THE IMPACT OF CAGE DESIGN ON BALL BEARING TORQUE BEHAVIOUR

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ABSTRACT

Cage design has a profound effect on ball-to-cage and cage-to-land interactions and, consequently, torque performance and cage wear rate. However, there has been little systematic study of the relationship between the cage design parameters and bearing performance.

ESTL has carried out a study of the influence of cage design on the behaviour of solid-lubricated bearings. An initial review of previous studies indicated a link between the orientation of the bearing axis under 1g (significant for ground testing), the relative importance of ball-to-cage and cage-to-land clearances, and the potential benefits of variability in circumferential pocket positioning.

The main part of the study consisted of a test programme in which the torque behaviour of lead-lubricated bearings fitted with leaded bronze cages of differing designs was investigated. This paper reports the findings and illustrates the sensitivity of bearing torque and torque noise to bearing cage design with reference to orientation, rotational speed, preload and environment. The implications of the findings with respect to optimizing cage design are discussed.

1. INTRODUCTION

In the vast majority of rolling element bearing applications a cage is employed to maintain the spacing of the rolling elements. The use of a cage prevents the inevitable migration of the rolling elements and subsequent crowding, resulting in high contact forces between these elements and increased wear between the counter rotating surfaces. Crowding also results in errors in the axis of rotation and leads to local variations in bearing stiffness. Another function of a cage, of particular significance in space mechanisms, is its use as a source of lubricant for both liquid and solid regimes. Self-lubricating cages apply or replenish the solid lubricant on the races, whilst porous cages can carry fluid lubricants that migrate over time onto the races.

Ideally, the primary functions of a cage should be performed without adversely affecting the bearing performance. Ideally the material exhibits low friction and acceptable wear characteristics, and the cage should be dynamically stable under rotation. It will however interact with one of the bearing rings (at the cage-to-land interface) and the balls (ball-to-cage interfaces) and it is these complex interactions which, given a variety of contributory factors, can have a detrimental effect on bearing torque performance.

The approach to cage design in ESTL has been developed over a number of years and uses a methodology, incorporating design rules for the fundamental geometrical parameters, based on extensive empirical experience in design and development of cages. However, for optimisation of these parameters in specialised applications and for the refinement of such design rules, a more detailed understanding of the sensitivities to a number of operational parameters is required.

2. BACKGROUND

ESTL have conducted work over many years within research, development and qualification programmes such as GERB, GOMOS, ATSR and MIMR where cage design has been critical to the success of these mechanisms. In order to build on this existing experience ESTL conducted a programme of work including:

1. A review of literature and techniques and initial characterisation of sensitivities.
2. Investigation into the measurement of cage motion.
3. Characterisation of bearing sensitivities with respect to speed and preload.

The literature review included past ESTL data and test reports as well as open references related to both terrestrial and space applications. Since the demands of space mechanisms are unique with respect to lubricants and materials, and they must function both during ground testing and flight in quite different environments, the observations made within these programmes are valuable in identifying the main influences on cage performance. Wider research into cage design has been limited and has tended to focus on terrestrial applications with an emphasis on high speed (>10000 rpm) operation, often theoretical in nature.

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2.1. Fundamentals of Cage Design

Cages, though performing an important function, do not always behave nominally. This can be due to debris build up or degradation of the lubricant, particularly towards the end of life. Certain aspects of the bearing assembly design may also contribute to poor torque performance.

Initially classified by the way in which they are guided, there are three main cage types - inner/outer-race-riding, ball/roller-riding or multi-element. Inner or outer-race-riding cages are typically one piece cages, machined from solid. They are used particularly with ball bearings and radial holes are used to position the balls. They are commonly employed in space applications using self lubricating materials. Ball or roller riding cages, used widely in industrial applications, are typically made from soft steels or polymers and are pressed around the balls thus controlling the position of the cage. This style is generally unsuitable for self lubricating cages since the wear quickly leads to a loss of guidance [1]. For this reason these are normally used only with oil lubrication. The third type - multi-element spacers - include slugs, toroids, springs and spacer balls, which find use where full cage designs are inappropriate. This is usually because of manufacturing difficulties.

Cage materials are typically metallic or polymeric depending on the structural or tribological properties required. In space applications using oil or grease lubricants, it is often possible to employ simple two-piece conformal steel cages as used in terrestrial applications. One piece, race-riding cages typically use bronze, for its self lubricating properties, or steel. Metallic cages offer good dimensional stability and expansion properties closely matched to the bearings themselves.

Polymers are widely used in cages for space applications. Delrin, Phenolic (cotton or fabric) and reinforced PTFE are commonly used with fluid lubricants, whilst for dry lubricated applications PTFE based cage materials (Rulon, Salox, Duroid and PGM-HT) and Vespel SP3 (Polyimide with MoS_2) are used. Polymeric cages exhibit reduced dimensional stability compared with metals and can relax or change dimensions for various reasons when in use. It can also be difficult to manufacture these to sufficiently tight tolerances in the first instance.

2.2. Cage Misbehaviour

The most common modes of cage misbehaviour in unidirectional motion are cage hang-up and cage instability. Hang-up is caused by complex interactions between the balls and the cage in the presence of small misalignments, moments or radial loads. This is characterised by high torque throughout the rotation of the bearing. Instability is the excessive motion of a cage with frequent damaging collisions at the ball-to-cage or the cage-to-land interfaces. There are several contributory factors related to instability, which is a function of rotational speed, cage clearances, friction coefficients and the structural damping properties of the cage material. In order to predict it, mathematical models have been developed [2], though these have not been correlated with test results. The complexities in measuring cage motion are the main reason. There is some disagreement [3,4] as to whether there is a clear link between speed and cage stability, and it is clear that little is known about cage motion and its effect on torque performance.

Further misbehaviour is exhibited in oscillatory applications where the balls are forced out of their nominal position. The presence of lateral creep forces, combined with cage motion and misalignment mean that the balls are forced to the extreme positions allowed by the cage. The torque peak exhibited in this situation is known as blocking and is most evident where bearings are consistently operating within angular limits.

2.3. Functional Dimensions

The working clearances (ball-to-cage and cage-to-land) are fundamental to stable operation during rotation with standard clearances being employed in ESTL cage designs over many years [1]. However, deviations have been made in applications during this time due to the identification of limitations during testing.

Ball-to-cage clearances govern the amount of time the balls come in contact with the cage. Too little clearance and the balls are in continuous contact, resulting in high torque noise and wear [2]. Too much clearance and the cage itself is under-constrained, leading to un-controlled motion, particularly at high speeds. In space applications low clearance tends to be associated with high speed oil-lubricated bearings, whilst larger clearances are more appropriate for solid lubrication. Elongated pocket designs have also been employed successfully in order to minimise problems of blocking [5].

The cage-to-land clearance is critical in maintaining cage stability, whilst avoiding self locking. The cage is piloted by the land, made possible by a small amount of contact on either the inner or outer race, though it is mandatory that the cage is unable to touch both. Inner-race-riding cages have a smaller diameter and hence lower mass, although these can become unstable if excessively worn. The ultimate decision on the running land is, however, based on which race is relieved [6][7].

This clearance is also affected by cage roundness, as noted in [8], which can cause significant problems at this interface.

The effects of g-vector have been significant on ATSR [9] and more notably on GOMOS APCM life test [6], where a direct comparison was made between horizontal and vertical orientation, although it is unclear which interfaces are responsible for these variations in torque. The GERB [10] programme was also useful in looking at the effects of higher lateral g-loads, which saw considerable wear on the cage-to-land interface despite the use of a lightweight hybrid cage.

3. EXPERIMENTAL PROGRAMME

The initial review of cage design and behaviour allowed the main influencing factors to be identified. This facilitated a comprehensive and systematic experimental programme to be carried out examining the relationship between the critical cage design parameters and bearing torque performance.

3.1. Identification of Test Parameters

The literature review highlighted the importance of cage clearances at both the ball-to-cage and cage-to-land interfaces. It was clear that these two parameters should be examined in order to validate the standard approach to cage design, previously based on empirical evidence rather than systematic study. The circumferential distribution of pockets was also selected as a test parameter due to the observed benefits in relation to cage stability.

In addition to those relating to cage design, environmental variables including orientation (important during ground testing) and air/vacuum environments were also identified as important parameters to control.

3.2. Test Facility Description

Due to the requirements of the proposed tests, a dedicated facility was developed to conduct the experimental programme. This consisted of a stainless steel test chamber mounted, via a pivoting support shaft, on a frame structure allowing orientation of the chamber in both vertical and horizontal axes. Critically, this was achievable without breaking vacuum, and thus leaving the lubricant lubricity unchanged in the absence of air.

The chamber, shown in Fig. 1 consisted of a lid-mounted stepper motor with a ferro-fluidic feed-through at one end, whilst vacuum ($<5 \times 10^{-6}$ mbar) was achieved and maintained using a turbo-molecular pump mounted at the lower end.

Figure 1. Test Chamber

Within the chamber the test bearings were mounted in a test housing (Fig. 2) suspended from the chamber lid. The housing was split so that bearing torques could be measured independently using a pair of Kistler torque transducers. The reaction torques were measured through the outer races. The shaft was driven via an Oldham coupling in order to minimise misalignment induced forces. An axial preload was applied through the use of a spring.

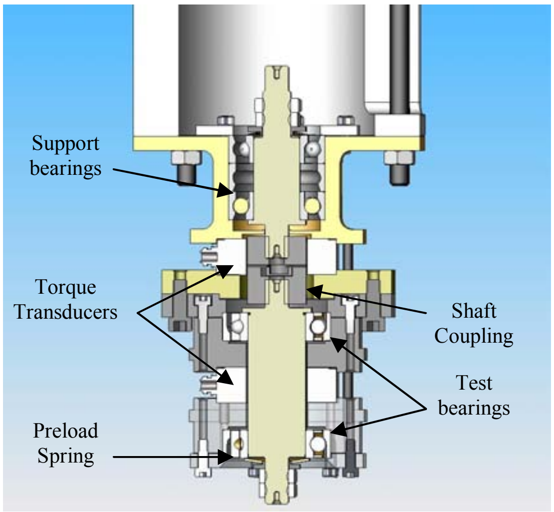

Figure 2. Bearing Test Housing

The experimental programme used SNFA EX25 angular contact bearings (Tab. 1). These were chosen for their relatively close conformity, expected to be more sensitive to the effects of variations in cage design.

Table 1. Bearing details

Type	Angular contact
Precision	ABEC 7
Contact angle	15°
Conformity	$C_i = 1.06$, $C_o = 1.08$
Outer diameter	47mm
Bore	25mm
Ball diameter	7.14mm
Number of balls	12

The lubrication regime was the commonly used lead ion plating with inner race riding leaded bronze cages.

4. TEST METHOD

4.1. Phase 1 Tests

The first tests were carried out under low preload levels of 50N and concentrated on characterising the sensitivity of bearing torque performance to environmental, orientation and cage geometry parameters, identified following the initial study.

Seven pairs of bearings were tested, with cage design parameters varied as shown in Tab. 2. Bearing pair 1 uses the standard cage design clearances.

Table 2. Cage parameters – Phase 1

Bearing pair no.	Ball-cage clearance	Cage-land clearance	Circumferential pocket spacing
1	Nominal (0.4mm)	Nominal (0.2mm)	Equi-spaced
2	Nominal	Small (0.1mm)	Equi-spaced
3	Nominal	Large (0.65mm)	Equi-spaced
4	Small (0.2mm)	Nominal	Equi-spaced
5	Large (0.8mm)	Nominal	Equi-spaced
6	Nominal	Nominal	Non-uniform Small (±0.5°)
7	Nominal	Nominal	Non-uniform Large (±4°)

Each bearing pair was subjected to the same test. The outline steps of the procedure were:

- Application of 50N±5N preload
- Low speed (2 rpm) bearing torque check
- Vacuum run-in (6000 revs @ 100 rpm)
- Solvent rinse to remove debris
- Low speed torque check
- Torque test sequence

The test sequence for each bearing pair was as shown in Tab. 3. Repeated measurements at each rotational speed were separated by a period of running (in a clock-wise direction) of 15 minutes at 25 and 100 rpm, or 30 minutes at 5 rpm. Each low speed torque signature was taken with the bearing rotation in the following sequence: 3 revs c.w., 3 revs c.c.w., 3 revs c.w. The scan rate was 50Hz.

Table 3. Bearing test sequence – Phase 1

Axis	Environment	Speed	Test no.
Vertical	Air	5 rpm 25 rpm 5 rpm	1-3 4-6 7
Horizontal	Air	5 rpm 25 rpm 5 rpm	8-10 11-13 14
Vertical	Vacuum	5 rpm 25 rpm 5 rpm 100 rpm 5 rpm	15-17 18-20 21 22-24 25
Horizontal	Vacuum	5 rpm 25 rpm 5 rpm 100 rpm 5 rpm	26-28 29-31 32 33-35 36

4.2. Phase 2 Tests

Following the successful completion of Phase 1 a further series of tests were carried out in order to evaluate the repeatability of torque measurements as a function of bearing orientation and speed. For consistency the speeds chosen were 5 rpm and 100 rpm. A subset of bearing pairs was chosen for further tests with the following characteristics:

- Pair 1 – Standard cage design
- Pair 2 – High sensitivity to orientation
- Pair 3 – Low sensitivity to orientation
- Pair 6 – Low torque noise characteristics

The test sequence shown in Tab. 4 was followed for this second phase of testing.

Table 4. Test sequence – Phase 2

Axis	Environment	Speed	Test no.
Vertical	Vacuum	5 rpm	1
Horizontal			2
Vertical			3
Horizontal			4
Vertical			5
Horizontal			6
Vertical	Vacuum	100 rpm	7
Horizontal			8
Vertical			9
Horizontal			10
Vertical			11
Horizontal			12
Vertical	Air	5 rpm	13
Horizontal			14
Vertical			15
Horizontal			16
Vertical			17
Horizontal			18
Vertical	Air	100 rpm	19
Horizontal			20
Vertical			21
Horizontal			22
Vertical			23
Horizontal			24

4.3. Phase 3 Tests

The final phase of testing aimed to study further areas of interest as follows:

- Combination of the beneficial factors in order to optimise cage design.
- The effects of elevated axial load
- The effect of velocity and velocity profile on torque noise

In order to test these additional factors, changes were made to one of the cage designs, whilst Pairs 1 and 3 were unchanged for these further tests. The bearing pair designated 2/8 combined two deviations from the standard cage design, namely large cage-to-land clearance and non-uniform circumferential pocket spacing.

The phase 3 cage designs are shown in Tab. 5.

Table 5. Cage designs – Phase 3

Bearing pair no.	Ball-cage clearance	Cage-land clearance	Circumferential pocket spacing
1	Nominal (0.4mm)	Nominal (0.2mm)	Equi-spaced
2/8	Nominal	Large (0.65mm)	Non-uniform Large (±4°)
3	Nominal	Large	Equi-spaced

For each bearing pair the following outline steps were followed:

- Application of 50N±5N preload
- Vacuum run-in (6000 revs @ 100 rpm, vertical orientation)
- Solvent rinse to remove debris
- Torque test sequence
- Application of 500N±50N preload
- Vacuum run-in (6000 revs @ 100 rpm, vertical orientation)
- Torque test sequence

The sequence (Tab. 6) contained a constant speed motion profile at each speed/orientation combination (5 revs c.c.w., 50 revs c.w., 5 revs c.c.w.), whilst for the ramped tests, the bearing pairs were driven from 0 to 100 rpm and back down at two acceleration rates.

Table 6. Test sequence – Phase 3

Axis	Environment	**Speed /** ***Accel.*** **(rpm)/(revs.s^{-2})**	Test no.
Vertical	Vacuum	5	1
Horizontal		5	2
Vertical		20	3
Horizontal		20	4
Vertical		50	5
Horizontal		50	6
Vertical		100	7
Horizontal		100	8
Vertical	Vacuum	0-100-0 / **1.0**	9
Vertical		0-100-0 / **0.1**	10
Horizontal		0-100-0 / **1.0**	11
Horizontal		0-100-0 / **0.1**	12
Vertical	Air	5	13
Horizontal		5	14
Vertical		20	15
Horizontal		20	16
Vertical		50	17
Horizontal		50	18
Vertical		100	19
Horizontal		100	20
Vertical	Air	0-100-0 / **1.0**	21
Vertical		0-100-0 / **0.1**	22
Horizontal		0-100-0 / **1.0**	23
Horizontal		0-100-0 / **0.1**	24

5. RESULTS

5.1. Phase 1 findings

The low preload tests of Phase 1 immediately yielded interesting results. The plot of mean torque for the 36 measurements made on the standard cage clearances are shown in Fig. 3 and it is apparent that orientation is linked to the variation in mean torque. In order to standardise results for different tests or bearings, these variations due to orientation are shown as a percentage deviation from the mean torque in the vertical axis in air case.

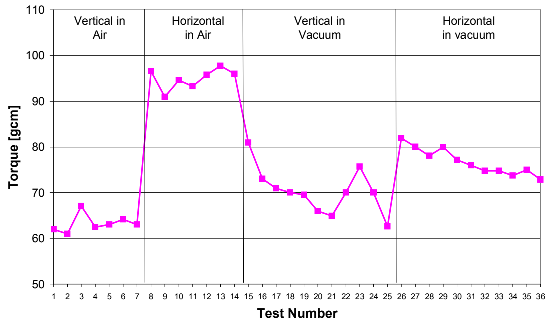

Figure 3. Standard cage mean torques

On completion of testing of the seven bearing pairs the results were normalised relative to the air/vertical and shown as a percentage deviation from this norm. This clearly shows that the large cage-to-land clearance reduces the sensitivity of mean torque to orientation (Fig. 4). It can also be seen that circumferential pocket variability yields little improvement in this case.

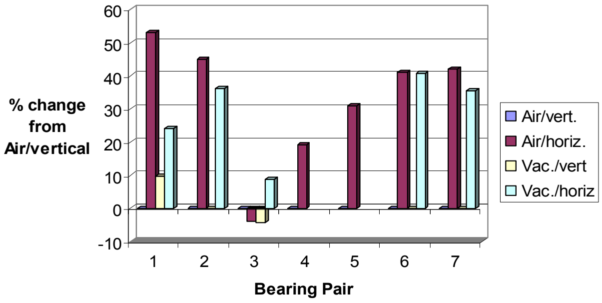

Figure 4. Mean torque deviation from air/vertical

Analysis of the torque noise characteristics of the different test bearings was based on the percentage deviation from the mean torque for that particular test. This shows that the pocket variability has a clear positive effect on torque noise performance (Fig. 5).

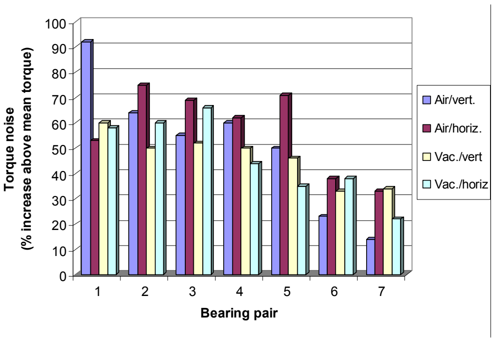

Figure 5. Torque noise performance of bearings

5.2. Phase 2 findings

As in Phase 1, the tests on the four bearing pairs in Phase 2 show an increase in torque following reorientation from the vertical to horizontal axes. Fig. 6 shows that this is repeatable with multiple reorientations.

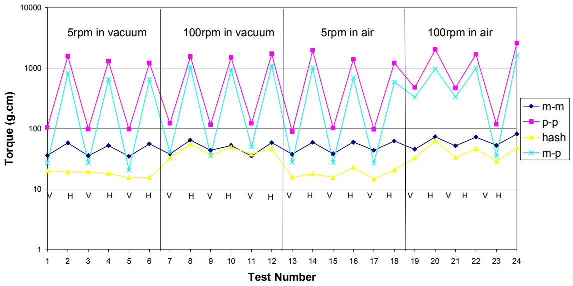

Figure 6. Phase 2 test results - standard cage

When comparing the standardised results from all cages, the bearing pair with the large cage-to-land clearance was once again the least sensitive to this change in orientation (Fig. 7).

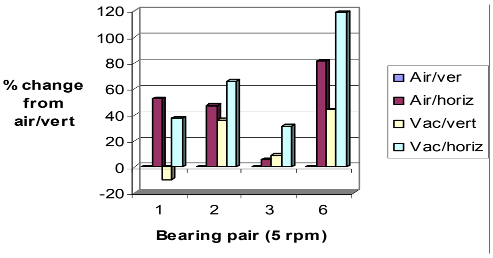

Figure 7. Mean torque deviation 5 rpm

The results at 100 rpm also indicated that this was true at the higher rotational speed (Fig. 8).

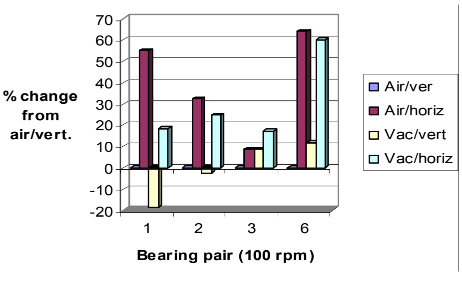

Figure 8. Mean torque deviation 100 rpm

Although the mean torque was not sensitive to rotational speed, it did however make a significant difference to torque noise as can be seen in Fig. 9. The plots of the “hash width” clearly show the increase in torque noise with rotational speed. The vertical results are shown although the horizontal case yielded similar results with generally higher noise.

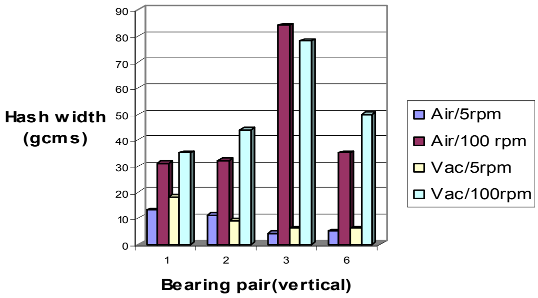

Figure 9. Bearing noise variation with speed

5.3. Phase 3 findings

The findings of attempting to combine the beneficial factors can be seen in Fig. 10, which shows the results of bearing sets 1, 2/8 and 3. These again show the relatively constant mean torque over the speed range.

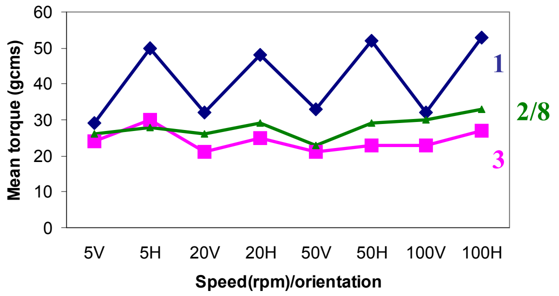

Figure 10. Optimised cage mean torque

When we consider the torque noise over the same speed range, a notable increase is seen with increasing speed for both orientations (Fig. 11).

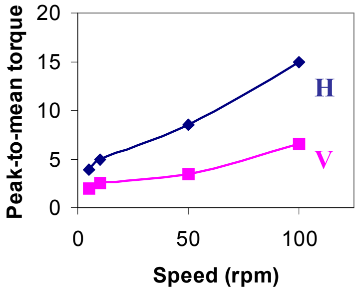

Figure 11. Torque noise variation with speed

Phase 3 also introduced the increase of preload on the bearings. The increased axial load naturally gave a corresponding rise in mean torque, but the effect of orientation at higher preloads was less pronounced. Fig. 12 shows that the ratio of horizontal to vertical mean torque was much lower both in vacuum and in air at 500N.

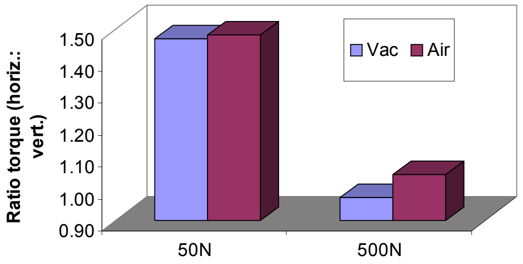

Figure 12. Orientation sensitivity with preload

This increase in preload also had an effect on torque noise with the peak-to-mean torque ratio being significantly lower under lower preload. In addition this ratio was insensitive to speed, unlike the 50N case where it increased with the rate of rotation (Fig. 13).

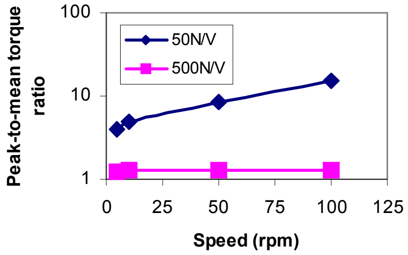

Figure 13. Torque noise vs. speed at high and low preload

The acceleration testing showed little correlation between acceleration and torque noise with the rotational speed being the most influential factor.

6. DISCUSSION

Bearing torque is generated by frictional losses at the ball-to-race interface as well as the ball-to-cage and cage-to-land interfaces. The first is caused by slip, spin and elastic losses in the region of contact, and is referred to as Coulombic torque. It is a function of friction coefficient and load for a given geometry and is essentially independent of speed and orientation (under 1g). In contrast the losses due to cage interactions are caused by inertial and dynamic loads and, as such, will be affected by the rotational speed, acceleration and orientation of the bearings,

Throughout the study it was clear that the orientation of the bearings was significant in mean torque performance at low preloads. An increase in clearance at the lands was the most critical parameter in minimising this. However, with higher preload this becomes less critical due to the increase in contribution of Coulombic torque, reducing the overall significance of the cage interactions. This has important consequences in the design of cages for low preload applications where the effect of orientation may be significant, such as in ground testing. Experience in life testing has shown orientation to be significant in terms of wear, torque measurement and cage misbehaviour.

It was also shown that torque noise can be minimised by the inclusion of variable pocket spacing, whilst the increase in ball-to-cage clearance did not give a significant reduction in torque noise. Thus variable circumferential spacing should be considered for applications requiring low noise performance. However, this design feature may limit the ball complement requiring a trade-off against contact stress or bearing stiffness.

With regard to the effects of bearing load, our observations indicate that the contribution of the cage to bearing torque noise is, relatively, much greater at lower loads i.e. the peak-to-mean and hash-to-mean torque ratios at low load (50N) exceed significantly those at high load (500N). In our tests peak-to-mean torque ratios as high as 18 were measured at low load (50N) whereas at high load (500N) peak-to-mean torque ratios were typically in the order 1.5. Because of the above effect, cage design has much less of an impact at higher loads.

There are two important consequences of the above observations:

a) The impact of cage design appears relevant at low loads only. Whereas a standard cage design should suffice at high loads, at low loads consideration should be given to modifying the cage design (e.g. introducing uneven pocket spacing) depending on the application requirements (e.g. low torque noise).

b) The standard guidelines on peak-to-mean torque for dry-lubricated bearings must be revised. As a rule of thumb it is often stated that the peak torque in a dry-lubricated bearing is a factor ~3 higher than the mean torque. Our test data show that - for lead-lubricated bearings - this is an over simplification. Within the test parameters of our study, at low-load/low-speed (vertical orientation) the factor of 3 is, in general, about right. However, at low-load/high-speed the factor is overly optimistic, a factor of between 5 and 10 being more appropriate. Conversely at high load the factor of 3 is overly pessimistic, a more accurate figure being 1.5.

At low loads, increasing rotational speed has been shown to increase torque noise, with the mean torque remaining relatively constant. The mean torque, being dominated by Coulombic friction, is relatively constant, whilst the increase in dynamic interactions at the cage interfaces explains the increase in torque noise.

7. CONCLUSIONS

The following conclusions are drawn based on our study of the torque behaviour of lead-lubricated, angular-contact, steel ball bearings fitted with leaded-bronze cages having a range of clearances and pocket spacing:

- The relative contribution of cage interactions to bearing torque behaviour decreases as the Coulombic torque increases (i.e. bearing load increases). In consequence, the impact of cage design on bearing torque noise is greatest at low loads where modifications to cage design can reduce torque noise and lessen sensitivity of bearing torque to orientation under 1g. In high preload applications there appears to be no discernable benefit in departing from the standard cage design.

- Cage contributions to torque noise increase with speed and are particularly noticeable at low loads.

- Dependent on the operating conditions, peak-to-mean torque ratios can be significantly lower or higher than the standard rule-of-thumb factor of 3.

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