PLANET PAC: INCREASING EPICYCLIC POWER DENSITY AND PERFORMANCE THROUGH INTEGRATION

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Abstract

Epicyclical gear systems are typically equipped with straddle-mounted planetary idlers and are supported by pins on the input and output sides of a carrier. These carriers can be either one-piece or two-piece carrier designs. Traditionally many of the higher power rated epicyclic gear systems use cylindrical roller bearings to support the planetary gears. This paper will demonstrate that using a preloaded taper roller bearing in an integrated package should be the preferred choice for this application to increase the bearing capacity, power density, and fatigue life performance. Based on DIN281-4 calculations, this patented [1], fully integrated solution allows for calculated bearing fatigue lives to be 5 times greater than a non-integrated solution and more than 1.5 times greater than a semi-integrated solution, without changing the planet gear envelope.
Introduction - Design Challenges of an Epicyclic Gear System

An epicyclical gearing system is particularly well suited for achieving a high reduction ratio in a relatively small, power dense package. A typical straddle mounted planetary idler utilizing cylindrical roller bearings is shown in Figure 1.

Because of the power density, epicyclic systems have become a popular choice for designers, and consequently it has been incorporated into countless types of equipment including automobile transmissions, off-highway equipment final drives, wind turbine gearboxes, and cement mill crusher drives, to name a few.

As with any type of power transmission system, an engineer is faced with many analytical challenges during the design phase to ensure that a highly reliable power train is achieved. In the case of an epicyclical gearing system, this challenge is made particularly difficult due to the complex interaction of revolving and rotating components as they transmit power.

But, for just about all equipment types, economics dictate the need for increased power density and improved reliability. A Planet Pac can be used to further utilize an existing design and provide increased reliability, while minimizing the expense of design changes. On the other hand, power density also allows for a design to be made smaller, thus reducing cost and weight.

What is Planet Pac?

Traditionally high power planetary gear sets are composed of a gear, two outer races, two inner races, two rows of rolling elements, two cages, and a carrier pin. Some applications may also include spacers or snap rings. Most times the gear lives are calculated using a 99% reliability or L1 fatigue life; whereas the bearings that support the gears are calculated using a 90% reliability, an L10 fatigue life.

Some gearbox manufacturers have implemented semi-integrated bearings into their planetary systems. The semi-integrated solution, as shown in Figure 2, involves integrating the bearing outer races into the gear. There are design guidelines that define recommended gear rim thicknesses as a ratio of the gear module, i.e. three times the gear module. By making this change, the bearing pitch diameters and roller diameters can be increased, thus increasing the bearing capacity and resulting fatigue performance.

Substantial improvements can be made by taking advantage of modern bearing technology and further integration of components to achieve an extremely power dense design. This integration, as shown in Figure 3, may include full integration of the gears with the bearing outer races and full integration of the carrier pin with the bearing inner races. A full complement of rollers is used in combination with a proprietary coating, ES300, to prevent metal adhesion from roller to roller. This advancement is the Planet Pac. This specific design requires a two-piece
carrier design that must be bolted together for assembly of the planetary system. This design eliminates two outer races, two inner races, a spacer, and four surfaces interfaces. Eliminating the interfaces will eliminate potential precessing of the races, fretting corrosion, and loss of bearing setting which then leads to premature bearing failure. There is an additional rib ring that is required to control the bearing setting and unitize the package product. Additional features like force oil lubrication can be added to the package.

Integration allows for increased bearing capacity by adding additional rolling elements to the bearing, increasing the size of the rolling element, and/or increasing the bearing pitch diameter. This novel approach to design and construction provides increased opportunity to add power density to an epicyclical gear drive in the axial and radial directions.

By integrating the inner races into the shaft, the shaft sections will increase under the bearing rolling elements, resulting in decreased beam stresses. The pin diameter into the carrier plate can be maintained at the same size and the bending and shear stresses will not increase. However the integration will introduce a square corner at the pin-carrier interface. This will require a stress concentration factor analysis, per the ANSI/AGMA 6001-D97 [2] and if necessary, a pin diameter adjustment.

As mentioned previously, both of these designs utilize a detachable large rib ring on the inner race, as shown to the right of the right row of rollers (see Figure 3 and Figure 4). For tapered roller bearings this rib ring would be used to very accurately define the bearing setting at the bearing factory. This eliminates the need for the epicyclic gearbox manufacturer to preload the bearings, one reason that many gearbox manufacturers use cylindrical or spherical roller bearings. A combination of press fitting and welding may be used to ensure adequate holding force and durability at loads significantly in excess of the maximum applied loads.

The ES300 is a proprietary diamond-like coating (DLC) that may be used to prevent adhesive wear in a full complement bearing. Testing has shown that this coating is beneficial when used in a full complement bearing. Additionally, during conditions where there is an interruption in lubrication supply, the bearings have been made more forgiving because the coatings have been effective at eliminating adhesive wear between the rollers and the races.
Preloaded Tapered Roller Bearing
- Preferred Bearing Choice for the Planet Pac

Although the Planet Pac could be manufactured utilizing the cylindrical roller bearings, needle roller bearings, or other bearing types, the preloaded tapered roller bearing is deemed to be the bearing of choice for a Planet Pac. It can be shown analytically that a preloaded tapered roller bearing offers advantages over other bearing types that possess larger amounts of radial clearance, especially when the bearing is required to operate with misaligned gear contacts.

This has been demonstrated in a paper written by Flamang and Clement [3]. One key to increased power density is improved load distributions in the bearings and gear. It was shown in this paper that the tapered roller bearing is the preferred solution to an equivalent CRB design. The tapered roller bearing design resulted in lower stresses and more than doubles the expected fatigue life because of the tapered roller bearing's wider support distance, preload, self-centering, and self-adjusting effects.

This paper does not focus on the details of showing that the tapered roller bearing is the best bearing, as this was already shown by the Flamang and Clement paper. It merely builds on what others have already demonstrated.

Comparisons of Various Levels of Integration

A comparison of various levels of integration was performed to show the power density that can be incrementally obtained by increased integration. It is assumed that the carrier is a split, two-piece carrier. The material used for the bearings was assumed to be constant and an ISO 281 material factor equal to 1.1 was applied. The preload force in the bearings was constant, regardless of the bearing ratings. The speed and bearing cleanliness, ISO --/15/12, were also constant throughout the analysis. Finally, it was assumed that the planetary gear envelope could not be any larger than the non-integrated design.

The gear loads that were used in the analysis were defined by a gearbox manufacturer. It is well known that offset loading will create an uneven load distribution on the bearings. For this analysis, the resultant gear loads assumed that the loading was not centered. Figure 5 shows that the loads were applied with a “cross-over” effect which induces an over-turning moment on the bearings. This loading condition has been found to be the most aggressive loading to increase the loads on the bearing and reduce the predicted bearing fatigue lives.

The torsional wind up of the planetary carrier creates misalignment of the gear contact and the planetary bearing axis. While lead correction on the gear face helps correct the effect on the gear contact, it does not correct the misalignment on the bearing. Likewise, while profiling the gear face helps minimize edge loading at the tooth contact, the contact itself drifts from side to side depending on the gear manufacturer's tolerances and process controls. A modest off-center gear mesh condition can redistribute loading unequally to the bearing rows, significantly reducing the life of the heavier loaded row. Unfortunately, the misalignment values and contact drifts discussed here are not usually communicated to or accounted for by the bearing supplier. Through closer interaction between the bearing and gear drive manufacturers, a more thorough analysis of the gear and bearing system can account for these phenomena and others like “gear wrap”.

The first step was to evaluate a non-integrated design. This analysis was performed using an ISO tapered roller bearing (32248). This is really the base line to which all other designs are compared. This is the basic design as most manufacturers employ in their gearbox designs. As shown in Figure 6, the outer races are pressed in to the gear. For wind turbine applications, the gear rim thickness was equated to 3 modules per the AGMA6006-A03 [4].

The next step was to integrate the bearing outer races into the bore of the planet gear, as shown in Figure 7. The integration was performed to maintain the rim thickness, as in the non-integrated design. Since the inner race surface is tapered, the mean cup race diameter was used for calculating the rim thickness. This allows for the roller and bearing pitch diameters and the roller lengths to increase. All of this increases the bearing rating, power density, and predicted L10 life.

A comparison of the non-integrated and the semi-integrated designs can be seen in Figure 9. The non-integrated solution is shaded and the semi-integrated design is outlined. It is easy to see that the semi-integrated design will be capable of achieving an increased fatigue life.
Table 1 below shows a ratio comparison of the bearing ratings, bearing pitch diameters, and the mean outer race diameters for the three incremental designs. The purpose of this table is to show how the bearing ratings will increase with increased integration. Simultaneously the bearing pitch diameters increase, though the outer race diameter may not.

<table>
<thead>
<tr>
<th></th>
<th>ISO C1 Rating</th>
<th>Pitch Dia.</th>
<th>Mean Cup Dia.</th>
</tr>
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<tbody>
<tr>
<td>Non-Integrated</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Semi-Integrated</td>
<td>1.26</td>
<td>1.08</td>
<td>1.07</td>
</tr>
<tr>
<td>Fully-Integrated</td>
<td>1.52</td>
<td>1.03</td>
<td>1.05</td>
</tr>
</tbody>
</table>

**TABLE 1: BEARING SIZE RATIOS**

The bearing designs were compared by several life analysis methods, which included a basic (non-adjusted) ISO L10 life calculation, the DIN 281-4 stress adjusted L10 life [5], and the DIN 281-4 fully adjusted L10 life. In these comparisons the kappa viscosity ratio, k, and the contaminations factor, hc, were nearly identical because the same ISO bearing cleanliness and lubrication was used. Because the bearings were all of similar size, the assumed surface finishes were similar, per the DIN 281-4.

As seen in Table 2, the basic catalog life and DIN281-4 stress adjusted lives increase proportionately the same. When all of the adjustments are applied, there is a significant increase in bearing life by partially integrating the bearing; however the maximum potential of the bearings is not reached without going to a fully-integrated solution.

<table>
<thead>
<tr>
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<th>DIN 281-4 / ISO L10 Life Calculations</th>
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<tr>
<td></td>
<td>ISO Basic Catalog</td>
</tr>
<tr>
<td>Non-Integrated</td>
<td>1.00</td>
</tr>
<tr>
<td>Semi-Integrated</td>
<td>2.13</td>
</tr>
<tr>
<td>Fully-Integrated</td>
<td>3.73</td>
</tr>
</tbody>
</table>

**TABLE 2: BEARING L10 LIFE RATIOS**
The bearings were also analyzed using the Timken Company proprietary bearing analysis program, SYSx. The analysis that was performed accounted for gear wrap; the gear rim will distort into an oval shape as a result of the applied loading. It predicted the L10a3k, the load zone adjusted life, life ratios similar to the DIN281-4 stress adjusted lives. The L10a (fully adjusted) bearing life ratios per SYSx were 1.0, 7.4, and 13.5 for the non-integrated, semi-integrated, and fully-integrated designs, respectively.

Although the DIN281-4 is acceptable to compare different bearing manufacturer's designs, Kotzalas and Fox [6] have shown that the bearing analysis software, like SYSx, of a given manufacturer, like Timken, is more accurate at predicting the life of their own bearings. Based on this knowledge, the fully integrated design will have a calculated fatigue life 1.8 times the semi-integrated design and 13.5 times greater than the non-integrated design. This is phenomenal power density.

In general, as the calculated L10 bearing life increases, then so does the reliability for the same time period. As shown in Table 3 and Equation (1), if the bearing life is 100,000 hours for a 90% reliability, L10. The required calculated L10 life for a 99% reliability would be 4.79 times greater or a calculated L10 of 479,000 hours.

\[ I_1 = a_1 I_{10} \]  

\[ \begin{array}{|c|c|c|c|c|} 
\hline 
Life & Reliability & \text{Reliability factor, } a_1 & \text{Inverse} & \text{Hours} \\
\hline 
L10 & 90 & 1.000 & 1.00 & 100 000 \\
L9 & 95 & 0.619 & 1.62 & 61 900 \\
L2 & 98 & 0.333 & 3.01 & 33 300 \\
L1 & 99 & 0.209 & 4.79 & 20 900 \\
\hline 
\end{array} \]

\text{TABLE 3: RELIABILITY TABLE}

It is possible, without changing the envelope of the existing planetary system, to achieve a calculated 99% bearing fatigue reliability to match the fatigue calculations performed by the mating gear. This can be done by either using the DIN281-4 methods or by using proprietary bearing analysis software, like SYSx.

Furthermore, the calculated stress levels from the Timken SYSx program show that for all three designs the contact stresses are below the endurance limit of 1500-MPa. However the stresses in the semi-integrated and the full-integrated solutions are 89% and 84% lower, respectively, than the non-integrated design.

**Additional Features Available to the Integrated Planet Pac**

Power density does not stop at just bearing integration. These are other changes that can be made to the bearing that will increase the calculated fatigue life and increase the bearing performance.

**Surface Finish Enhancements**

Some of these features are reduced surface finishes and cleaner and increased fatigue resistant steels. Smoother finishes will result in improved lambda ratios. The rollers and/or bearing races finishes can be improved by grounding, honing, or application of topographical modification.

**Material Modifications**

For example, when appropriate, MAP steel can be used to increase the bearing rating by 23%. Based on the bearing life equation, a 23% increase in bearing capacity will increase the calculated fatigue life by a factor of 2. Timken DuraSpexxTM Power Rating Series is an application of these enhancements [7].

**Contamination Resistant Features**

If debris in the lubricant is an issue, the predicted bearing fatigue lives can be calculated with various levels of ISO cleanliness levels. If ISO cleanliness levels are not applicable, actual bearing surfaces can be mapped and the bearing lives can be adjusted based on actual field history [8, 9]. The bearing fatigue life can also be adjusted based on the accumulation of debris damage over
time [10]. In the case of off-highway vehicles where debris is a serious issue, this has been done and Timken has applied their Debris Resistant Bearing (DRB) technology [11] to the bearing to limit the effect that the debris has on the bearing fatigue life.

**Debris Excluding Seal Upgrade**

If forced oil lubrication with properly designed filtration is used to lubricate the planet bearing, then sealing the Planet Pac helps eliminate debris from the gearbox sump from contaminating and subsequently damaging the planet bearings. Furthermore, lubrication holes can be added in the roots of the gear teeth to allow improved oil lubrication at the interface of the sun and the planet gears.

**Pre-greased and Sealed Version**

Many applications with epicyclic gear sets are oil lubricated and in some cases, access to the planetary gears for service may be restricted. Therefore most Planet Pac designs may be designed for forced oil lubrication. However in cases where the planetary gears may be more accessible for re-greasing, the Planet Pac design can be pre-greased and sealed and may require periodic re-greasing maintenance intervals. Sealing and greasing the planet bearings can allow for a reduction of the oil level in an oil sump lubrication system. This will help reduce the churning losses associated with the higher oil levels. The effect is to reduce the operating temperatures and increase the fatigue lives of the bearings and gear.

**Summary of Benefits and Features**

(1) May be used to retrofit existing planetary gear designs in either one-piece or two-piece carrier designs.

(2) Integration of components promotes power density, increased bearing life, and permits elimination of the bearing retainer.

(3) Full complement of rollers, with or without proprietary coatings, may be used to increase bearing capacity and bearing life.

(4) Very precise control of the bearing clearance set at the bearing factory for maximizing bearing life, gear positioning and consistency of deflection between adjacent planets.

(5) Reduction of the number of components for improved reliability analysis.

(6) Elimination of planetary gear sub-assembly.

(7) Elimination of tight fitted outer races which may still precess inside the gear creating wear, debris and excessive bearing clearance

(8) Other optional features can be added, such as hydraulic assist for planet removal, oil holes for forced oil lubrication, and locking tapered bearing bores for easy planet removal.

(9) The planetary bearings can be manufactured using Timken’s DuraSpexxTM Power Rating Series, or Debris Resistant Bearing (DRB) technologies to improve bearing fatigue lives under tough operating conditions.

**Conclusion**

The use of the Planet Pac, a fully integrated planet bearing and gear package, is a natural progression in the field of epicyclical gearing system design. It affords the designer an effective approach to improving the system reliability and power density, while maintaining a cost efficient design. The bearings can be designed to 99% reliability to match the gear reliability by retrofitting the bearing package assembly into the existing available space.
Acknowledgments


