SPEED DEPENDENCE OF BEARING TORQUE - ANOMALOUS EFFECTS WITH GREASE LUBRICATION

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ABSTRACT

In a number of cases, anomalously high bearing torque has been seen under slow-speed rotation with grease lubrication. This is of particular relevance to low-speed applications such as SADMs and pointing/tracking mechanisms. Here we report results from a series of tests aimed at elucidating speed-dependent torque effects, including a recent study of bearing torques over an extremely wide range of rotational speeds (6.0×10^{-4} rpm to 1.7×10^{1} rpm).

The results indicate a number of different effects for the different lubricants. Torque for bearings lubricated with MoS_2 is invariant with speed. In the oil lubricated case, the mean torque increases with speed. The speed-dependence of grease lubricated bearings showed a variety of effects.

The study has reinforced the view that grease lubrication can, under some operational conditions, yield higher-than-expected (and erratic) torques.

1. INTRODUCTION

Fluid-lubricated bearings would be expected to follow a torque-speed behaviour which mirrors the well-known Stribeck curve (Fig. 1).

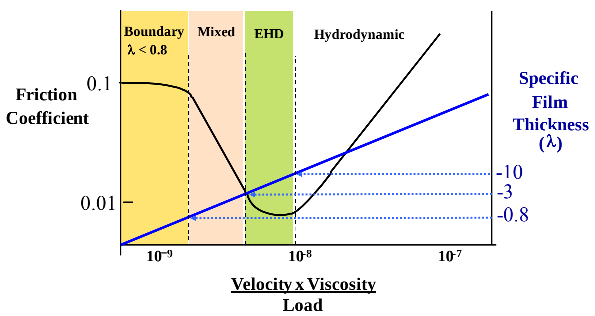


Fig.1 Stribeck curve: illustrating the various lubrication regimes for oil-lubricated contacts

However, tests at ESTL on grease-lubricated bearings have shown deviations from this behaviour and in particular the development of anomalously high torques at low bearing speeds.

An example of this effect is shown in Fig. 2, from work undertaken as support to a programme on Sentinel 3 SADM development. The bearings in question were of type SR4. The results show that while tests with the base oil followed the expected trend of increasing torque at the higher speeds of operation, the bearings lubricated with Maplub SH100b grease showed the opposite effect [3] – with the low-speed torque being an order of magnitude higher than that obtained with oil.

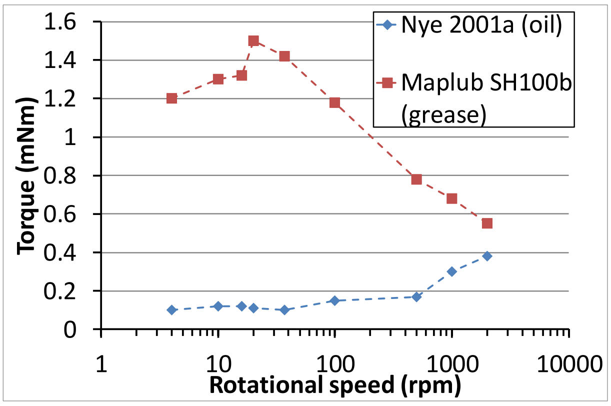


Figure 2. Showing torque vs. speed characteristics for SR4 bearing pair lubricated with SH100b grease and Nye2001a oil. 10 N preload, tests at 85°C [3].

The results reported herein were generated by two series of tests [1, 2], referred to as Test Programme 1 and Test Programme 2, as summarised in Tab. 1.

2. TEST METHODS

All bearings tests were performed using test rigs which enabled the rotation of the preloaded bearing pairs and the measurement of reacted torque by a torque transducer mounted to the bearing housing.

Tests in Programme 1 were performed in air, whilst Programme 2 was performed in vacuum. Fig. 3 illustrates the test rig used for Test Programme 2. Bearings were driven by means of a motor located external to the vacuum chamber.

'15th European Space Mechanisms & Tribology Symposium – ESMATS 2013'
Noordwijk, The Netherlands, 25–27 September 2013

Table 1. Summary of test conditions.

	Test Programme 1	Test Programme 2
Lubricants tested	Oil Grease	Solid Oil Grease
Bearing type tested	MPB S1724M5P58LDDB20-25 (see Tab. 2)	FAG XCB71916 (see Tab. 3)
Test rotation speeds	0.01–10 rpm	6×10^{-4} –16.67 rpm
Preload	100 N Hard preload (all greases). Peak stress: 1011 MPa. Hard and soft preloads in the range 10–200N (Braycote 601EF only). Peak stress range: 490 to 1257 MPa.	1200 N (Oil and grease). Peak stress: 1300 MPa. 500 N (Solid lubrication)
Test environment	Air	Vacuum

The details of the tested bearings are given in Tab. 2 and Tab. 3. Phenolic bearing cages were used for the oil and grease lubricated tests. These were impregnated with the lubricant oil (or base oil of greases) in line with an established flight process before testing, to prevent the uptake of oil by the cage. Bearing cages made of PGM-HT material were used for the solid lubricant tests.

The lubricated bearings were run in until torque values were stable prior to commencing the variable speed experiments. Torque measurements at each speed were made by performing a "reversal" consisting of movements in alternating directions, in order to assess the bearing torque. Typically a number of complete revolutions in each direction are performed. In the case of the extremely slow speed tests of Test Programme 2, it was not practical to complete whole revolutions due to the time required, and a reduced movement was performed instead.

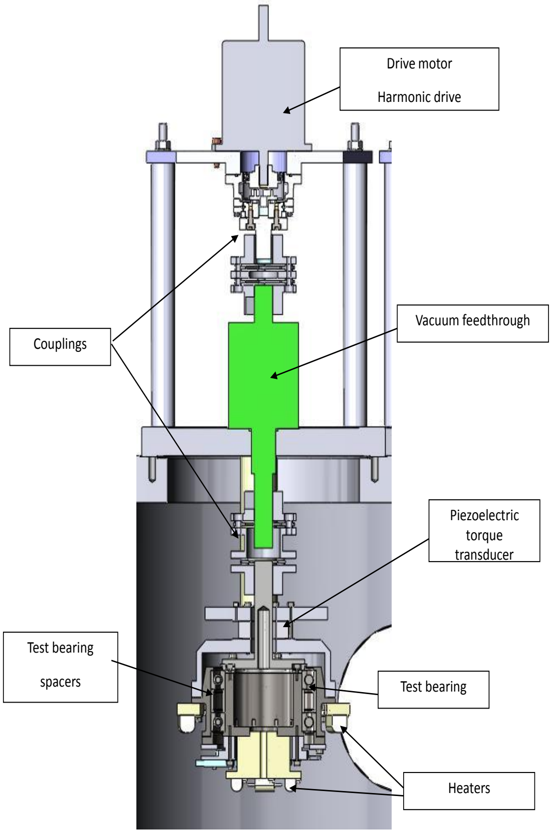


Figure 3. Bearing torque test rig. (Test Programme 2)

Table 2 Bearing details – MPB S1724M5P58LDDB20-25 *used for Test Programme 1.*

Ball material	440C
Ring material	440C
OD (mm)	38.1
ID (mm)	26.99
Width (mm)	6.35
Ball complement	24
Ball diameter (mm)	3.18
Conformity	Close (< 1.1)

Table 3 Bearing details – FAG XCB71916 used for Test Programme 2.

Ball material	Silicon nitride
Ring material	Cronidur 30
OD (mm)	110
ID (mm)	80
Width (mm)	16
Ball complement	25
Ball diameter (mm)	9.525
Conformity	Close (< 1.1)

3. RESULTS

3.1. Solid lubrication

Solid (MoS_2) lubricated bearings were tested over a range of bearing rotation speeds in Test Programme 2. Bearing races and balls were both coated with 1 µm sputtered MoS_2. The mean torque (as shown in Fig. 4) was shown to be independent of speed, across the whole range of speeds tested.

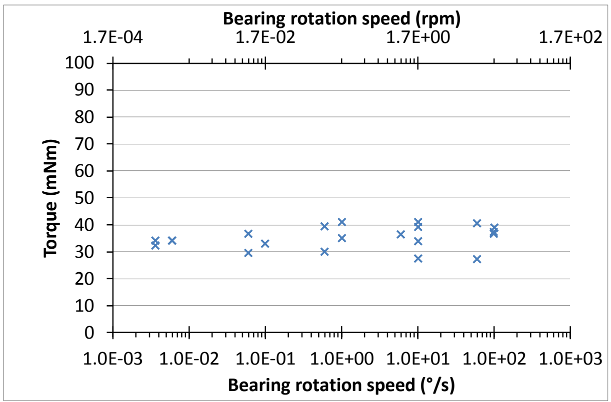


Figure 4. Solid lubrication mean torque. MoS_2 lubrication, 500 N preload (Test programme 2).

This result is consistent with expectations, as solid lubricants are understood to be unaffected by rotational speed. Lubrication is always in the boundary-regime and there are no viscous effects to cause speed-dependent changes in torque.

The observed invariance of mean torque for solid lubricated bearings demonstrates the suitability of our test apparatus for the measurement of torque over this wide range of speeds. This gives us confidence that the effects seen for oil and grease lubrication, presented later, are consequences of the lubricant rather than artefacts of the test rig or the bearings themselves.

3.2 Oil Lubrication

On moving to a fluid lubricated system, it is expected that there will more variation of torque behaviour with speed. In Test Programme 1, two common space oils were tested, Fomblin Z25 (a perfluorinated polyether, PFPE) and Nye 2001a (a multiply alkylated cyclopentane), mean torque results are shown in Fig. 5.

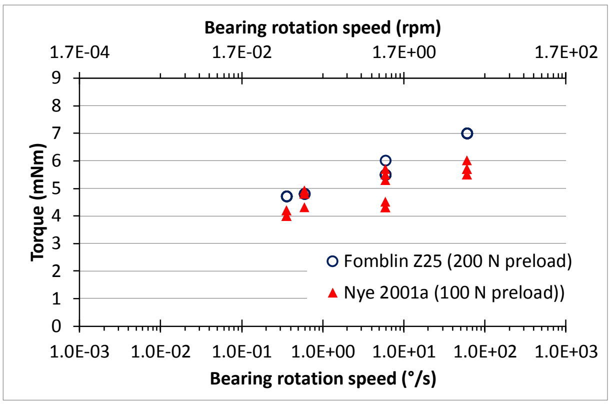


Figure 5. Oil lubrication mean torque. Test Programme 1.

In the case of both oils, there is an increase in mean torque with higher rotation speeds. The Nye 2001a lubrication gave slightly less consistent results for repeat tests with the same conditions.

The trend for increasing torque with higher rotation speeds is attributable to increased viscous drag as the speed increases.

These effects were also investigated in Test Programme 2, over a wider range of rotation speeds. These tests were performed on different size bearings, with Nye 2001a lubrication.

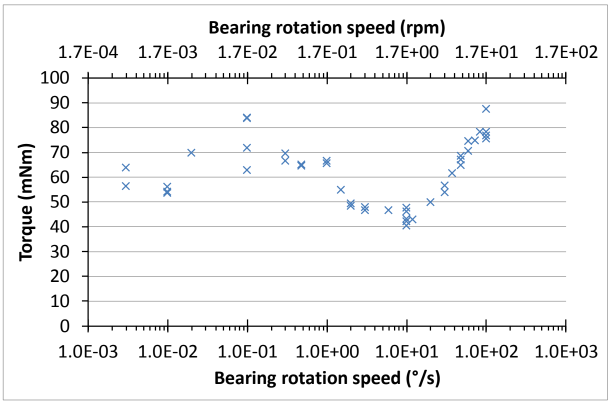


Figure 6. Oil lubrication mean torque. (Test Programme 2) Nye 2001a, 1200 N preload.

Again, the mean torque (Fig. 6) of the oil lubricated bearings showed a clear correlation to rotation speed – and consistent with the trend shown by the Stribeck curve (Fig. 1). There is a clear increase in (viscous) torque above rotation speeds of around 1 °/s. At lower speeds – below ~1 rpm (0.7°/s) – there was more variability between measurements for a given rotation speed.

In Test Programme 2, torque noise across a wide range of rotational speeds was investigated. The peak-to-mean torque ratio (Fig. 7) was shown to be invariant with speed.

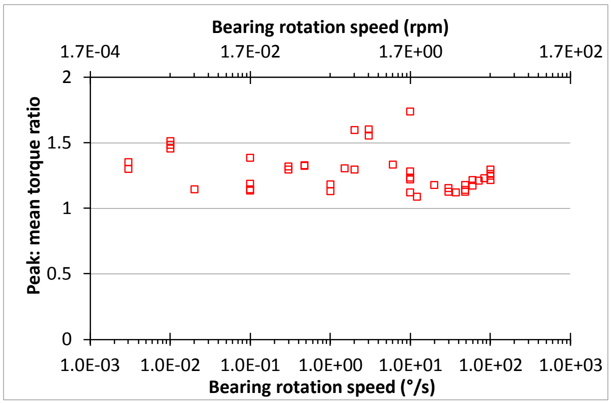


Figure 7. Peak-mean torque ratio. Test Programme 2. Nye 2001a, 1200 N preload.

The standard deviation of torque, another measure of torque noise, shows a different relationship to speed (Fig. 8). The standard deviation showed a clear decrease as the speed increased from 0.003 °/s to 30 °/s. With increasing speed thereafter, where torque behaviour appears to be dominated by viscous losses, the standard deviation increased sharply.

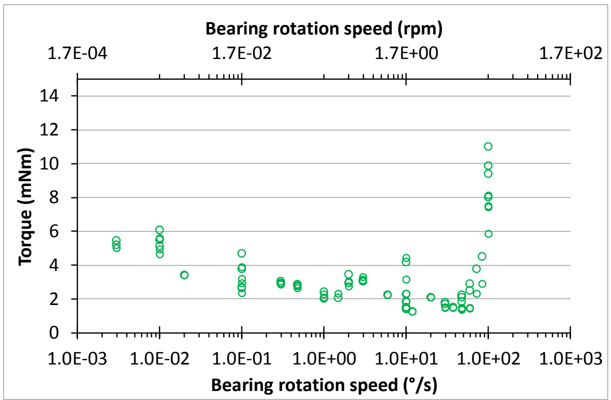


Figure 8. Standard deviation of torque. Test Programme 2. Nye 2001a, 1200 N preload.

3.3 Grease Lubrication

Grease lubrication brings added complications, since as well as the effect of fluid viscosity as seen with oil lubrication, the grease filler particles may affect the bearing torque behaviour.

A range of greases was tested, as listed in Tab. 4, most of which contained polytetrafluoroethylene (PTFE) filler particles. Rheolube Nye 2000 contains a sodium complex filler.

Table 4. Greases used for testing.

Grease	Base oil	Filler
Braycote 601EF	PFPE	PTFE
Braycote 601 micronic	PFPE	PTFE
Maplub PF100-a	PFPE	PTFE
Maplub SH050-a	Synthetic hydrocarbon	PTFE
Maplub SH051-a	Synthetic hydrocarbon	PTFE and MoS_2
Rheolube Nye 2000	Synthetic hydrocarbon	Sodium complex
Maplub SH100-b	Synthetic hydrocarbon	PTFE

Mean torque results for a variety of greases are shown in Fig. 9. Several tests were performed with each grease, for clarity only the highest recorded mean torque at each speed is shown.

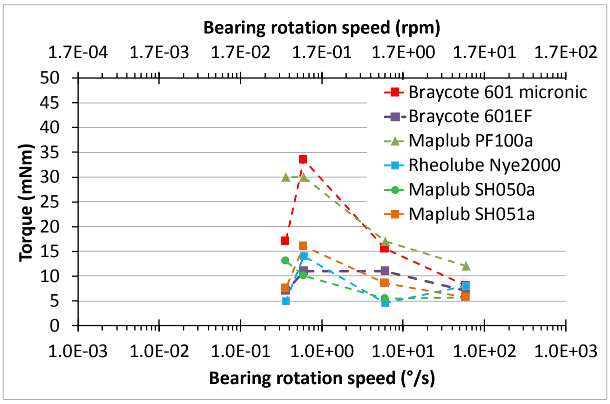


Figure 9. Grease lubrication mean torque, Test Programme 1, 100 N hard preload, range of greases.

It is notable that in all cases the highest mean torque is seen at one of the lower rotation speeds. This behaviour is clearly quite different to that seen with oil lubrication, and it may be concluded that the high torque is attributable to the grease filler particles. In some cases, the mean torque at low speed was as much as five times greater than at 10 rpm.

The effect of preloading was also investigated for Braycote 601EF lubrication. Bearings were tested under both hard and soft preloading conditions, and results are shown in Fig. 10. Again, only the highest measured torque at each speed is shown in each case.

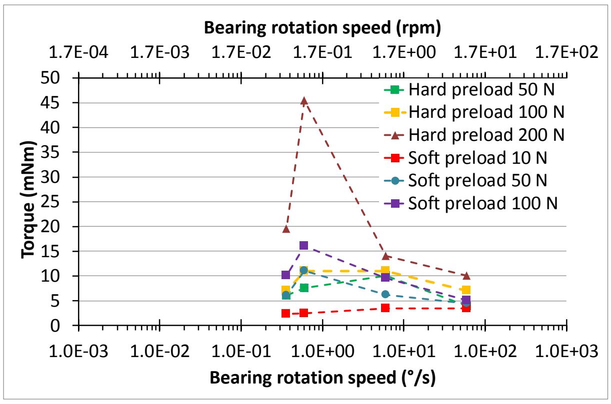


Figure 10. Grease lubrication mean torque, Test Programme 1, Braycote 601EF, various preload settings.

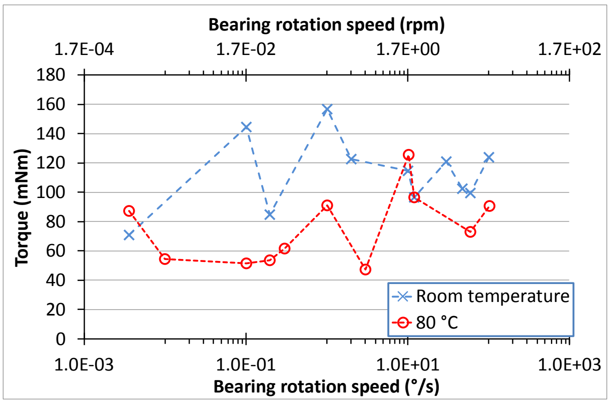
At the lowest preload tested, there is very little effect of speed, whilst the highest mean torque is seen with the highest applied preload. In most cases, and most notably with the 200 N preload, the mean torque is greatest at either 0.1 or 0.06 rpm.

In Test Programme 2, using different bearings, Maplub SH100b grease was tested, over a wider range of rotational speeds, at room temperature and 80°C.

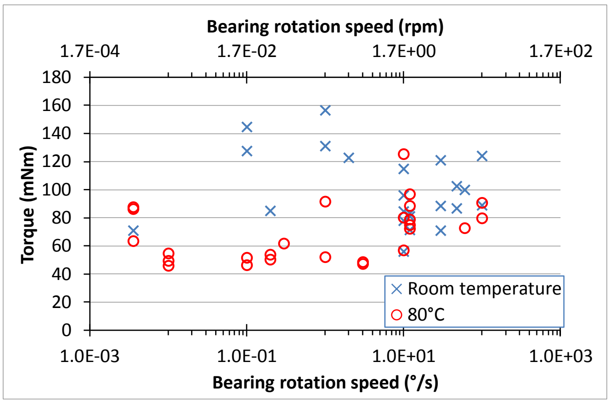
The mean torque results (Fig 11(a)) were highly variable, and did not show any consistent relationship with speed. Whilst this does not reproduce the extreme high torque excursions at low speed seen in Test Programme 1, it does nevertheless confirm that higher-than-expected, and somewhat erratic, torques occur with greased lubrication. The tests at elevated temperature generally show lower mean torque than at room temperature, although the variation with speed is still erratic.

Fig 11 (b) shows the results of all tests on the Maplub SH100b lubrication, illustrating the variation of torque under nominally the same operating conditions. At a speed of 1.7 rpm (10 °/s) at room temperature – under which conditions nine separate measurements were made – the mean torque varies by a factor of two (between 56 and 115 Nmm).

Some of the results from Test Programme 1 demonstrate that the recent history of bearing running can have a large effect on the mean torque level. In several cases the highest torque was seen on reducing speed, and then stabilised with further running at low speed. This is exemplified in Fig. 12, in which results from a series of tests on Braycote 601 EF micronic are plotted in chronological order.



(a) Highest mean torque at each speed.



(b) All test results.

Figure 11. Grease lubrication mean torque. Test programme 2. Maplub SH 100b, 1200 N preload.

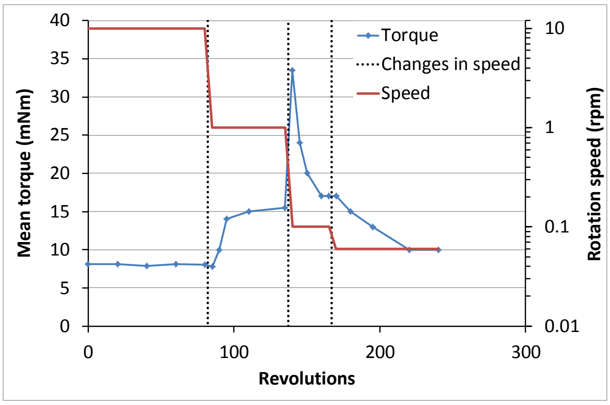


Figure 12. Series of tests of Braycote 601EF micronic. Test programme 1. 100 N hard preload.

It is clearly seen that the torque is at its greatest when reducing speed from 1 to 0.1 rpm, and then reduces after some running at 0.1 rpm. Similar effects were also seen for other greases.

Some additional tests were also performed as part of a separate test programme. These tests were not primarily aimed at characterising low speed behaviour, but unusual effects were observed for bearings lubricated with Maplub SH100b. It was observed that the mean torque was abnormally high for speeds in the range 1—20 rpm (see Fig. 13). In tests of the same bearings with different greases, Maplub PF100-b and Braycote 601EF Micronic, the torque was consistent across the range of speeds tested (1 to 50 rpm).

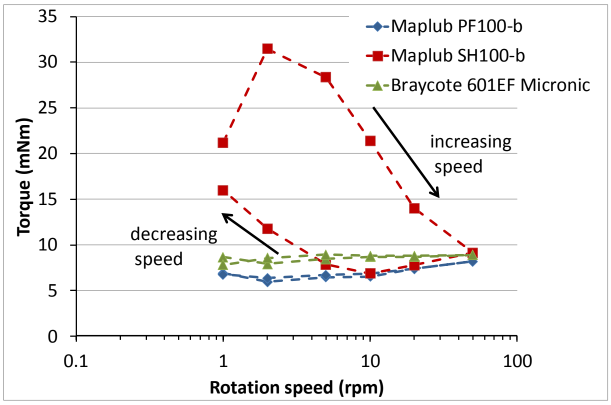


Figure 13. Tests of grease-lubricated angular contact, ball bearings (Barden type 104HC, 320 N preload) at speeds 1 to 50 rpm).

4 DISCUSSION

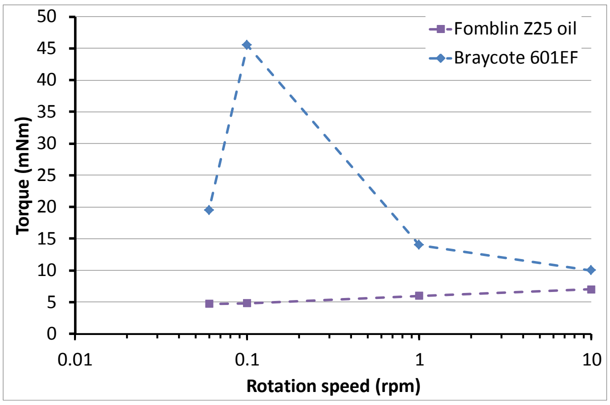
The tests of solid lubrication showed low torque which was independent of speed consistent with expectations.

The oil lubricated bearings generally displayed a trend which was broadly in line with expectations based on the Stribeck curve, increases in torque at the higher speeds being attributable to viscous drag.

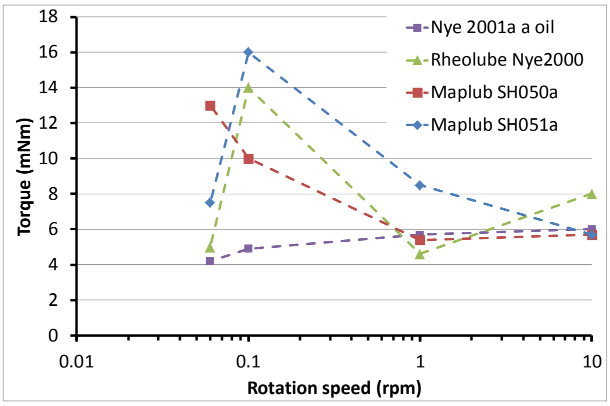
The grease lubrication tests showed torque variations with speed which were inconsistent with the Stribeck curve. Thus bearing tests in Test Programme 1 exhibited anomalously high torques at slow speed but at higher speeds the torque behaviour converged to that of the base oils. This is illustrated by Fig. 14. Additionally, the grease-lubricated tests in Test Programme 2 showed erratic torques which were notably greater than the base oil tests, even at higher speeds.

It is concluded that the high and/or erratic torques observed in the grease lubricated bearings are related to the presence of the grease filler particles (PTFE) and that, in general, the anomalous torque behaviour is favoured by operation at low speeds and high loads.

It has been argued [4] that if the balls (in angular-contact bearings) run continuously on the same equatorial track then a channelling of the grease can occur leaving dry, uneven 'rolled-on' PTFE film in the ball track and the equatorial band of the ball. Balls will only run on the same equatorial band when one race/ball contact has full control over the ball spin component so that there is no spin at that point [4]. A relatively high friction coefficient is required for this to occur such as is likely in the boundary lubrication regime at low speeds (at higher speeds as the oil thickness increases the friction coefficient decreases – Fig.1 - any increase in torque that occurs being due to viscous drag). In such a situation, even though there is a supply of oil at the sides of the running tracks and indeed on those areas of the ball outside the equatorial band this lubricant will not wet the PTFE transfer film (the surface tension of the oils exceed the surface energy of PTFE) or is not released from the grease unless moved into the contact area (e.g. if the balls start to slip bringing 'ball' grease into the running track).



(a) Fomblin Z25-based lubricants, 200 N preload.



(b) Nye 2001a based lubricants, 100 N preload.

Figure 14. Maximum mean torques for lubricants with same base oil. Test programme 1.

This proposed mechanism is consistent with our observations that the anomalous torque behaviour occurs at low speeds and is favoured at high loads (*i.e.* under conditions when *all* balls are highly loaded and less likely to slip).

In the situation postulated the balls run on a dry, uneven transfer film. This would account for the erratic torque behaviour but not the highest torques seen in Test Programme 1 as this would require a maximum friction coefficient of around 0.6 which would only be credible for an un-lubricated steel contact. However, we should be aware that PTFE is unable to lubricate at contact stresses above 1200 MPa (peak) and it is noted that in

Test Programme 1 the highest 'anomalous' torque was observed in the most highly loaded (200 N) bearings where the peak stress exceeded this limit (see Table 1). So the possibility arises that at high stresses the 'plated' PTFE does not provide protection to the bearing and very high friction ensues.

In this context it is of interest to note that the Castrol data sheet for Braycote 601EF grease stipulates that in vacuum the grease should not be subjected to stresses in excess of 689 MPa (100,000 psi). It is not stated whether this stress is a mean or peak value nor does it give the reason for this limitation. However the observation that some of the largest anomalous bearing torques have occurred in air would suggest that the Castrol stress limit is unrelated to the torque anomalies reported here.

A possible contributory factor to high torque development is that the conformity of the bearings is increased by a build-up of PTFE along the edges of the wear track. An increase in conformity of the bearings would cause a consequent increase in torque. However, this would not explain why the high torques subside with continued running.

Whilst it is not possible at present to give a definitive explanation of the observed variable torque, what is clear is that many of these effects are difficult to predict, and a combination of factors such as the speed, load, running history, temperature and type of grease appear to be involved. The fact that torque levels are not consistent between tests made under the same operating conditions indicates how unpredictable the behaviour can be.

5 CONCLUSIONS AND RECOMMENDATIONS

Several tests of grease lubricated bearings have shown unpredictable torque behaviour. The torque is often inconsistent for repeat measurements made under the same conditions.

The fact that such erratic behaviour does not occur with the base oils of the greases indicates that the peculiar behaviour of greases is related to the filler particles

Given that, at worst, greased bearings can yield excessively high torques at low speed and, at best, a wide variation in torque values for a given set of operational conditions, we advise that in applications where bearing torque is a driver in the overall mechanism losses, the use of oils rather than greases should be considered so as to reduce overall torque levels and improve the repeatability/predictability of mechanism behaviour (especially for low speed applications).

Where greases are to be used, early testing under representative conditions is to be strongly recommended. The results presented here give further weight to the argument that accelerated testing should not be considered valid for grease lubricated systems. If grease lubrication of low-speed bearings is unavoidable then generous torque margins would be advisable to allow for some unpredictable behaviour.

6 REFERENCES

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ACKNOWLEDGEMENTS

Test work was conducted under contract to ESA-ESTEC.