Gear Failures, Reasons and Preventions

P. Vijayraghavan

Technical Sales, Shanthi Gears Ltd., Coimbatore (T.N.)

Abstract

Causes of gear failure may be due to a design error, an application error, or a manufacturing error. AGMA recognizes four main modes of gear failure, plus a fifth that covers everything else. They are wear, surface fatigue, plastic flow, breakage, and associated gear failures. A review of all gear and gearbox failures investigated shows that the failure sequence frequently starts with a bearing, rather than a gear Starting torque related failures (3%) are quite small, indicating that starting torque effects are in general well understood and allowed for by designers. Misalignment affects both gears and bearings, although some types of bearings (spherical roller bearings) are immune to it. They are also susceptible to damage from excessive forces used during fitting of couplings etc. Unfortunately, with the general trend in machinery to higher power, higher speeds, and higher stresses, the probability of resonant vibration occurring is ever increasing. It is difficult to separate these categories, which account for at least 25% of failures. Excessive churning from large, high speed gears immersed in the oil, can result in excessive temperatures. It should also be noted that lip seals can sometimes have a pumping effect, either pumping contaminants into the gearbox, or pumping lubricant out. Modern gear systems are in general very reliable

INTRODUCTION

Failure never occurs as an isolated event

Causes of gear failure may be due to a design error, an application error, or a manufacturing error. Design errors include such factors as improper gear geometry as well as the wrong materials, quality levels, lubrication systems, or other specifications. Application errors can be caused by a number of problems, including mounting and installation, vibration, cooling, lubrication, and maintenance. Manufacturing errors may show up in the field as errors in machining or heat treating.

AGMA recognizes four main modes of gear failure, plus a fifth that covers everything else. They are wear, surface fatigue, plastic flow, breakage, and associated gear failures. We can classify the types of failure into two

a) Failure where there is loss of drive, such as due to breakage of teeth.
b) Failure where the tooth form or tooth material is affected, such as in pitting scuffing etc.

The former type is called as Breakage Failure. The later is called as Surface Failure.

Breakage failure

Normally it occurs at the root of the tooth around the fillet which is under tension because this is the area which is highly stressed. Breakage may occur due to high stress or fatigue.

In failure due to high stress tooth breaks when the loading exceeds the ultimate tensile stress of the material. This type of failure is not very common and may occur due to load reaching accidentally high value, for example, due to drive getting jammed.

Fatigue failure occurs due to repeated action of load and after a number of cycles. If the actual load is more than the design load, then the gear will fail under fatigue at a reduced number of cycles.

This can be due to

a) Incorrect assessment of load (due to limitations in data availability)
b) Impact load (shocks due to the characteristics of the drive not taken into account).
c) Incorrect choice of material (design/procurement mistake/production mixup).
d) Increased load due to mal distribution of load (helix angle error due to distortion in heat treatment / manufacture error / axis alignment error / structural rigidity not enough)
e) Errors in gear teeth (relative velocity changes result in momentary acceleration and deceleration of the gear train resulting in dynamic load).

Surface Failure are of normally three types.

a) Failure due to pitting
b) Failure due to plastic flow
c) Failure due to scoring or scuffing.

Pitting

Pits are formed on the tooth flank. These pitted areas can occur on both addendum and dedendum areas. The most commonly accepted explanation for pitting is like this. Initially a crack is formed in tooth flank, which may occur due to various reasons. One may be that there are high spots in the flank surface which carry the load initially, and these localized stresses may exceed the limiting fatigue strength of the material. If this stress persists for a larger number of contacts, a crack will be formed. Into this crack oil will be forced due to the oil film pressure. If the movement of the load is such that it closes the mouth of the crack, thereby preventing the oil from escaping, the pressure of the oil will increase more and more ad the load progresses further. This will extend the crack along the line of maximum stress and a pit will be formed. Viscosity of the oil also has got some effect on pitting.

Pitting can be avoided by having uniform loading of the tooth instead of having load concentration, increasing the surface strength by a) case hardening, and b) using material of higher ultimate tensile strength value. It can also be avoided by using high viscosity lubricants.

Plastic flow

With softer steels, when the loading is high enough to exceed the yield stress, plastic flow of material takes place. This can be avoided by using better material having more yield stress value and by reducing the load by increasing the tooth width or by increasing the hardness of the steel used.

Scuffing (Scoring)

When the film lubrication breaks due to heavy load or poor surface finish of the tooth metal to metal contact takes place and the temperature raises to an extent that welding takes place. With further rotation the welding separates there by one tooth takes material from the flank of the mating flank. When no corrective action is taken to stop the breakage of lub film scuffing increases progressively and the tooth gets damaged. To prevent this use high viscosity oil as well as use of EP additives, and forced lubrication systems help a lot in reducing scuffing.

When a gear is suspected of showing signs of failure, if possible it should be examined periodically over time. Recording contact patterns or taking photographs at intervals will aid in comparison and help determine whether the condition is progressive. Keep in mind also that failure never occurs as an isolated event. Two or more failure modes may occur simultaneously or in succession, and the eventual failure mode may be different from the root cause.

An analysis

Gears and gearboxes are generally robust and reliable devices. However, problems do occur, and many are caused by unforeseen system interactions or consequences of the mode of operation, rather than gear faults per se. A prime observation is that gearbox failures frequently initiate in the bearings rather than the gears themselves.

A review of all gear and gearbox failures investigated shows that the failure sequence frequently starts with a bearing, rather than a gear. The results show that the failure due to bearing is 49%, the failure due to gear teeth are 41% and the rest 10% is due to various other factors.

This may at first sight seem surprising, since rolling bearings (used in the majority of gearboxes) seem to have a relatively easy job compared to the gears. The gears have substantial sliding in the tooth contact, and substantial bending stresses in the teeth. Rolling bearings have neither, just (nominally) pure rolling.

However, rolling bearings operate under high contact (Hertzian) stresses, and are susceptible to the effects of small debris particles in the lubricant. These may well be the reasons why the bearings frequently suffer before the gears.

A more detailed analysis divides the failures into further categories, as given below

Bearing failure - thermal instability 9%
Bearing failure - various factors 13%
Lubrication debris 19 %
Resonant vibration 9%
Unexpected loads 13%
Starting torques 3%
External contamination 9%
Manufacturing errors 6%
Gear misalignment 19%

Detailing

Starting torque related failures (3%) are quite small, indicating that starting torque effects are in general well understood and allowed for by designers.

Manufacturing errors (excluding design errors) are also quite small, at 6%. There are many cases where a minor manufacturing error or deficiency has been found. There is a tendency for users and manufacturers alike to identify a small manufacturing error and then correct it.

Generally, the gear design standards are conservative, and a manufacturing error has to be quite severe to be the prime cause of failure.

Misalignment

Misalignment affects both gears and bearings, although some types of bearings (spherical roller bearings) are immune to it. Misalignment is probably the most common single cause of failure. In gears it is exhibited as premature pitting at one end of the tooth. In bearings it may exhibit as pitting, or it may result in cage wear and failure.

There are many causes of misalignment, both static (manufacturing or setting-up errors) and dynamic, due to elastic deflections of components under load, and also due to thermal expansion.

On large gear systems where setting-up and alignment may be done during installation, it may be impractical to physically check that the shafts are parallel to the required accuracy. In such cases, blueing checks on the teeth are correctly regarded as the best way of confirming correct alignment. If the drive operates with torque in both directions, it is essential to check the tooth bending for both directions. The reason for this is that it is quite feasible for the shafts to be misaligned in such a way as to give good tooth contact in one direction, but severe end-loading in the other direction.

There is a natural tendency to minimise the number of stages in a gearbox, and this sometimes results in very long and slender pinions, which are often made integral with the shaft. Such pinions can suffer from relatively large bending deflections, and also from torsional wind-up.

With geared motors, to avoid use of couplings etc., it is common to mount the gearbox input pinion on the motor. This overhung pinion then may deflect substantially, causing misalignment at the input stage.

It is common to support shafts in a pair of spherical roller bearings one being fixed to carry axial loads, the other being free to float in its housing.

Gearboxes adjacent to hot machinery or hot processes may suffer misalignment from thermal growth. The hot side of the gearbox expands more, resulting in shaft centre distances increasing on that side.

Misalignment effects tend to be more severe on larger units. This is because the required accuracy of mesh contact (or bearing alignment) does not vary substantially with size, whereas the difficulty of achieving it is greater with large units.

Bearings

Most small and medium sized gearboxes use rolling bearings, with plain bearings being used on very small sizes (for simplicity), and on very large sizes (for improved performance). However, for the vast majority of industrial gearboxes, rolling bearings are the appropriate choice.

Rolling bearings have been found to be quite sensitive to various effects, including misalignment (not all types), debris, lubrication deficiencies, contamination, and vibration and shock. They are also susceptible to damage from excessive forces used during fitting of couplings etc.

A particular problem occurs when designs of gearbox, which may have been designed mainly for horizontal shaft orientation, are used with vertical shafts. A typical problem which can arise is that any debris or contaminants accumulate in the bottom, and result in wear of the bottom bearings. Of course, as long as the oil remains clean, there is no problem, but this type of design is clearly sensitive to any external contamination, or even to the effects of the small amount of wear debris from gear teeth in normal operation. Where contamination is likely to occur, a substantial sump area below the bearings is highly desirable, where contamination can collect and do no harm.

Thermal instability

It is a mode of failure which is becoming more common on many classes of machinery, including gearboxes. It is very difficult to diagnose with certainty from examination of failed parts, because often all that remains is blackened, twisted bits of metal.

This failure mode occurs when a large temperature difference builds up between the shaft inside a bearing and the housing surrounding the bearing. The differential thermal expansion causes the bearing to lose internal clearance and become pre-loaded. This results in increased heat generation which will increase the differential temperature. This is positive feedback which rapidly leads to thermal runaway and melt-down.

The mechanism is classically associated with high speed shafts, and is most likely to occur soon after start-up. This is because the shaft has much less thermal mass than the housing, so during the warm-up period a differential temperature occurs naturally, perhaps building up to 130 degrees differential during the first 10 minutes of running, then dropping back to about 10 degrees as temperatures stabilise. Various features can make this form of failure more likely, including high speeds, rapid acceleration, hollow shafts, external heat conducted into the shaft, and many more.

The failure may happen with a single ball or roller bearing, but is more common with a pair of locating bearings on a shaft, perhaps a pair of taper roller bearings in face-to-face configuration. With this set-up, both radial expansion of the shaft and axial expansion combine to reduce clearance and increase preload. Therefore this configuration is particularly prone to this problem. A better arrangement is back-to-back, as the radial and axial thermal expansions counteract each other.

Even where two spherical roller bearings are used, with one free to slide in its housing, this mechanism can still occur. This is because the sliding bearing may jam in its housing, either due to corrosion, or due to relative thermal expansion during warm-up.

As mentioned above, this mode classically occurs during an early life start-up, preferably in cold weather. However, it can still happen later in life, perhaps triggered by increased rates of heat generation as a result of bearing or lubrication degradation.

Torsional and Lateral Vibration

Resonant torsional vibrations and lateral vibrations always seem to come as a surprise, except in classes of machine such as turbine trains where they are analysed as a matter of course. Unfortunately, with the general trend in machinery to higher power, higher speeds, and higher stresses, the probability of resonant vibration occurring is ever increasing.

Analysis is in principle fairly simple, if all the relevant masses, inertias and stiffnesses are known. For components such as motors, driveshafts and flexible couplings, these data are either given or easy to calculate. However, for gearboxes, the same cannot be said. Attempts to theoretically analyse the torsional stiffness are fraught, and measurements are greatly preferred. If the system designer is to be able to analyse the torsional and lateral vibration frequencies, he/she needs data from the gearbox manufacturers.

Additional complications arise in the calculation of mounting and supporting structure stiffness, which also affect the natural frequencies.

If torsional vibration is suspected, it is usually necessary to instrument a driveshaft or gearbox shaft and measure it. This is because the magnitude of the vibration is strongly dependent on the damping, to the extent that a system operating at resonance may have torque fluctuations of only a few percent, due to inherently good damping.

Lateral critical speeds (shaft whirling) have occurred on some occasions purely from the mass of a flexible coupling or fluid coupling mounted on the gearbox input shaft. This is relatively easy to analyse if the gearbox internal arrangements are known.

Unexpected loads

Unexpected torques and forces can occur for a multitude of reasons. A few of general interest are mentioned here. Cardan shafts (with universal joints) operating at large angles, 5° or more, cause pulsating bending moments at 2 x shaft frequency, which can excite lateral resonance on the cardan shaft, or other resonance in the system.

Over-sized electric motors, which are frequently specified, can give excessive starting torques, and can also change the system resonant characteristics. Even with controlled soft-start characteristics, over-sized motors are dangerous; the operators may re-program the soft-start system to improve performance.

Locked in torques can occur with multiple path drive systems. Those who have driven a 4-wheel drive vehicle on tarmac with the front-rear differential locked will know about this phenomenon. It has been known to shear gear teeth on mono-motor bogies (one motor driving 2 axles).

Shaft torsional deflections on multiple path systems can result in the torque being maldistributed between the paths. On one design of crank press, these deflections led to one pair of gears carrying 75% of the torque, instead of the intended 50%.

Lubrication and contamination

It is difficult to separate these categories, which account for at least 25% of failures. The lubricant viscosity is rarely critical to within one ISO grade. However, there have been some cases where too low a viscosity lubricant has led to disaster. Therefore if there is a choice, or an ambiguity, it is usually best to error on the side of high viscosity. The type of lubricant is more important, with some gears and gearboxes requiring E.P. lubricants in order to survive. Any gears with high degrees of sliding, eg. hypoid gears, are particularly critical.

Most horizontal shaft gearboxes are satisfactorily splash lubricated. Conventional speed limits for the use of splash lubrication can be exceeded by a factor of 2 or even 4 with careful development of guides and deflectors to distribute and circulate the oil correctly.

Vertical shaft systems however usually need a pump and circulation system to feed the upper bearings and gears. Problems which typically occur with these are failure to prime the pump, debris clogging the pump and filter (if fitted), and mal distribution of oil between the various bearings. If there is any possible doubt regarding the direction of rotation in service, then a bidirectional pump should be used.

Excessive churning from large, high speed gears immersed in the oil, can result in excessive temperatures. This usually only applies to the higher speed shafts.

Breathers and vents are a problem area, particularly for outdoor duty. Falling temperatures at night or due to rainfall inevitably cause moist air to be sucked in through the breather. Intermittent operation, with periods of weeks or months between runs, is often blamed for failures. Unless there is evidence of water contamination, or damage from vibration while stationary, it is difficult to see why intermittent operation should necessarily be a problem. However, if the manufacturer's instructions suggest the units be run at certain intervals, it is obviously wise to comply.

Sealing is an area where little attention is paid, because in the majority of cases, simple lip seals to retain oil and exclude contaminants are adequate. However, in outdoor or corrosive environments, corrosion of the running surface of the shaft under the seal can soon render the seals useless. For such applications it may be necessary to specify a corrosion resistant sleeve (stainless steel or similar) on the shaft. It should also be noted that lip seals can sometimes have a pumping effect, either pumping contaminants into the gearbox, or pumping lubricant out.

CONCLUSION

In gearboxes and gear systems, problems occur at least as frequently with the bearings as with the gears. Overall system dynamics need checking if the design falls outside any parameters of successful existing systems of the same type. (Parameters include power, power density, speed, size, environment etc.) Modern gear systems are in general very reliable. Attention paid to the types of failure modes discussed in this should result in even greater reliability.

REFRANCES

1. Gray De Lanji Filure analysis for Gearing.
2. Sandy Poliak I Mech. Engg. Gear Confrence in Londan.