High Expectations for Gearbox Bearing Lives

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Performance

Bearing specifications are written by companies for the purpose of defining anticipated machinery performance.

The traditional approach in writing such specifications for anti-friction bearings has been to request "calculated bearing life" for an L-10 life of 50,000 or 100,000 hours (hrs), as examples, based on an anticipated five (5) or ten (10) year operating life before "major repairs" are required. The L-10 bearing life is naturally understood to be a bearing's defined life expectancy (for the sake of engineering simplicity, bearing manufacturers define failure as a fatigue spall size 6 mm^2) based on a statistical 90 percent reliability *(Timken, p. 21)*.

To achieve such life values, calculation methods have become more and more sophisticated.

Traditionally, calculating L-10 was a matter of knowing the speed of the bearing (cycles), taking the equivalent load on that bearing and comparing it to the bearing's dynamic capacity.

Gearbox Performance

Today it is common practice to calculate an adjusted L-10, which takes the traditionally derived results, and allows for the influence of various operating parameters.

With the base L-10 calculation, everyone gets the same answer — which is not the case with adjusted L-10 calculations.

The predicament for the specification writer therefore becomes twofold:

Predicament #1: Given that an L-10 value has to be specified, what is a reasonable value?

Predicament #2: Given that adjusted L-10 calculations can sometimes appear to be a function of the wizard behind the curtain, how can one judge the validity of the lives calculated?

What to do

In this paper, we will explore methods that will aid in answering these questions for the author of the specification.

Predicament #1

Answering this question accurately and adequately requires more questions:

1. Have failed (catastrophic or no longer roll as intended) bearings been an issue?
2. How does that failure rate correlate to the expected life of the equipment?
3. Was it determined that the failed bearings were the cause of a stoppage, and not a consequence?

4. If it was the case that the bearings were the main failure component, and that their failure initiated other failures rather than vice-versa, how were those bearings selected?

5. Was it the correct style of bearing for the application?

6. Were there initiating factors, such as natural frequencies, or alignment and deflection issues (thereby generating loads not predicted) that were responsible for the failures?

7. Were there maintenance issues that needed to be addressed?

8. Is the specification value a commercial (marketing/sales/purchasing) tool?

From the above questions, it should be evident that a target for L-10 life MUST be based on some kind of performance experience vs. simply applying a value found in previous specifications.

If there is a bearing life expectation for a machine that has never been built before, then past experience of similar applications and expectations could certainly serve as a guide.

So, the answer to predicament #1 is really nothing more than to define the reason or reasons for the specified L-10 life — whether technical or commercial.

Assuming this has been done for a particular machine or system, we now have a target and can move on to the second predicament.

Predicament #2

In this case, the predicament for the specification author is how to judge the method that has led to the answer which claims to meet the specification.

The purpose of this paper is then to present tools to make such judgments, demonstrate their use, and provide insight as to how those tools may or may not lead to validating the claim of meeting an L-10 specification.

Bearing Calculations

First, let us assume that the intent of the specification is to have an operating life of 20 years.

- Assume the application runs 24/7 for 95 percent of the year.
- Operating hours per year = 0.95 x (24 hrs/day x 365 days/yr) = 8,322 hrs/yr.
- 20 yrs x 8,322 hrs/year (yr) = 166,440 hrs.

I have personally never seen an industrial specification that calls for such a value, so it is perhaps a good one to use as a calculation example.

As noted before, offering a base (unadjusted) L-10 is textbook: we all get the same answer within the tolerances of computer lint, based on vectors and dimensions.

So this should definitely be the first line of defense.

- 166,000 Hr L-10
- Method of calculation per standard equation L10 hrs = (revolutions or hours reference) x $(C90/P)^{exp}$ *(Timken, p. 21)*

However, even if we use the textbook calculation method, have we clearly defined the high expectation of a 20-year operating life, let alone calculated life?

The simple answer is "no."

Why not? What is at issue?

The *system life* is at issue.

Keeping things simple and staying with the textbook calculation method, if we assume a triple reduction gearbox, and are calculating the L-10 system life of the bearings, we are calculating the increased probability in finding the statistical 10 percent of the bearings that evidence the failure criteria.

This is not to say the bearing(s) that evidence the failure criteria will actually fail, i.e., stop rolling. It is just to say that the bearing(s) show clear evidence of a meeting a failure criterion.

In the example of a triple reduction gearbox, assume there are eight bearings, and assume further that each of these eight bearings has a minimum calculated base L-10 of 200,000 hrs, very comfortably over the 166,440 hr target. That means the L-10 system life (finding the bearing that shows the prescribed evidence failure) is as follows:

- L-10 system = $((1/L_{10A})^{3/2} + (1/L_{10B})^{3/2} + \ldots(1/L_{10n})^{3/2})^{-2/3}$ *(Timken, p. 47)*
- = $(8 \times (1/200{,}000)^{3/2})^{-2/3}$
- L-10 system = 50,000 hrs

This is clearly less than 166,440 hrs; and, uncertainty has now been thrown into using the 166,440 hr target. After all, we specified 166,440 hrs with the intent of prescribing that value as an operating parameter of the machine. We cannot close our eyes to the fact that there is more than one bearing, correct?

So, it is obvious that specifying a high individual bearing life does not ensure that the bearing system will meet that original life target.

Perhaps one could change the L-10 criteria to line up more with experience, and posit that the average or median life would be a more reasonable expectation, as that value would be a multiple of, say, three or four times the L-10 life?

But that approach is nothing more than changing or manipulating the failure criteria/or reliability to a lower value. It would be the same as saying that the performance of the bearing is strictly a matter of whether it continues to roll — regardless of the size of any disparities on the rollers or the raceways — an awkward position if this were a precision instrument.

To take system life a step further, it could be asked: What is the overall system life if the gearbox has eight bearings with individual lives of 200,000 hrs L-10 (consider a conveyor), all the pulleys and idlers have a total of twenty (20) bearings with a 200,000 life, and the motor has two bearings, also with a 200,000 hr life each.

Do we have to calculate the system life including all thirty (30) bearings? Won't the system life fall even further short of the goal?

I don't think we have to do the math to answer "yes" to both questions.

Given enough bearings in the system, the calculated L-10 system life shows that if this were a train with 100 box cars and two locomotives, figuratively speaking, it wouldn't make it far enough to get out of the station. And if it were an overland conveyor delivering ore to the train station, that wouldn't be a problem — because there would be no ore pile for the train haul!

We know that's not our experience because trains travel across North America and other continents daily. That is our experience. Does this mean that we need to revert to perhaps other reliability criteria, as mentioned earlier? Should we change the reliability directly by using a very conservative L-1 approach vs. the L-10 approach?

Or — is changing the L-10 criteria simply the opposite of what was proposed earlier, changing to an average life criteria?

Assume for a moment that L-1 is the new calculation criteria. We can adjust the capacity of the anti-friction bearing needed for the original load conditions to meet the new life criteria as follows:

- $a1 = 4.48 (\ln (100/99))^{2/3}$ *(Timken, p. 21)*
- $a1 = 0.208$

Therefore, given the same load conditions, new bearings have to be selected that have a capacity that is 1/0.208 = 4.8 times greater than those originally selected.

However, besides there being a potential space issue (more capacity => larger bearing), and a monetary issue (assuming price/lb, the larger the bearing, the more expensive), <u>there is the issue of the newly selected bearings being too lightly loaded.</u>

If the mass of a roller or cage is such that it reacts to its own inertia rather than the external forces applied from the external load, the roller may skew and skid rather than roll as intended. The failure will look quite different from the originally defined failure — *but it is failure nonetheless.*

- Rule: Bigger may not be better.
- Corollary: Less can be more.

One overall conclusion that can be drawn from specifying bearings lives, using the most basic methods of calculation, is that an L-10 life target is an objective guide and nothing more.

How do bearings fail?

If using one set of bearings gives a minimum value of L-10 = 166,000 hrs, and another bearing set gives a minimum value of L-10 = 200,000 hrs, both designs meet the specification. However, neither design may meet the intention of the requirement. It is NOT a case where 200,000 hrs will offer 200,000/166,440 = 1.2 x 100% = 120% of the specified life: it's the same number!

So, why do bearings fail?

The first point to understand is that bearings in machines generally don't fail due to the failure criteria defined for them. Ask any bearing manufacturer!

With the initial base L-10 calculations under our belts, just for the sake of argument let us assume that all bearing manufacturers make bearings of equal quality. Equal quality will be defined as same material, same heat treatment, same physical geometry, and same fitting practice for a particular style and size of bearing.

Therefore, given that the base L-10 calculation has two factors, capacity and load, and that we have just defined capacity to be the same regardless of where we get the bearings (obviously not true), what do we use for load?

Loads: The Meter is Running!

There are three common approaches to specifying loads:

Load Case #1: If we base our requirement on the **motor capacity**, assuming the motor runs at full load continuously for the life of the application, the "P" in the equation is most likely very conservative as motors come in integer sizes, and loads generally do not.

Load Case #2: If we base our requirement on a **calculated load** that is, say, 20 percent less than the continual rating of the motor, often referred to as the Normal Running Load (NRL), then the bearing life naturally increases dramatically because this is an exponential function. Correct?

- L-10 life x $\left(\frac{1}{0.8}\right)^{10/3}$ for roller bearings = L-10 life x 2.1 — basically twice the life.

Load Case #3: If we get even more sophisticated and express our loads in a **histogram**, the "correct L-10" estimate can be calculated to a gnat's eyebrow — or maybe *not*.

The observed fact here is that the loads as given in the specification will have an enormous impact on the L-10 results, and can drastically change the perceived longevity of the individual bearings and the bearing system. The point of this observation is certainly not to make the selection of an L-10 target more confusing or labor intensive.

Rather, it is nothing more than to point out that in order to develop the best guide for L-10 life, the author of the specification needs to supply the best available load data upon which the L-10 is to be based.

To Load Case #1, using the motor nameplate and assuming something like a 100 percent start capacity is certainly the simplest approach. Whether it is the most conservative approach could be argued at another time.

To Load Case #2, whether calculated or assumed (no one specifies a 50 HP motor for a conveyor that has a load of 50 HP), the specification has to be clear. Required:

- "X" base L-10 hours per motor HP, and
- "Y" base L-10 hours per load HP.

To Load Case #3, offering a histogram definitely allows the best chance for the most accurate calculation. The only problem is, though the amount of load, the speed, and the amount of time for each load/speed combination has been defined — has the sequence of those parameters also been accurately defined? For example, if peak loads all occur at the test stand because someone wants to check what happens at 75 or 90 percent yield of the machine (as is not uncommon for bridge drives), will that damage or enhance the odds of reaching the calculated L-10 life?

If experience is the guide for selecting an anticipated L-10 target, then it certainly stands to reason that the types of loads (most generally, #1, #2 or #3) for calculating that target must at least be considered, if not fully defined, to reach that calculated target, and must be part of the bearing life specification.

So — the author of the L-10 target life calculation must also specify the load conditions associated with his expectations.

Now assume that a common "reasonable guide" of 100,000 hrs is selected, and that it is based on the "simplest load" nominal motor HP.

This is a traditional approach that has been used over the years in many industries with the expectation that the bearing SYSTEM will last somewhere around 10 years without actually having a major overhaul to replace the bearings. The assumption here is that the manufacturer's installation, lubrication, and maintenance recommendations are actively followed.

Adjusted L-10 Life

By understanding that the 100,000 hrs as a guide has been selected, the sophistication of bearing life calculations has increased as bearing manufacturers have recognized that they must be allowed to consider the actual operating environment and conditions which the bearings experience.

For simplicity, the system life calculation will not be considered in conjunction with the next set of calculations — namely the adjusted L-10 bearing lives — remember: the calculation where nobody gets the same answer.

Great efforts have been made to show and calculate the fact that the operating environment for a bearing is absolutely crucial to its survival.

And it has been shown that the environmental conditions can increase the calculated bearing life by multiples — but — environmental conditions can also decrease the bearing life by multiples.

As a start, the equation from the International Standards Organization (ISO) 281-2007 can be used to calculate adjusted L-10 life:

- $L_{nm} = a_1 \, a_{ISO} L_{10}$

The bearing life calculations can be performed using motor load, or NRL, or the loads determined from a histogram.

For some cases, such as wind turbines, it may also be necessary to consider the static capacity of the bearing and understand the result when comparing it to the adjusted L-10 hours as a "sanity check."

The base definitions of the adjustment factors are *(ISO 281 International Standard, pp. 20, 26)*:

- a_1 = reliability (90 percent, 95 percent, 99 percent, etc.)
- $a_{ISO} = f\left(\frac{e_C C_u}{P}, \kappa\right)$ where these factors describe:
  - Lubrication, bearing speed, and bearing geometry
  - Environment, as in contamination
  - Contamination specifics such as size, hardness, and particle count
  - Mounting specifics

Additionally to be noted is that ISO 16281 separately addresses the influences of misalignment and clearances on the base L-10 rating.

The most commonly used factors for adjusting the base L-10 hrs are lubrication (ISO 281) and load zone (ISO 16281).

Contamination (the type, size and quantity/concentration of particles, for example, along with lubricants and filtering systems — not to mention their interrelations) is another factor that could be considered, but is extremely complex, and beyond the scope of this paper.

For most industrial applications, only lubrication is applied, and all other influences are assumed to be set at 1.0.

The lubricant temperature and corresponding viscosity are often assumed at the actual bearing to be the same as the sump temperature for ease of calculation, since the actual temperatures at the bearings are most often unknown, and they will not be the same for all bearings in all positions at all times.

Going back to the conveyor drive example, if the gearbox runs continuously at a synchronous speed such as 1750 RPM, the high speed shaft (HSS) bearings will run warmer — certainly during the start-up period — than will the intermediate and low speed shaft (LSS) bearings. And assuming load changes, those temperatures will also fluctuate. Again, for the sake of simplicity (a broad hint to the specification writer), we will focus on the sump temperature only.

Where ISO cannot formulate a single answer is in the absolute single values to be used for these factors. Remember that in the beginning, it was clearly stated that it is possible for NO ONE to get the same answer using adjusted lives, yet everyone's calculations are correct.

In an effort to keep this calculation method simple and solely focusing on lubrication, it is understood that:

1. Oil film becomes thinner as the temperature rises.
2. Oil film is not drawn into the bearing at lower speeds.
3. Extreme Pressure (EP) oils provide a thicker/stronger film at low speeds than non-EP oils.
4. Synthetic oils have a flatter viscosity curve than mineral oils.
5. Cooling systems that provide positive lubrication to each of the bearings will allow for more predictable bearing life in relation to the calculations than general sump temperature calculations.
6. If filters are provided, no real benefit from filtering will be incorporated in the calculation since the base contaminant condition of the gearbox has likely not been defined.
7. Lucky 7, and the Coup de Gras — If no practical experience or physical viable means (equipment) are used to provide for the assumptions of temperature and viscosity in the calculations (ISO 480 mineral oil at 0 degrees Fahrenheit (F) starting ambient - and no heater), the calculations cannot be considered reliable.

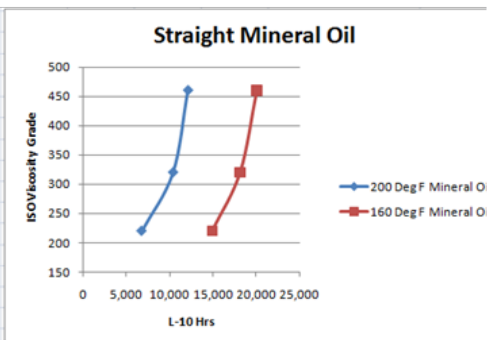
Using the adjusted L-10 calculation method, the definitions of the factors, and that only the lubrication factor will be incorporated due to the limit of this paper, we can now take an example through various viscosities and temperature ranges to get a feel for what these parameters may represent.

SPECIFICATION:

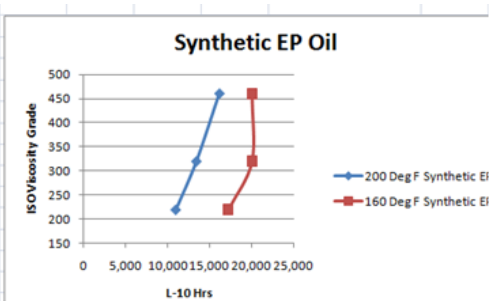
- Belt Conveyor Drive
- 400 HP Motor @ 1750 RPM
- 389 HP NRL
- 35:1 Nominal Ratio
- Minimum 1.5 Mechanical SF
- Minimum 20,000 hrs L-10

(This type of request for quotation (RFQ) is an extremely common one.)

Base L-10 Hrs =	8,036
ISO Mineral Oil	L-10 Hrs
200 deg F (93.3 deg C) Sump	
220	6,740
320	10,388
460	12,103
160 deg F (71.1 deg C) Sump	
220	14,917
320	18,153
460	20,090



Base L-10 Hrs =	8,036
ISO Synthetic EP	L-10 Hrs
200 deg F (93.3 deg C) Sump	
220	10,970
320	13,428
460	16,173
160 deg F (71.1 deg C) Sump	
220	17,215
320	20,090
460	20,090



Note a maximum limit of 2.5 x Base L-10 hrs was applied to the lubrication factor.

SELECTION:

- Ratio of 35.33:1 exact.
- The selection meets the 1.5 mechanical SF requirements as the gearing rates 594 HP since 594/389 = 1.53.
- The selection meets the 20,000 hr minimum L-10 requirement with 20,090 hrs calculated.
- The selection is quoted, agreeing to the technical requirements.

It's looking pretty good. But now, let's look behind the magician's curtain. Calculations of the individual bearing lives were made under various conditions, and are presented below.

(The below calculations are based on a proprietary Falk® Rating program.)

If different suppliers come up with different selections at different prices – and the question never arises as to "How do you meet the bearing life specification?" the lowest bid probably wins. And if there is no method clearly indicated that the 160 F sump temperature will be met with certain required cooling, or no mention of the requirement to use synthetic oil, then one or both of two conditions is true:

1. The intention of the technical specification was not met, since the specification author assumed base L-10.
2. The initial commercial offers may not be on par when one considers the price of required cooling and synthetic lubricants.

The pitfalls for such a selection process should be evident: the specification author did not require the calculation method to be used for achieving the requested L-10 life, nor did he specify the parameters of expected operation in terms of the sump temperature or the potential lubricant available to him or his customer. (Where the 20,000 hrs specification came from is a totally different matter of concern.)

And for the purchasing agent, all is well, as the letter of the specification is met.

If these omissions create issues for the conveyor OEM for this particular application (expected 20,000 hrs base, but is getting 20,000 hrs adjusted), imagine the commercial ramifications and impact down the road for all the other applications — not so much in terms of initial cost, but in terms of potential warranty claims, as the base L10 8,036 hrs is significantly less than the assumed 20,000 hrs base L-10 intended.

Judge the Results

The preceding descriptions of L-10 calculations with their variations should make it clear that simply specifying an L-10 value may not achieve the intended purpose of machine life expectations.

With that fact being understood, the initial question implied by predicament #2 ("How does one judge which adjusted L-10 calculation is closest to the intent of the specification?") can be answered with the following suggestions:

1. Ensure that the L-10 requirement is consistent with the rest of the specification. Calling for a gearbox 1.5 service factor, for example, but a minimum 100,000 hr base L-10 means the selection is driven by the L-10 requirement. Unless the item is a specialty design, the features are designed for economic competitiveness, and the bearing life (no pun intended) comes along for the ride.
2. Make sure the load base is clear by having everyone calculate base L-10 on motor and NRL. Consider that the catalogued design non-adjusted L-10 life of most industrial gearboxes is less than 5,000 hrs based on a mechanical SF of 1.0. To get 100,000 hrs requires an impossible adjustment factor in relation to the 1.5 SF on the gearing, for example.
3. Apply limits that can be used for the various factors, as that creates a level playing field for everyone responding to the RFQ. For example for lubrication (initial oil viscosity and nominal and nominal sump temperature) allows a maximum of, say, 2.5.
4. Use a factor of 1.0 for oil cleanliness as this takes into account initial and operating cleanliness, and does not get into discussions of "initial start-up damage" or "filtration healing."
5. Allow a load zone factor only if detailed Finite Element Analysis (FEAs) were performed with conclusive deflection results — especially for prescribed variable loading conditions (histograms). Such an approach will be expensive as the supplier may be exposing proprietary design details. However, interpolations or extrapolations of a general design method would not qualify, as their validity could not be confirmed.
6. Make sure that there are features, i.e. physical means, of getting to the assumptions that make sense. From our temperature/viscosity example, if the cataloged capacity of a commercial gearbox is 400 Thermal HP without cooling at 80 deg F ambient, but it operates continuously in a 110 deg F ambient temperature with a 389 HP load, then using a 2.5 adjustment factor — without any means of auxiliary cooling — would have to be scrutinized very carefully.

Summary and Conclusion

When specifying anti-friction bearing life for any piece of equipment, the writer of the specification assumes a purpose (or purposes) for targeting a particular value. Once a value has been defined, it is of the utmost importance that the specification writer defines the loads, operating conditions, methods of calculations, and even values for particular factors in the calculations, in order to help assure accuracy and integrity of the claimed values that will be offered.

Additionally — and this is really the critical overall systems-purpose for the specification — with the interpretive ability to understand what calculated bearing lives can and cannot guarantee, the author of the specification can outline a clear road map for associated functions, such as initial design, manufacturing, maintenance, and warranty, to meet the high expectations of specifying a particular L-10 life for the equipment.

References

1. ISO 281 International Standard, Second Edition, 2007-02-15, "Rolling bearings — Dynamic load ratings and rating life." Reference number ISO 281 2007(E). © ISO 2007
2. TIMKEN Bearing Selection Handbook Revised 1986, The TIMKEN Company, 50M-9-86-4.

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