and

interpretation, thermal (infrared) imaging, motor circuit monitoring, oil sampling with spectrometer or microscope analysis, and vibration analysis. In fact, as we'll explore, vibration analysis is essential to any such Predictive Maintenance program.

Predictive Maintenance (PdM) programs are used by many companies and have myriad benefits. Most importantly, Predictive Maintenance programs:

- Allow repairs to be scheduled during preplanned machine downtime, reducing unexpected shutdowns.
- Can detect specific problems through targeted tests, so only failing parts need to be replaced.

Vibration analysis is the investigation of system oscillations. It has a reputation for being the most complicated Predictive Maintenance approach, perhaps rightfully so—as the analysis of data collected can be quite complicated, and require substantial expertise.

How is vibration analysis executed? Typically, vibration probes are affixed to or installed near the machine. Often, mounted multi- or single-axis piezo-based accelerometers are used with tachometers. The former convert acceleration into electric signals; output is expressed in gs or converted to m/sec^2 . Useful on rotating machinery, tachometers use optical or mechanical wheels mounted to a machine's shaft to measure angular velocity and position. One technique is to shake or strike a machine (in a controlled manner) then record the wide-band excitation with accelerometers for modal analysis. Another is to record vibration data while the machine is running. In other cases, when measuring low-level acceleration, microphones or noncontact displacement probes are used.

Next, using standalone vibration-analysis equipment or PCs loaded with the proper software, vibration spectrum analysis is performed. Collected data is put under bandwidth spectrum analysis; that reaching over multiple frequency decades gives a sweeping overview of all machine faults. Then mathematic filters and techniques are applied. Often,

Fast-Fourier Transform (FFT) analysis drills down on narrow frequency bands exhibiting fault vibrations, to allow more in-depth analysis of problems.

Measuring the vibration motion of machinery incorporating gearboxes is more complicated than measuring that of most machines. Testing over a larger frequency range is required for both 1x rpm and Gear Mesh Frequency—so two transducers are needed to reach over this larger range, along with two measurements at each point. That said, many problems can be detected in a gearbox, depending on which range is used.

Let us now explore how vibration analysis is applied to identify the ways in which motion system machinery that incorporates gearboxes can encounter problems.

Problems revealed under RPM-based vibration analysis

Five problems associated with motion system machinery that incorporates gearboxes reveal themselves under RPM-based vibration analysis: Mass unbalance, misalignment, a bent shaft, mechanical looseness, and bearing wear.

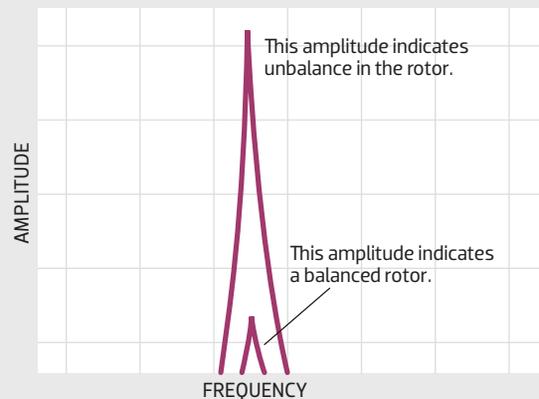
① MASS UNBALANCE

It's impossible to perfectly balance the mass of rotating motion components, which is why all exhibit some vibration. In other words, a small amount of mass imbalance is common and, in a typical motion system, is due to slight imperfections inherent to physical subcomponents such as motor rotors and shafts. See Figure 1 & 2.

When investigated through vibrational analysis, unbalanced design masses appear at a frequency equal to that of the shaft's rotational speed. For example, an unbalanced electric-motor-powered design running at 2,200 rpm can display excessive vibration at that frequency, with resultant amplitude proportional to the unbalance magnitude. Typically, vibrations are less prominent in the machine's vertical direction, as gravity and mounting tend to

Figure 2: Excessive amplitude at 1x rpm

Unbalance excites vibration in the machine's vertical direction at 1x system running rpm, but exhibits no such result in the axial direction.



mitigate vibrations. However, a hallmark trait of unbalance-induced vibrations is that this vertical vibration is actually the dominant direction of excitation, as unbalance causes almost zero frequency-amplitude peak at the running rpm in the axial direction.

② MISALIGNMENT (LINEAR AND ANGULAR)

Misalignment is caused by an installation in which the centerline of the motor or gearbox output shaft does not line up with that of the driven machine. The three types of misalignment include angular (in which one shaft is skewed off of the centerline of the other); offset (in which the shafts are parallel, but exhibit deviation); and combination misalignment (in which angular and offset divergences exist).

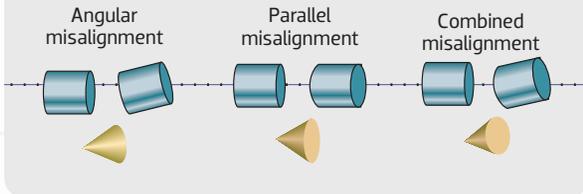
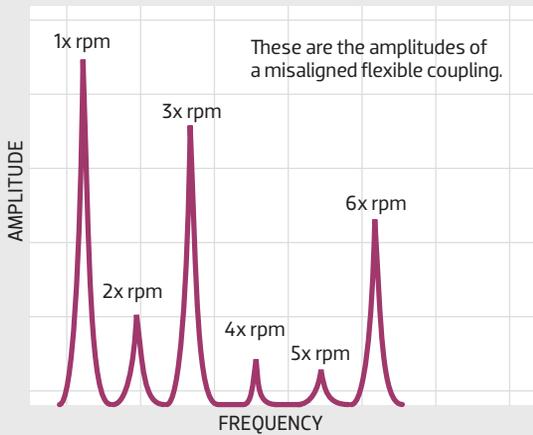
Harmonics arise from induced shaft strain, causing misalignment to show itself in vibration analysis in the form of spikes at 1x system running rpm as well as multiples of this frequency. See Figure 3.

Misalignment also generates both axial and radial vibration. However, between the vibrations experienced by the bearing on one end of a shaft span of the bearing on the other end, angular misalignment causes a 180° axial phase shift. In contrast, parallel misalignment induces a 180° radial (vertical or horizontal) phase shift in vibration

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Figure 3: Vibrations associated with coupling misalignment

The three types of misalignment include angular, offset, and combination. This type of problem causes a cascade of peaks in the frequency domain. Typically, these peaks arise at 1x system running rpm, and then at multiples of this frequency.



between the same reference bearings. Here, unlike the vibration signature of unbalance, the radial vibration isn't consistent, but will typically show significantly higher peak amplitudes in one particular direction.

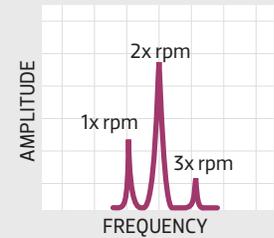
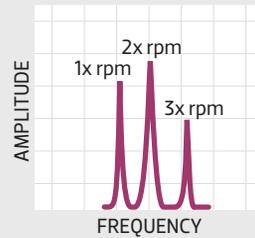
Typically, engineers investigate suspected misalignment with multiple sensors and phase analysis—identifying the telltale 180° shifts or combinations of them. The axial spectrum is of particular importance: Axial vibration equal to or exceeding half the highest radial (vertical or horizontal) magnitude indicates angular misalignment. Another indicator of angular

Figure 4: Angular and offset misalignment profiles compared

In machinery exhibiting angular misalignment, peak amplitude at 1x system running rpm is matched or nearly matched in amplitude by the 2x and 3x rpm peaks. In machinery exhibiting offset misalignment, the 2x peak amplitude is often larger than that of the 1x rpm.

Regular high-amplitude peaks in the system's axial orientation suggests that the coupling is angularly misaligned.

When the 2x rpm peak dominates, it suggests that the coupling is exhibiting offset misalignment.



misalignment is peak amplitude at 1x system running rpm matched or nearly matched in amplitude by 2x and 3x rpm peaks. See Figure 4.

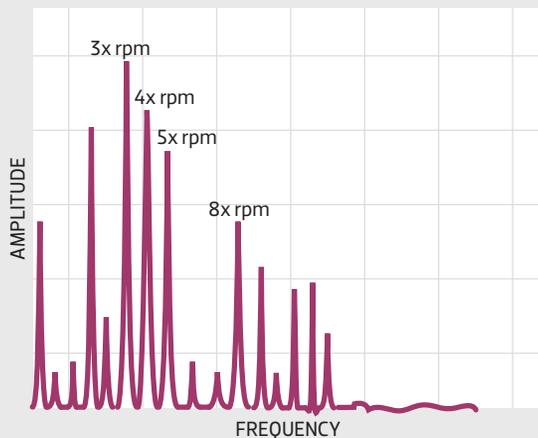
In contrast, offset misalignment causes a 2x rpm peak in the radial (vertical or horizontal) direction that often exceeds the magnitude of the 1x rpm peak; magnitude also indicates the severity of the misalignment. In the axial direction, offset misalignment causes negligible response.

③ BENT SHAFT: A bent power-transmission shaft betrays no signs of problem under vibration analysis of the design's radial (vertical or horizontal) directions; it causes wobble at both support bearings that is revealed under axial vibration analysis, in the form of peaks at 1x rpm.

④ MECHANICAL LOOSENESS: See Figure 5. Loose mounting or play in a machine's structure

Figure 5: Vibrations of mechanical looseness

A raised noise floor in the vibration-analysis plot indicates that the machine is exhibiting mechanical looseness.



exacerbates vibration arising from bent, misaligned, or unbalanced subcomponents. Causes include excessive gear play, worn mounts, excessive bearing clearance, or other physical margins. Under vibration analysis, looseness appears as a cascade of amplitude spikes excited at each multiple of 1x rpm. In addition, the plot of vibrational amplitude exhibits a raised floor of noise—a dead giveaway of mechanical looseness.

🔗 **BEARING WEAR:** Bearing damage, uneven wear of the outer or inner raceways, cage (if present), and rolling elements all cause predictable bearing vibrations. Two characteristics make these vibrations unique: They are generated at non-integer multiples of operating system speed, and they always signal problems—unlike the vibrations of other components, which can be generated during healthy system operation. Often the first subcomponents to exhibit defects, the bearing's inner and outer races (and their frequencies) determine overall bearing vibration. The latter is normally larger than that of the former, as probes can better detect them due to closer proximity and a more direct path to outer-race vibration propagation.

Damaged balls or rollers generate vibrations at their spin frequency, and at the rpm of the cage containing them. A bearing with more than one compromised ball or roller exhibits vibrations at spin frequency multiplied by the number of faulty rolling elements.

Those bearing vibrations appearing at an rpm lower than that of system operation—and around a race frequency, or as sidebands to roller-spin frequency—indicate degradation of or damage to the rolling-element cage. What's more, a compromised cage can also induce vibrations at roller spin frequency.

As mentioned, special attention must be given to any vibration exhibited by bearings—because their subcomponent rpms are significantly higher than that of system speed, and catastrophic failures can occur suddenly. More specifically, bearings generating multiple harmonics, especially those with 1x sidebands around a key bearing frequency, even at low amplitudes pose imminent danger of failure to the overall design, and should be replaced immediately.

Problems revealed under Gear Mesh Frequency-based vibration analysis

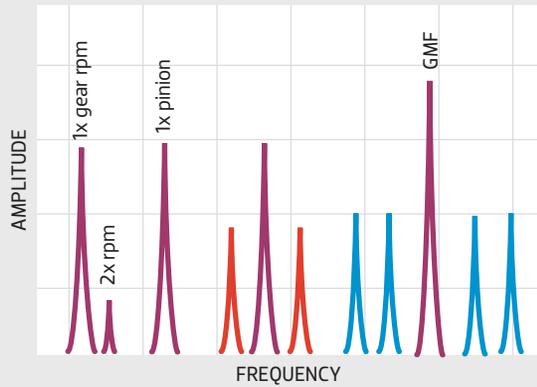
Four problems become apparent under Gear Mesh Frequency-based analysis: Tooth wear, gear misalignment, incorrect backlash, and cracked or broken teeth. The Gear Mesh Frequency (GMF) is equal to 1x system running rpm multiplied by the number of teeth on the attached gear. This Gear Mesh Frequency applies to all gears in the train, as any given gear's rotational speed multiplied by that gear's teeth gives a product equal to the Gear Mesh Frequency.

🔗 **TOOTH WEAR:** Nicks or dings on gear teeth sometimes result in a recurring click as the degraded tooth's face contacts the face of the mating gear. Damaged teeth profiles on input or output pinions often exhibit high vibrational excitation at GMF, in addition to multiple sidebands at multiples of GMF.

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Figure 6: Peak frequencies due to backlash

Vibration due to backlash is detected in the radial direction in spur gears, and the axial direction in helical gears.



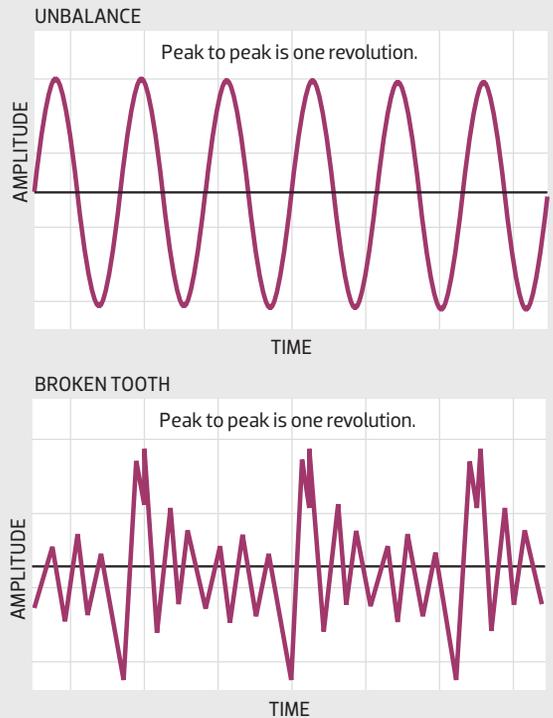
② GEAR MISALIGNMENT: The modulation of eccentricities in both pinions causes repetitive patterns at some multiple of GMF. Three or more GMF harmonics are required to identify this problem; therefore, scanned frequency should extend to beyond 3x to 5x GMF for the geared design's full vibrational profile.

③ INCORRECT BACKLASH: As mentioned, backlash—space between teeth in gear sets—is required for the gears to properly mesh. Excessive backlash degrades positional accuracy and causes unwanted system vibration. The latter is denoted in the frequency spectrum by high-amplitude GMF and gear natural frequency, each with sidebands at 1xRPM around them, plus an additional sideband at 2xRPM around GMF.

④ CRACKED/BROKEN TEETH: Broken or cracked gear teeth tend to generate short-lived impulses at a regular GMF interval—each time they mesh with another tooth. This impulse spreads across many frequencies, which hides it from conventional spectrum analysis. Here, enveloping analysis—

Figure 7: Vibrations of gears with unbalance and broken tooth

A broken tooth reveals itself through pulses repeating at every gear revolution. Unbalanced gears induce a sinusoidal time waveform.



consisting of a rectifier, peak hold, and smoother—is typically used to trace the impulse's excitation of high-frequency system resonance. In short, overall structural resonance is obtained by band-pass filtering; then, side-band activity excited by broken or cracked gear teeth is isolated from this signal by enveloping analysis. **See Figure 7.**

Time waveform analysis is useful in differentiating a gear with a broken tooth from one that is unbalanced.

Section 4: Application example

Let's explore one example of a gearing installation—that of one U.S. beverage supplier with a location in the Midwest. At this modern facility, billions of gallons of refreshments are made and packaged every year. To keep the production lines running continuously and without issue, three Predictive Maintenance (PdM) technologies are used: vibration, infrared, and ultrasonics. When one technology detects a problem, the others are used to narrow possible causes. Vibration is the most common issue, so vibration analysis is used most often. The others are only used first when vibration testing is impossible, either due to space or speed restrictions.

In short, two team members take vibration measurements every day for all 10 lines of the facility; it takes a full month to get a reading for every machine in the plant. In most instances, the transducer is placed on reset mounts attached to the machines. Where space is restricted, permanently mounted transducers are fed back to a control box where they can all be read at once.

Thanks to a diligent PdM approach, this U.S. beverage supplier was recently able to detect a faulty bearing before the machine failed. This allowed the facility's engineers to replace the unit during regular plant downtime, with zero breakdowns or unplanned downtime.

Figure 8: This frequency spectrum shows a large vibration at a bearing fault frequency.

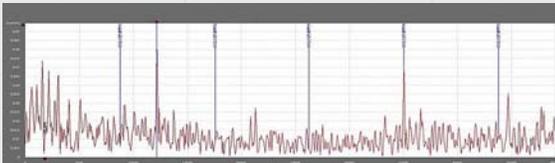


Figure 9: This is the vibration trend for the machine exhibiting the bearing fault.

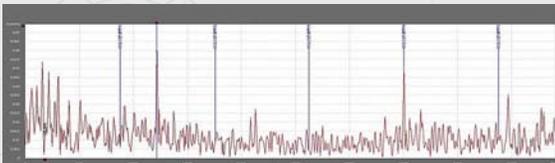


Figure 10: Permanently attached transducers send information back to a control box.



Figure 11: Here, the control box is pictured. It is set up to accept and analyze information from multiple permanently mounted transducers.



Section 5: Make contact

Over the last decade, manufacturing accuracy has taken motion componentry—particularly gear-reducer technology—to new levels, reducing noise and vibration.

On issues of condition monitoring and gearbox vibration analysis, STÖBER Drives Inc. works in close partnership with the design-engineering group at parent company STÖBER in Pforzheim, Germany, as well as engineers at SKF Reliability Engineering. A pioneer in the gearing industry since 1934, STÖBER employs 20 engineers who are devoted to gearbox design. For more information, visit stober.com.

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