PRACTICAL FACTORS AFFECTING GEAR UNIT BEARING LIFE

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INTRODUCTION

It has become standard practice for conveyor manufacturers to specify the bearing life required of a conveyor gear unit. In the recent past it was accepted that the bearing life of a gear unit should be 50 000 hours $L_{10h}a_{23}$. Prior to that no bearing life was specified and gear units were sized and selected purely for its mechanical and thermal capabilities. Today that is no longer the case If a gear unit is sized and selected today, the driving factor is bearing life requirements. Many end users today specify an $L_{10h}a_{23}$ life of 100 000 hours.

Due to the emphasis being placed on bearing life, it has become extremely important that the concept of bearing life, what it means, the limitations and exceptions, be fully explored and understood. The purpose of this paper is to display how the concept of L_{10h} bearing life can be understood within the realm of practical and realistic operating conditions.

BEARING LIFE AND PRACTICAL OPERATION

Bearing Life Rating

Conventionally, bearings are rated in terms of L_{10} life. L_{10} life is that life which 90% of a group of bearings operating at a given set of conditions will complete or exceed. Failure of bearings, in terms of L_{10} life, is defined as the first occurrence of fatigue on one of the rolling elements or on one of the raceways. This fatigue is usually in the form of spalling. The L_{10} life concept is based on extensive experimental data. It has also been found that the median life or life that 50% of a group of bearings will achieve is five times that of the L_{10} life.

The term 'rating life' and 'life' of a bearing has been standardised as the L_{10} life by organisations such as American National Standards Institute (ANSI) and the International Standards Organisation, hereafter referred to by its acronym ISO. The dynamic load ratings and rating life of roller bearings are standardised in the ISO standard *ISO 281: Roller bearings- Dynamic Load Ratings and Rating Life*. It is important to note that the L_{10} life concept is relevant only to fatigue of the rolling elements and raceways. It must be stated, and stated clearly, that failures due to causes such as wear, excessive heat generation and retainer failure are not covered by the L_{10} life concept and in many cases limit bearing life.

Understanding L10 Bearing Life

All gear applications, excluding those of spur and double helical gears, generate a combination of radial and axial loads. These loads are carried by the bearings located within the gear unit.

When calculating the L_{10} life of a bearing, this combination of axial and radial loads must be converted to an equivalent load. This equivalent load is equal to the constant stationary radial load which applied to the same bearing with a rotating inner ring and stationary outer ring, would yield the same life as the actual combination of loads [1]

One general equation is used for this conversion:

$$P = XF_r + YF_a \quad (1)$$

Where P is the Equivalent Dynamic Load [N]
F_r is the Radial load component [N]
F_a is the Axial load component [N]

The factors *X* and *Y* are respectively known as the Radial factor and Thrust factor. These factors are bearing specific and are found in bearing manufacturers' catalogues.

The basic life equation, as given in equation *2*, represents all roller element bearings as covered in ISO 281.

$$L_{10} = \left(C / P\right)^{n} \qquad (2)$$

Where L_{10} is the basic life rating [x10^6 rev]
C is the basic bearing load [kN]
P is the equivalent dynamic load [kN]
n is the bearing specific life exponent
$n = 3$ for ball bearings
$n = 10/3$ for roller bearings

L_{10} life is not commonly used as it is expressed in millions of revolutions. This is a cumbersome way to deal with bearing life. Hence, L_{10h} life is commonly used, as it is expressed in the easier to use from of hours of operation. The L_{10h} life is calculated using equation 3 or 4 below.

$$L_{10h} = \left\{10^6 / \left(60 \times N\right)\right\} \times L_{10} \qquad (3)$$

$$L_{10h} = \left\{10^6 / \left(60 \times N\right)\right\} \times \left(C / P\right)^{n} \qquad (4)$$

Where L_{10h} is the basic life rating [hrs]
L_{10} is the basic life rating [x10^6 rev]
C is the basic bearing load [kN]
P is the equivalent dynamic load [kN]
n is the bearing specific life exponent
N is the rotational speed of the bearing [rpm]

Bearing Life: The Case Study

Consider a common conveyor application of a gear unit with a shaft supporting two gears, a pinion and a wheel. For a given power and speed, the L_{10} bearing life was calculated for varying axial and radial load contributions. The load conditions were varied using the helix angle to alter the axial load contribution, while the radial load remained nearly constant, due to the power and speed remaining constant. The bearing life was calculated for both spherical and taper roller bearings, as these are most commonly used within gear units.

The data for the case study was populated onto the graph, figure 1.

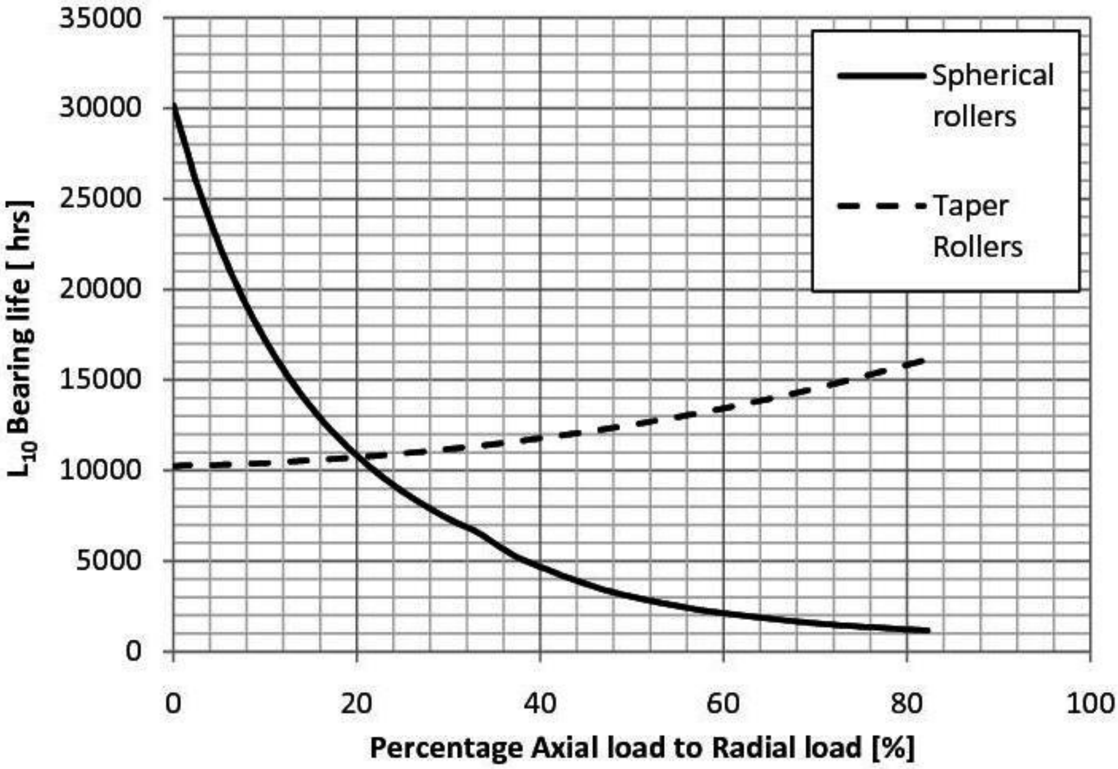

Figure 1. L_{10} bearing life with percentage axial load

The case study yielded four pertinent facts:

1. For spherical roller bearings there is a rapid deterioration of L_{10} life with an increase in the axial load.
2. Taper roller bearings show a moderate increase in bearing life with an increase in the axial load.
3. For Helical gearing, where spherical roller bearings are preferred, the axial load should be less than 20% of the radial load. Otherwise the use of taper roller bearings should be considered.
4. For Bevel gears, with high axial loads, the preferred bearings should be taper roller bearings.

It is also interesting to note that there exists a percentage axial load point at which both spherical roller and taper roller bearings will theoretically achieve the same L_{10} bearing life.

This is important to gear unit manufacturers, as both the loading conditions, radial and axial load contributions, and the type of bearing used, need to be balanced to provide not only the most efficient mechanical solution, but also an economical one.

Gear Unit Bearing Life

The L_{10h} life typically referred to specifies the life of a single bearing and not that of the gear unit.

The L_{10h} life for a gear unit assembly consisting of *n* number of bearings is calculated as expressed in equation *5* [2].

$$L_{10h}(ass) = \left(1/L_{10h}(1)^{1.5} + 1/L_{10h}(2)^{1.5} + ... + 1/L_{10h}(n)^{1.5}\right)^{-1/1.5} \quad (5)$$

Where $L_{10h}(ass)$ is the L_{10h} life for the gear unit as an assembly [hrs]
$L_{10h}(1); L_{10h}(2); L_{10h}(n)$ are the L_{10h} life for the individual bearings in the assembly [hrs]

The standards that gear unit manufacturers use, such as AGMA, are generally and historically quite lax with regards to bearing life requirements. The minimum criterion for an L_{10h} bearing life at a mechanical service factor of 1.00 is as low as 5 000 hours. For a continuously operational gear unit this amounts to 6.9 months of operation.

Often the bearing life specified is 50 000 hours to 100 000 hours. This equates to 5.71 years to 11.42 years of continuous operation. However, this too may not be realistic.

So what should a conveyor gear unit end-user specify? Do all the gear unit manufacturers provide the same calculated bearing life? It would be preferential to end-users to specify the recommended minimum individual L_{10h} bearing life in accordance with ISO 281.

Gear Unit Assembly Bearing Life versus Individual Bearing Life

A triple reduction, right-angled gear unit, such as those commonly used for conveyor applications, has eight bearings within its assembly as depicted in figure 2.

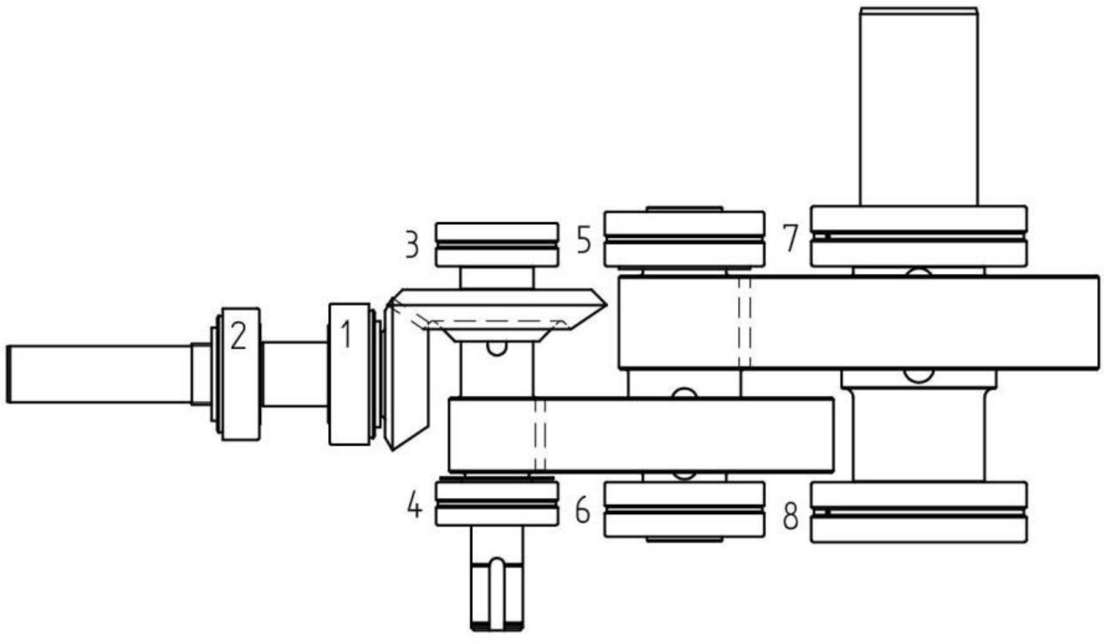

Figure 2. Typical conveyor gear unit layout

The individual L_{10h} bearing lives are as follows:

Bearing	L_{10h} life
1	174,248
2	165,598
3	125,120
4	61,166
5	131,731
6	111,276
7	993,794
8	26,713,820

Table 1. Individual L_{10h} bearing life for a typical conveyor gear unit

If the above unit were to be adjudicated on its individual bearing life, it would be stated that the bearing life of bearing 4 is the limiting life at 61,166 hrs. *How realistic is this assumption?*

However, should one consider the gear unit assembly bearing life, as expressed in equation *5:*

$$L_{10h}(ass) = \begin{Bmatrix} 1/174,248^{1.5} + 1/165,598^{1.5} + 1/125,120^{1.5} \\ +1/61,166^{1.5} + 1/131,731^{1.5} + 1/111,276^{1.5} \\ +1/933,794^{1.5} + 1/26,713,820^{1.5} \end{Bmatrix}^{-1/1.5} \quad (6)$$

$$L_{10h}(ass) = 336086hrs$$

The L_{10h} life for the assembly is calculated as being as low as 33,086 hours. This however, is also unrealistic, as this states the unit will only have 3.78 years of continuous operation.

The a_{23} Factor

The a_{23} life adjustment factor was first introduced by ISO in 1977. The a_{23} life adjustment factor adjusted for material and lubrication. The adjusted L_{10h} life is known as $L_{10h}a_{23}$ or $L_{10h}a$ bearing life.

The a_{23} factor was originally introduced due to the upgrading of steel quality over the years improving the bearing lives achieved. It was felt that lubrication conditions should also be taken into account. Hence, the value of the a_{23} factor is a function of the viscosity ratio. The viscosity ratio is defined as the actual viscosity (v) divided by the viscosity required for adequate lubrication at the operating temperature (v_1). This ratio represents the size of the oil film thickness relative to surface irregularities of the bearing elements. The required viscosity is determined from figure 3.

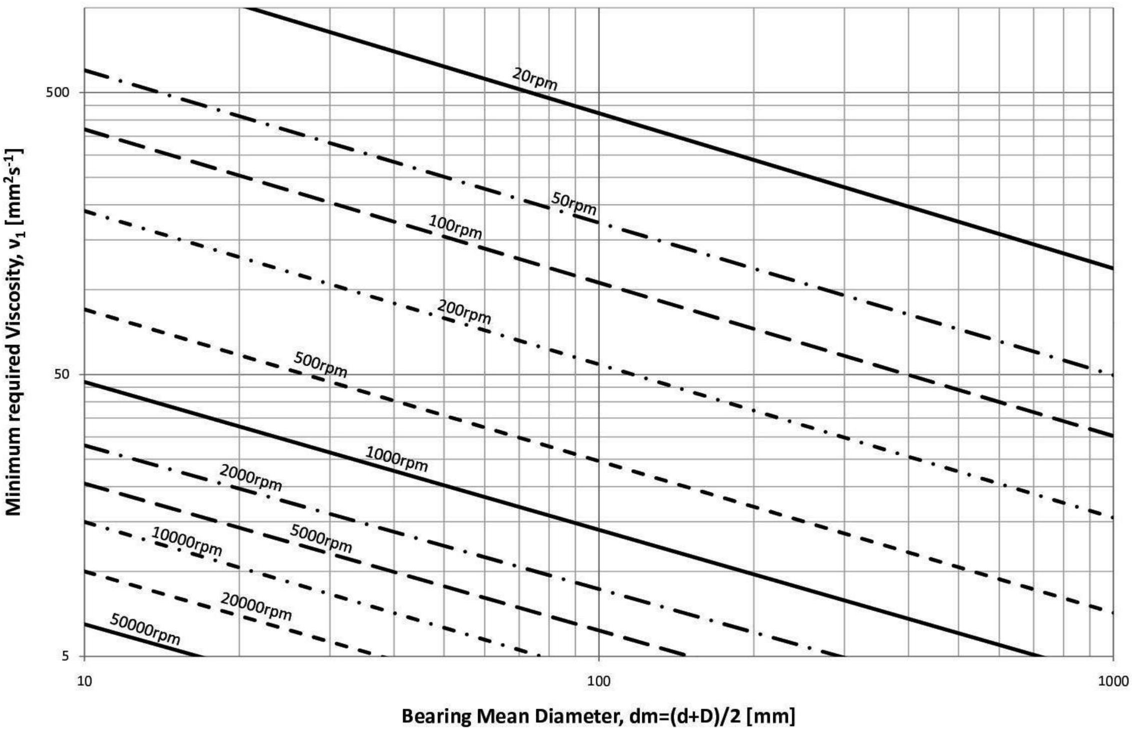

Figure 3. Minimum required viscosity, v_1 [Reference 3]

The actual viscosity of the lubricant is dependent on the lubricant used. The actual viscosity is determined at the operating temperature of the gear unit. Figure 4 below shows the operating viscosity versus the operating temperature.

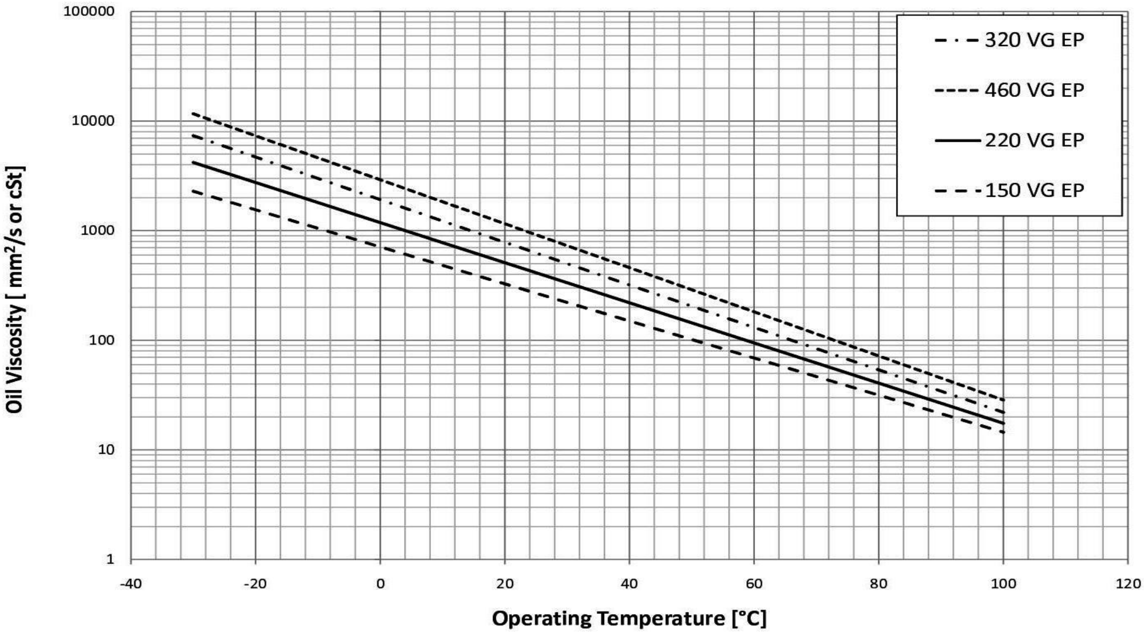

Figure 4. Actual operating viscosity, v

The a_{23} life adjustment factor is determined using figure 5. The value for the a_{23} factor can vary between 2.5 and 0.45. An a_{23} value of 2.5 represents ideal lubrication conditions and material.

Figure 5. a23 Life adjustment factor graph

With regards to a typical conveyor gear unit, the a_{23} life adjustment factor can vary from 2.50 at the input to 0.67 at the output. With reference to figure 3, it can be seen that for a smaller bearing, mean diameter and higher rotational speed, as experienced on the input shaft of a gear unit, the minimum required viscosity is lower. The converse is found with regards to the output shaft. Because the actual operating viscosity is constant within the gear unit, it will be found that the viscosity ratio for the input shaft of a gear unit will be substantially higher than that of the output shaft. This results in a lower a_{23} life adjustment factor for the output shaft than that of the input shaft. This is typical for most conveyor gear units operating at bearing temperatures of 60 °C to 90 °C with either ISO VG 220 or ISO VG 320 gear lubricating oil. This means that on the output line of the gear unit, the L_{10h} life exceeds that of the L_{10h}a life.

However, it should also be stated that the a_{23} factor was superseded by the a_{ISO} factor. At its conceptualization, the a_{23} life adjustment factor only took into account material of the bearing and the lubrication of the bearing at a standard cleanliness condition. The reason for the change of factor was to take contamination of the lubrication into account. It was found that the effects of lubrication contamination on the achieved bearing life were indeed significant. This is seen in the situation where abrasive wear due to contamination changes the load zones of the bearing, resulting in a reduced load carrying capacity and reduces achieved bearing life. Hence, due to the nature of industrial applications and the operating environment, especially that of the conveyor, the a_{23} factor cannot fully adjust for lubrication effects within a gear unit.

It must also be stated that there are many other life adjustment factors. Some of these factors are manufacturer specific. End-users must ensure that all life adjustment factors used with regards to gear unit bearing lives are evaluated and validated.

The Practical Effects of Large Fluctuations in Operating Temperature

It has long been noted that a relationship between bearing life and temperature exists. It has also been found that there exists a temperature band in which both the bearing and its lubricant can operate at peak performance. However, once outside this range, the performance of both these degrade at an accelerated rate.

The peak performance temperature band is dependent on the lubricant and bearing used, as well as the combination of these two. It is generally accepted that this temperature band ranges from 40 °C to 100 °C. It should also be emphasized that for most standard lubricants, with every 15 °C increase in temperature above 70 °C, the lubricant life is approximately halved, and there is a corresponding negative effect on the bearing life. Mineral oils operating above 80°C or 90°C display greatly diminished life.

At low temperatures, such as -20 °C to 0 °C, the viscosity of the lubricant becomes very high Although it is generally accepted that a thicker EHD (or *E*lasto*H*ydro*D*ynamic) film thickness gives more protection, at too high a viscosity the bearing elements begin to skid, drag and overheat. These conditions are not covered by the L_{10h} life concept and rapidly reduce the achieved bearing life.

Large variations in operating temperature have a large effect on the achieved bearing life. This is due to a decrease in the oil film thickness, increasing the stresses in the contact region of the bearing, while simultaneously, the temperature increase reduces the fatigue stress limit of the material and increases the hoop stress experienced in the raceway due to thermal expansion of the raceway and rolling elements. The basic L_{10} life concept does not take this effect into account, neither does the a_{23} life adjustment factor, as it only considers one operating temperature.

Temperature fluctuations also have an effect on the a_{23} life adjustment factor commonly used for conveyor gear unit life. For a given bearing at a given speed, the a_{23} factor was determined, as displayed in figure 6.

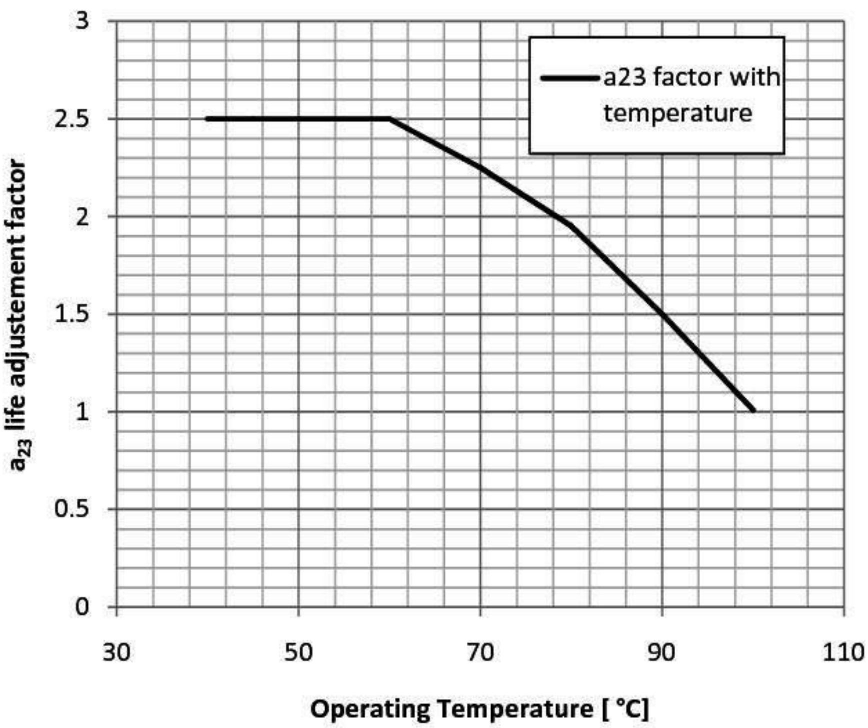

Figure 6. a_{23} Life adjustment factor with operating temperature

The data clearly showed that for large fluctuations in temperature, there is a correspondingly large variation in the a_{23} life adjustment factor. So for a unit that operates at 60°C above the surrounding ambient temperature that can vary between 0°C- 30 °C in a single operating cycle, the a_{23} factor will range between 2.5 at an operating temperature of 60 °C and 1.5 at an operating temperature of 90 °C. If the bearing considered in Figure 1 with a 20% axial load percentage is considered, this means that the bearing actually has an $L_{10H}a_{23}$ life of between 16 500 hours and 27 500 hours. If the criterion established by the end-user was 25,000hrs then under most of the gear unit's operating range, the unit would not theoretically achieve the requested bearing life.

This also brings forth an interesting point of discussion for gear unit end users: *at what temperature should the a_{23} life factor be determined, as only one temperature can be used*? From the above discussion, it can also be noted that the temperature at which the a_{23} factor is calculated can be manipulatively chosen from the operating temperature range to suit the gear unit manufacturer's needs, not those of the end users.

Practical Factors Affecting Bearing Life

Misalignment

Another practical factor that can affect bearing life is misalignment. The misalignment as discussed here can have two components- angular and offset. This misalignment can occur in both the horizontal and vertical planes. Each alignment plane has offset and angular components. When shafts are misaligned, forces are generated that may produce large stresses on both the rotating and stationary components within a gear unit. Although these stresses induced do not cause failure of the misaligned element, such as the gear unit couplings, it can lead to wear and fatigue of the bearings and failure of the shafts, also leading to bearing failures.

There are also thermal effects on misalignment to consider. The thermal changes in a gear unit are complex. Often the input and output shafts are at different temperatures. Hence, the shaft misalignments of a gear unit changes in both the horizontal and vertical planes. These induced misalignments may have an effect on the bearing lives of the gear unit.

If we consider the basic life equation:

$$L_{10} = \left(C / P\right)^n$$

If the equivalent load, *P*, increases by 10% due to the loads generated due to misalignment caused by installation and thermal effects, the basic bearing life rating is reduced by 27.2% for roller bearings and 24.87% for ball bearings. This reduction can have a significant effect on the achieved bearing life. If a bearing has a L_{10h} life of 106 948 hours without any misalignment, this bearing may only achieve a life of 77 847 hours. If the user requested a bearing life of 100 000 hours, this bearing does not meet that requirement if subjected to misalignment.

Light loads

In the case of light loads, the conventional L_{10} life concept will yield an unrealistically high bearing life This is due to the fact that under light load conditions the effects of lubricant contamination are greater in relation to the net effect of the general stress levels due to the applied load. Hence, for a light load, the bearing life is limited by the life of the lubricant.

At light loads, especially loads below the minimum load condition as specified by bearing manufacturers, the rollers will slide rather than roll, increasing the shear force within the lubricant, and results in an increase in friction within the bearing cage. This will cause elevated temperatures and a decrease in lubricant viscosity and effectiveness. This will significantly shorten the bearing life.

These conditions are also experienced on oversized gear units.

Acceptable operational conditions

For the L_{10} life concept to be representative and applicable, conventional operating conditions are assumed. These operating conditions include:

- Bearings are correctly mounted
- Adequate protection from foreign matter
- Adequate lubrication, with the correct viscosity
- Conventionally loaded
- No exposure to extreme temperatures
- Not run at exceptionally low or high speeds.

Once all these factors are coupled together the effect on the bearing life is no longer as insignificant as the factors may seem individually.

Variable Speed Drives and Bearing Life

It has become common practice to use variable speed drives (VSDs) on conveyors. However, very few people understand the implications on the bearing lives of a gear unit.

There are three conditions for VSD use on a gear unit:

1. Constant load and variable speed
2. Variable load and constant speed
3. Variable load and speed

1. Constant Load and Variable Speed

Before calculating the L_{10h} life, the equivalent speed must be calculated. Equation *7* [2] (International Standards Organisation 2007), as expressed below, is used to determine the equivalent speed for a constant load, variable speed VSD-controlled gear unit:

$$N_e = t_1.N_1 + t_2.N_2 + ... + t_n.N_n \qquad (7)$$

Where N_e is the equivalent speed [rpm]
N_1; N_2; N_n are the VSD-controlled speeds [rpm]
t_1; t_2; t_n is the fractional duration of use of each corresponding VSD-controlled speed

2. Variable Load and Constant Speed

With the occurrence that a VSD varies the load while the speed remains constant, the equivalent load must be determined. Equation *8* [2] is used to determine the equivalent load for a variable load, constant speed, VSD-controlled gear unit:

$$P_e = \left(t_1.P_1^n + t_2.P_2^n + ... + t_y.P_y^n\right)^{1/n} \qquad (8)$$

Where P_e is the equivalent load [kN]
P_1; P_2; P_y are the VSD-controlled loads [kN]
t_1; t_2; t_n is the fractional duration of use of each corresponding VSD-controlled load
n is the bearing specific life exponent

3. Variable Load and Speed

For the instance where a VSD will vary both the load and speed of a gear unit, the weighted L_{10h} life must be determined. This weighted life, equation 9 [2], is calculated after each condition of load and speed is taken into account with regards to the L_{10h} life.

$$L_w = \left(t_1 / L_1 + t_2 / L_2 + ... + t_n / L_n\right)^{-1} \quad (9)$$

Where L_w is the weighted L_{10h} life. [hrs]
L_1; L_2; L_n are L_{10h} lives calculated for each VSD-controlled condition [hrs]
t_1; t_2; t_n is the fractional duration of use of each corresponding VSD-controlled condition

The practical factors that influence the gear unit bearing life with regards to the use of VSDs are light loads and slow speeds that magnify the effects of lubrication and contamination.

Bearing Life and the Conveyor Industry

Most project specifications for conveyor gear units specify an L_{10h}a life of 100 000 hours, this equates to more than ten years of continuous operation.

This L_{10h}a bearing life specified refers to the lives of individual bearings within the gear unit, and not the bearing life of the gear unit as an assembly.

It is conventional for conveyor gear units to have splash lubricated bearings. Hence, at start up the bearings are essentially starved of lubrication, as is on certain gear units. This starvation at a start-up over a period of ten years may have profound effect on the operation and as a result the actual life achieved by the bearings.

Operational factors, such as alignment of the motor and the gear unit at installation and reinstallation may result in large amounts of strain of the bearing components due to an alteration in the loading of the said bearings, resulting in a reduced ability to carry the applied loads, as discussed previously. This may also deteriorate the bearing life achieved.

The ISO 281 concept of L_{10} life does not include these operational factors. Most bearing failures experienced on conveyor gear units are not the result of fatigue. It is generally found that if a bearing does not fail due to the effects of these operational factors, the bearing life achieved by the said bearing can greatly exceed the calculated L_{10h} life.

With the increased requirements of bearing life, larger and larger units are required for the same conditions. However, this may have the following implications:

- Economics: a larger unit costs more and has higher maintenance costs.
- Loading: The load applied to the larger unit, with larger bearings, may be too light. Resulting in the deterioration of the bearing lives.
- Installation: The larger the gear unit the more difficulty arises with regards to the installation, and alignment of the gear unit. This increases the chances of bearing life reduction due to misalignment.

It has been found that although larger bearings lives are being specified, requiring larger gear units, the time between bearing failure has not followed the same trend. So although the L_{10h} life has increased, the practical factors discussed in this paper lead to the same failures as on the previously smaller gear units.

Many end users spend increasing amounts on ever larger gear units. But are the manufacturers all supplying the same bearing life? It is in the best interests of gear unit end-users to specify one common format for bearing lives. It is the recommendation of this paper that the bearing life format be the ISO L_{10h} bearing life, and a specified bearing life value of 40 000 hours. This value is equivalent to the current commonly specified value of 100 000 hours

$L_{10h}a_{23}$ life. However, it does not allow for life adjustment factors, which as discussed in this paper, and do not adequately adjust for the practical operating conditions experienced in reality.

CONCLUSION

Understanding the result of a bearing life specification and its relationship to the practical operating factors that affect it is very important, especially today as the bearing life specifications escalate.

The important question to ask has been why are the required bearing lives escalating? The simple answer is that the end users want to maximize the operational life of their gear units But this is not so easily achieved. It is common after an end-user experiences a gear unit bearing failure, often not due to fatigue failure, that the bearing life requirement increases. This very often leads to larger gear units being required to meet this bearing life specification. However, by installing larger units, under the previous loading conditions, the light load factor becomes even more relevant than previous.

To optimize the bearing life and economics of a gear unit, the gearing should be designed with the bearings into consideration. The use of spherical roller bearings is generally preferred on helical gearing. As shown, the life of spherical roller bearings deteriorates significantly with the increase in axial load. Therefore, helical gearing, where spherical roller bearings are utilized, must have low axial loading. While for gearing with high axial loads, the preferred bearing should be taper roller bearings.

As discussed, most bearing life is limited not by fatigue, but by operational factors leading to wear and overheating. These operational factors include:

- Large fluctuations in temperature, as is common in South Africa, especially during the winter and spring.
- Unbalanced masses, due to misalignment during installation and reinstallation. However small, this does reduce the bearing life of the gear unit.
- Lubrication: Is it adequate and not contaminated?

As shown in this paper, the operational effects can result in a minimum of 30% deviation from the empirically based $L_{10h}a_{23}$ calculation. This means that the bearing life of a gear unit specified as 100 000 hours $L_{10h}a_{23}$ realistically will only achieve 7.98 years of service under normal South African operating conditions.

While conveyor gear unit costs increase, it is in the best interests of gear unit end users to specify one common, consistent format for bearing lives. It is the recommendation of this paper that the specified bearing life be 40 000 hours L_{10h} basic, which is equivalent to the current commonly specified value of 100 000 hours $L_{10h}a_{23}$ life.

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