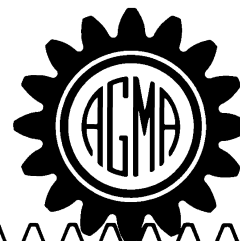


The Effect of Start-Up Load Conditions on Gearbox Performance and Life - Failure Analysis and Case Study

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American Gear Manufacturers Association



TECHNICAL PAPER

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

Most gearboxes are rated based on one or more of several criteria such as peak applied load, nominal operating load, prime mover rated power, driven machine load spectrum, maximum expected overload, etc. These load conditions are used to predict the expected operating life of the gear (and bearing) system. In many cases, especially where the load and/or speed vary significantly during the normal operational cycle of the gear system, a great deal of attention is paid to the spectrum of load conditions, often resulting in the definition of extensive load/time tables which are used in a Miner's rule (cumulative damage theory) or Weibull approach to the calculation of the expected life for gear systems under these widely varying load/speed/time conditions. While all of these are very valid methods of determining the expected life of a gear system, one important factor is very often neglected – the starting load! If a gear system is started up and then run continuously for long periods of time or if the starting loads are very low and within the normal operating spectrum, the effect of the start up conditions may, and often is, insignificant in the determination of the life of the gear system. Conversely, if the starting load is significantly higher than any of the normal operating conditions and the gear system is started and stopped frequently, the start up load may, depending on its magnitude and frequency, actually be the overriding, limiting design condition. In these cases, failure to account for the startup load¹ conditions in both the basic design of the gear system and in the proper attention to the details of tooth modification can lead to premature, seemingly unfathomable, failures.

This paper addresses the issue of start up loading and its effect on the performance of a series of gearboxes in an industrial application by way of a specific case study. A description of the failures that occurred and the test program and results that led to a definition of the root cause of the failures and a path of correction are also presented.

While not addressed in this paper, it should be noted that shut down load can, in rare cases, also be extremely significant in the design of the gears system due to the very high, short term loads that can be applied in certain applications. In one case in the author's experience, for example, a gearbox that was used in a high speed turbo compressor application failed due to very high loads that were caused by an improper shut down procedure on the driven machine that generated high back pressures and inertial forces sufficient to damage the gears.

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Introduction

When gearboxes are used in applications in which the connected load has high inertia, the starting torque transmitted by the gearbox can be very much higher than the rated load of the prime mover. Power plants often require several evaporative cooling towers or large banks of air cooled condensers (ACC) to discharge waste heat, Figure 1. Because of the very large size of the fans used in these applications, they fall into this category of high inertia starting load devices.



Figure 1. Air cooled condenser bank

The typical evaporative cooling tower or air cooled condenser unit is composed of an electric motor which drives a large fan through a gearbox. This assemblage generates air to flow for the purpose of removing the waste heat from the power generation process. In a typical air cooled condenser application, many identical units (typically 20 to 40) are installed in an array to provide the total cooling required for a large plant. Depending on the type of plant, these geared fan units may operate almost constantly ("base load" plants) or very intermittently ("peaking" plants).

The fans in these units are generally very large and thus have significant inertia, Figure 3. When started from zero speed, a very high torque is required to accelerate the fan to normal operating speed. If the fan is started infrequently and run continuously for

long periods of time, this high starting torque is of minimal significance. However, when the fan is started and stopped frequently, the number of cycles at the high starting torque can accumulate to a point where they can cause extensive fatigue damage even if the gear system is adequately rated. Where the gear unit is marginally rated, very early, catastrophic gear failure is often the result.

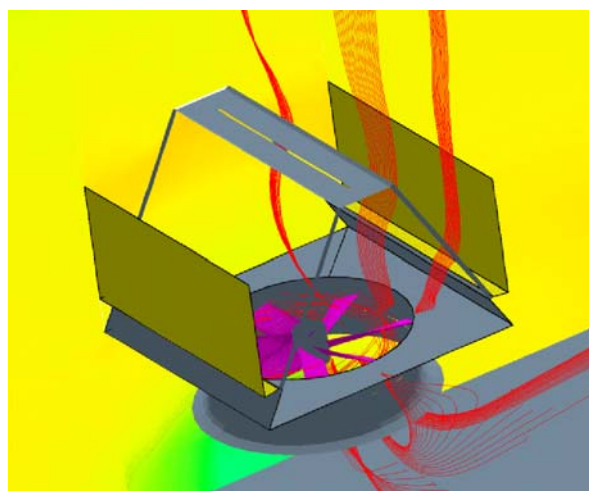


Figure 2. Air cooled condenser schematic



Figure 3. Installed air cooled fan

As part of the overall investigation of several failures in such gearboxes, we measured starting torque on a typical installation, examined many failed gears, and calculated the load capacity ratings for the gearboxes under actual operating conditions. This paper describes the failures observed, the testing conducted, the data analyses and the effect of the high measured starting torque on the life and performance of the gear systems. The test results revealed surprising results, especially during starts where the fan was already wind-milling due to natural air flow in the ACC bank. In the final analysis, the importance of appropriate profile modifications is also clearly demonstrated, Figure 4.



Figure 4. Spalled single tooth

The initial incident

A failure was reported in the low speed gear set of a triple reduction, single helical gearbox, Figure 5. The gearboxes are used in an Air Cooled Condenser (ACC) facility at a power plant and had been in service for about four years at the time this investigation was initiated.

The initial failed unit is one of thirty identical, units at the same facility, Site A. An identical bank of units, Site B, is also in service for a similar time period at a “sister” power plant in the same state. The first failed Site A unit that we examined had accumulated just over 13,000 hours of loaded service and during that time had been subjected to more than 7,000 start/stop cycles. All of the gears in these units are carburized, hardened, and profile ground.

Subsequent to this first failure, several additional, very similar, failures were also discovered on Site A gearboxes. Additional, ongoing periodic visual inspections of the remaining gearboxes at Site A continue to reveal additional failures. Careful evaluation of the additional damaged low speed gears showed them to have very similar characteristics. It is clear at this point that all of the units at Site A are very likely to eventually suffer similar failures over time.

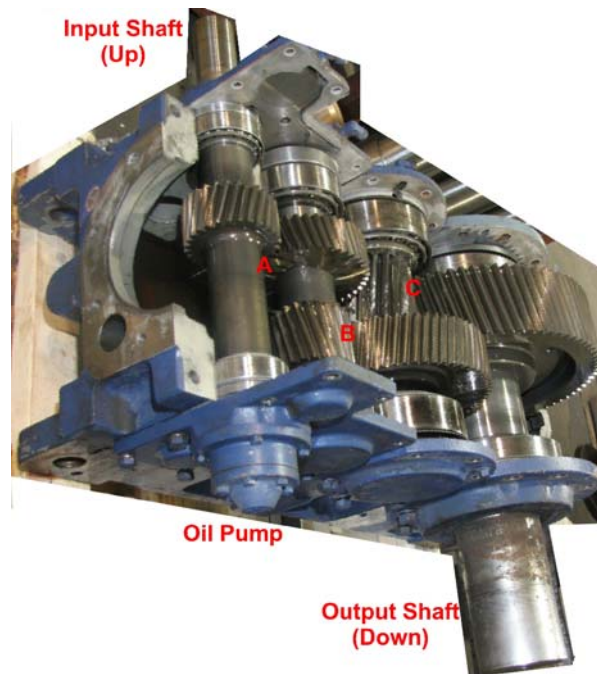


Figure 5. Triple reduction gearbox (shown in normally installed attitude)

It was initially reported that, though the systems (gearboxes, fans, motors, controllers, etc.) were identical at the two sites, the gearboxes at Site B had not experienced any failures. As the investigation progressed, however, we did find some indications of very early stage failures on low speed gears at Site B which were very similar in nature to those observed on Site A. The extent of the damage observed on the Site B low speed gears was much less than that observed on the low speed gears on the Site A gearboxes and to date none of the Site B gearboxes have actually been removed from service due to low speed gear damage.

Obviously, since the units are truly identical at both sites, this concentration of failures at Site A and lack of any apparent failures at Site B was something of a puzzle. Even with the discovery of some very early stage damage on the Site B low speed gears, it is clear, that something is different between the two sites.

After in depth evaluation of the characteristics of the sites, the only significant difference identified was the fact that Site A was operated as a “peak load” plant while Site B was operated as a “base load” plant. In the operation of a base load plant, the fans would run almost continuously with very limited start/stop cycles. In contrast, the operation of a

peaking plant involves multiple, frequent start stop cycles.

While the number of start/stop cycles is different between the two sites, the nominal power draw on the motors at both sites A and B during normal, full speed, steady state operation was found to be very much the same.

The failure

Initial evaluation of the gearbox indicated that the primary damage was on the low speed gear set. The high speed and intermediate gear sets did show some damage but it was largely consequential. The low speed gear, Figure 6, exhibited a very hard line of contact near the tip of the tooth. This hard, localized region of contact indicates that the tooth did not have sufficient profile modification for the applied loading. The shape of the damaged area suggests that the gear set had some crowning (probably applied to the pinion) to accommodate misalignment. The damage pattern observed on the gear tooth loaded flanks, however, is slightly heavier on the left end of the face (Figure 6). The relatively short area of damage indicates that the crown applied to the low speed gear mesh is likely to large for the applied loading. This tends to concentrate the load in the center portion of the face while unloading the ends of the face. This increases the localized stresses in the heavy contact region. This is very apparent on the loaded tooth flanks shown in Figure 6.

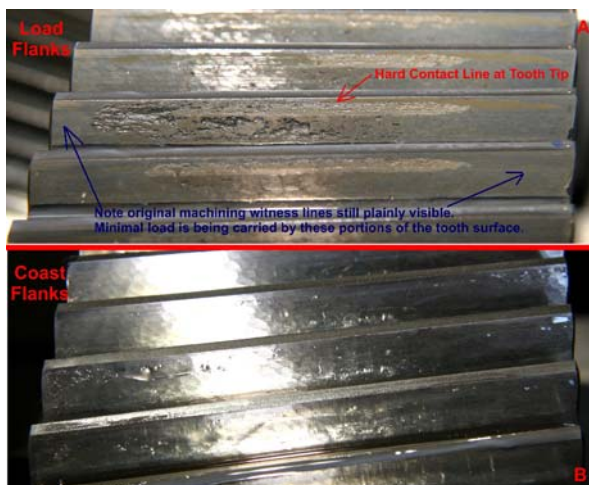


Figure 6. Low speed gear

The location of the damage observed on the low speed pinion, Figure 7, corresponds to the damage observed on its mating gear; however, the level of damage on the low speed pinion is much more severe than that on the mating low speed gear. Since the pinion sees many more cycles than the pinion, the disparity in the level of damage is expected. The location of the very hard line of contact near the tips of the gear teeth corresponds closely to the similar hard line of contact at the lowest contact point on the pinion teeth. As noted above, this hard contact indicates a lack of adequate profile modification on the pinion or gear or both.



Figure 7. Low speed pinion

The specific failure mode observed on the pinion is spalling which is a type of surface durability distress. Specifically, spalling is a fatigue mechanism that occurs when very high local stresses initiate cracks at or near the tooth surface. These cracks progress into hard case on the tooth surface and progress up along the tooth surface from the lowest contact point in the direction of sliding on the tooth surface. As the cracks progress, material on the tooth surface is “undermined” and eventually relatively large, somewhat fan shaped pieces of tooth surface are liberated. This mechanism is clearly shown in Figure 7. As the cracking progresses through the carburized case on the loaded flanks of the teeth, it eventually propagates across the tooth thickness, generally fairly close to the tips of the teeth and fractures the entire case off the tooth, even extending back onto the coast flanks. Essentially, the carburized case is “peeled” from the loaded and unloaded tooth flanks. More detail on this failure mode will be presented below.