CHARACTERISATION OF LUBRICATION EFFECT ON PERFORMANCES AND LIFETIME OF CERAMIC AND HYBRID BALL BEARINGS

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ABSTRACT

In the context of high accuracy pointing applications, Astrium SAS have investigated, with support of CNES, the use of bearings with silicon nitride balls as an alternative technological solution to the standard lubricated stainless steel ball bearings, in order to reduce as far as possible the torque noise in mechanisms, and to avoid outgassing pollution.

Performances of lubricated ceramic ball bearings are available in technological literature, therefore the effort was focused on the search of possible use of low speed rotating ceramic ball bearings without any lubricant, with the goal to achieve or exceed the lifetime performances of standard dry-lubricated stainless steel ball bearings, and to get rid of their on-ground operation constraints.

This three-year study exhibits promising results, limited by the behaviour of cage material under dry conditions. No visible wear of neither ceramic ball nor steel or ceramic rings was pointed out.

1 INTRODUCTION

In-orbit optical and communication payloads often require more stringent pointing accuracy than spacecraft pointing performances capability. They have to be implemented on pointing mechanisms. Each time the requested pointing range exceeds a value of a few degrees, the mobile part has to be rotation guided by ball bearings. These ball bearings are subjected to various environmental and operational constraints, including on-ground tests, launch and in-orbit life.

To avoid cold welding, the stainless steel ball bearings operation requires the use of a lubricant – either fluid or dry – which drives the design and the operational profile of mechanisms. Design must prevent from contamination issues related to fluid migration, or outgassing. Lubricant depletion in vacuum shall be consistent with the in-orbit lifetime. Fluid viscosity may jeopardize performances at low temperatures. On the other hand, dry lubricants offer a limited load capability, are sensitive to ambient air during ground test phases, and are subjected to wear.

Although these standard design features do operate successfully in space mechanisms, there is an obvious interest for ball bearings with less friction torque, no outgassing, higher lifetime and no operation constraint – such as limited number of operations or dry nitrogen purging – during Assembly, Test and Validation phases.

In this context, Astrium SAS and CNES have investigated the use of bearings with silicon nitride balls, and even no lubricant at all, as an alternative technological solution for high accuracy, long lifetime pointing mechanisms.

The major steps, achievements and prospects of this activity started in 1998 are detailed in this paper:

1. The **interest** of investigating a new solution is developed, because a well-established design standard is now widely implemented, despite its intrinsic limitations.
2. The **state of the art** of silicon nitride bearings applications is recalled; this will show why the application studied here is innovative, thus why a test campaign is necessary to obtain some technical background.
3. The dedicated **test set-up** developed for this activity, and the reference **test plan** applied to all samples.

4. The main **results** of the test campaigns are finally analyzed, and the lessons learnt highlighted.
5. The **conclusion** presents the future prospects to obtain a reliable and qualified technological solution, available for new pointing mechanisms development.

2 AREAS OF INTEREST

2.1 Limitations of the usual stainless steel bearings

Every mechanism engineer can now design space mechanism with conventional stainless steel bearings properly lubricated. However, each designer always keeps in mind the limitation of those solutions:

- Fluid lubricant generates a viscous friction torque which may jeopardise pointing requirement for some very demanding applications
- Fluid lubricants limit the acceptable environment temperature range, which can make life difficult when one wants to implement a pointing mechanism outside the spacecraft, for communication applications for instance.
- Solid lubricant is subjected to operating constraints, needing the record of the number of actuations performed, the optimisation of test campaigns to limit the use of mechanism in air, and sometimes to purge the mechanism with dry nitrogen when operated in air, or even stored for a long time.
- The particles normally generated by a solid lubricant may degrade the pointing performances when the mechanism is used for tracking purposes, i.e. operating a large amount of small angular range, low speed oscillations.

2.2 Candidates applications

Thus, the present work becomes attractive considering demanding applications, where one or several of the following requirements are applied to the mechanism:

- Severe contamination constraints forbidding the use of fluid lubricant. (i.e. optics vicinity)
- High contact pressure, (for instance during launch), or large lifetime required, making difficult the use of conventional solid lubricants such as MoS_2
- High accuracy pointing required: in this case, a closed loop control is implemented, but the bearings friction torque limits its performance.
- Extreme (in particular cold) temperature environment.

The work has been therefore focused on pointing mechanisms, demanding a large number of low angular range pointing cycles, severe cleanliness and friction torque requirements, and possibly operated in low temperatures environment. This criterion explains how the test sequence, developed in the following sections, has been built.

2.3 Silicon nitride choice justification

The proposed alternative design must be cost effective, which means that

- The proposed bearing must be already produced for industrial purposes; no specific development is envisaged at this stage. We will see how this constraint has limited the choice of cage materials, and brought some drawback linked to the cages available today in the industrial market.
- Once qualified, the proposed bearings shall not generate any specific constraint at mechanism level: no lubrication procedure, no operational constraint.

The choice of silicon nitride ceramic material (Si_3N_4) becomes then quite natural. Inside a hybrid ball bearing, the combination of a ceramic ball rolling on a stainless steel ring offers theoretically lower friction torque. The risk of cold welding is quite remote, removing –in theory- the need for lubrication.

Hybrid, but also full ceramic ball bearings are now widely used in some specific industrial applications. The cost of industrial hybrid bearings is not significantly higher than the cost of a custom stainless steel bearing developed for a space mechanism.

3 STATE OF THE ART

3.1 Definitions and keywords

It is necessary at this stage to give some reference data:

Ceramic: although this is a generic word describing all "non-metallic" material, ceramic bearings always refer to the silicon nitride, Si_3N_4 material.

Hybrid bearing: this is a bearing with silicon nitride balls, the rings being in stainless steel. Two steel alloys have been studied. First of all the standard well-known AISI 440C, but also the "CRONIDUR 30", which is a trade-mark from "Krupp-Thyssen-Nirosta" classified DIN 1.4108 or AMS 5898.

The cage is generally made of phenolic resin, but other cages materials are available and have been tested.

Ceramic bearing: the balls *and* the rings are made of silicon nitride.

Main material data:

The table 1. gathers the data of the material involved in our study

Parameter	Si3N4	440C	CRONIDUR 30
Composition %C %Si %Cr %Mo %N	- - - - -	 1.08 0.4 17 0.52 --	 0.31 0.55 15.2 1.02 0.58
Young Modulus	315 - 325 Gpa	203 Gpa	- - - -
Poisson Modulus	0.26	0.30	- - - -
Density	**3.2**	**7.7**	- - - -
Hardness	1450 – 1750 HV	> 58 Hrc	230 HB
CTE (/°C)	3.2 10^{-6}	$1.0.10^{-5}$	- - - -
Highest limit temperature	- - - - -	120 °C	**320°C**
Fracture Elongation		0.2%	**3%**

Table 1.: main material data

3.2 Industrial applications

Hybrid bearings were once reserved for sophisticated applications requiring precision performance at high speeds. They were typically used in the aerospace and machine tool industries, when high rotation speed and severe environment constraints limit the life of conventional standard stainless steel bearings.

Reduced costs and the benefits of the hybrid design are now opening up opportunities in "high end" deep groove ball bearing applications such as in gearboxes, pumps, high-speed electric motors and traction motors.

In aerospace applications, the use of silicon nitride bearings allowed to increase the time between two maintenances. For instance, the replacement of Boeing 737 flap ball joint by a silicon nitride one has suppressed the need for maintenance and refurbishing of this component.

Ball bearings in launcher turbopump are submitted to severe environment reducing life capability. The qualification of hybrid bearings for the space shuttle turbopumps has reduced motor maintenance constraints between two flights. The same process was engaged with respect to Ariane 5 turbopumps in 1999.

These examples show the advantages brought by these bearings:

- The better withstanding of aggressive environment limits the risk of corrosion.
- Even in case of degraded lubrication conditions, there is no cold welding between the ceramic ball and stainless steel ring.
- The lower density of the balls divides the rolling mass by a factor two: in high speed rotating applications, the contact pressure generated by the balls centrifugal force limits the bearing capability. For a given rotation speed, ceramic balls will provide less contact stress, and less vibrations during operations.
- High radial and axial stiffness, improving the guiding accuracy.

3.3 Application for pointing mechanisms

The literature does not refer to many examples of "low speed" rotating mechanisms using hybrid bearings, because the most obvious advantages are linked to a large rotating speed. However, a publication from TELDIX, dated 1981, describes the development of a Bearing And Power Transformer Assembly (BAPTA) using a hybrid bearing," to increase life in a wide temperature life and to avoid lubrication problems".

Another paper, issued by SKF, dated 1996, shows that hybrid bearings run steadily under low load and "virtually dry conditions".

In order to complete and confirm these facts, a first R&T campaign was decided by Astrium SAS in 1998. Three pairs of standard hybrid bearings were tested at ambient conditions. The encouraging results motivated CNES & Astrium SAS to extend the work by a more systematic test campaign, with the goal to find the most suitable cage material, this parameter appearing as one of the major keys of the success.

4 TEST PLAN AND TEST SET-UP

4.1 Test plan

All test samples have been subjected to the same test sequence, thus the results are directly comparable.

The test have been conducted in ambient conditions, but under dry nitrogen purging to prevent air moisture from giving some undesired lubrication which could have improved the bearings performances.

The test sequence simulates the bearings life, at ambient conditions:

- Initial performance measurement
- Run-in
- Performance measurement
- Vibration test
- Performance measurement
- Life-test
- Performance measurement
- Inspection

The bearing pair is rigidly and highly preloaded, to get permanent contact pressure greater than 200 hbar. This choice aims at reducing life test duration, and making comparison between the different test specimens.

The table2. details the test conditions:

Name of the test	Kinematics	Measurement
Performance	Continuous rotation, CW and CCW, at three speeds : 0.6, 6 and 60 rpm	One torque acquisition for each speed case (6 per test) with a spatial sampling of approx 4° Higher resolution on some samples, to monitor torque noise
Run-in	10 000 rotations at 60 rpm, with rotation reverse every 500 rotations	None
Vibration (axial only)	Random low level Sine sweep 30g, 3min Random low level	Resonance survey
Life-test	±2° sine oscillations	Torque survey

Table 2.: test description

4.2 The test set-up

<u>Functional and life test</u>

A dedicated test set-up has been designed, developed and validated to perform the bearings functional and life test.

The test set-up architecture is depicted in the following figure 3.

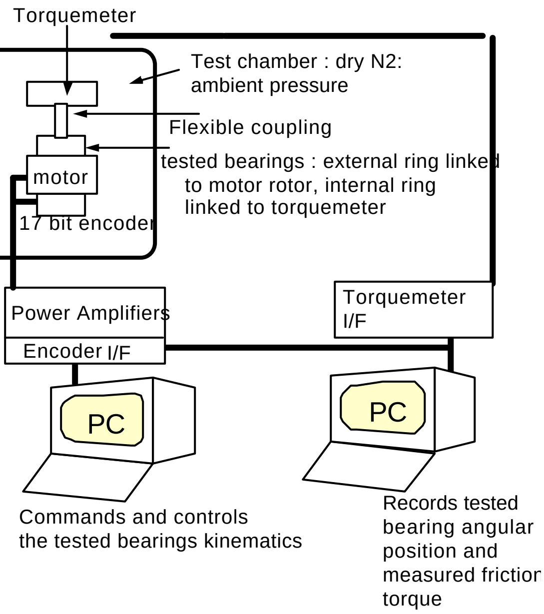


Figure 3.: test set-up architecture

Acquisition and command channels are fully decoupled in order to avoid interferences and sample frequency limitation for the acquisition channel.

The closed-loop controlled drive channel allows defining and controlling the tested bearings motion profile. Two types of profile are used: a controlled constant speed for torque characterisation, and a controlled sine oscillation for the life test.

The test set-up hardware is made of standard industrial components:

- DC brushless torquer from Kollmorgen
- 17 bit CODECHAMP industrial encoder
- High accuracy torquemeter (2 available, one from DORDELEC, one from SCAIME)
- Standard flexural joints

The test set-up structure (motor housing and guidance, test chamber) has been designed and built at Astrium for the purpose of this activity. The figure 4 next page shows the test chamber. From top to bottom we see the torquemeter, the flexible joint, the ball bearings assembly housing, the filtering inertia (necessary to make movement control smoother), and the motor/encoder assembly housing.

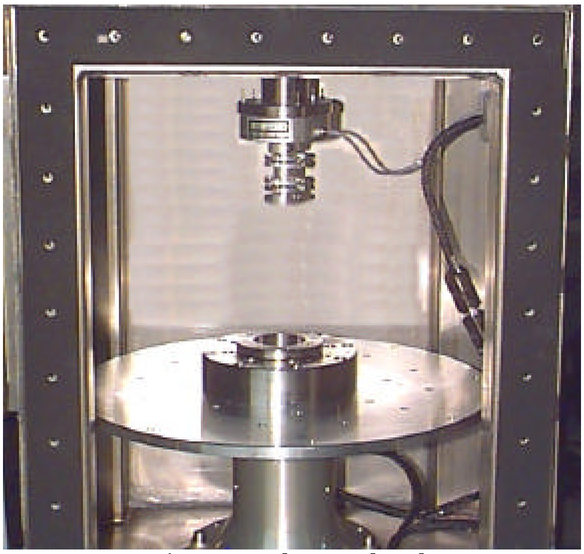


Figure 4.: The test chamber

4.3 Vibration test facility

The bearings were vibrated on LTV A286 shaker.

Figure 5.: The LTV model A286 shaker

The main characteristics of the set-up are recalled in table 6.

We can see (figure 5) on the top of the shaker the bearings assembly housing, and a 6kg mass mounted on the rotor shaft, to bring the 180 daN axial load under 30g.

Balls gapping occurred during all tests.

Armature mass	1600 kg
Max. static load	272 daN
Max. load under 20g	12kg

Table 6.: Shaker properties

4.4 Test samples selection

The first test campaign in 1998 compared the performances of three pair of hybrid bearings from ADR. Two pairs were built with phenolic resin cages; the third one was using ring PTFE separators.

One of the resin phenolic cages pair was lubricated with PENNZANE SHSX2000 oil; the two other pairs were dry.

Following the test, the bibliographic study and the contact and technical advise with different suppliers, the selection of bearings for the second test campaign, carried out in year 2000, was made according to the following criteria:

- Comparison of different cages material
- Comparison of hybrid bearing vs. full ceramic
- Effect of fluor grease on silicon nitride material
- Comparison of different rings material, in particular advantages of the CRONIDUR 30 steel compared to standard AISI440C.
- Use of standard hardware: standard catalog bearings, as far as possible, and standard cage material

One shall keep in mind that the number of samples to be tested had to be limited by budgetary constraints, which explains why it was not possible to test bearings from all the suppliers contacted, and that a selection had to be made to find the best compromise.

The following table 7 lists all the bearings tested during the two test campaigns. The table 8 summarises all the tests carried out

Suppl.	Ref.	Balls	Cages	Rings	Lubricant	Preload
ADR	WA725	Si3N4	Phenolic	AISI 440C	*Pennzane*	500N (200 hbar)
ADR	WA725	Si3N4	Phenolic	AISI 440C	No lub.	500N (200 hbar)
ADR	WA725	Si3N4	*PTFE annular rings*	AISI 440C	No lub.	500N (200 hbar)
KOYO	3NC7005CST4DB10	Si3N4	Phenolic	AISI 440C	*MAPLUB PF100*	500 N – (180 hb)
KOYO	NC7909C-1DB10	Si3N4	Phenolic	*Si3N4*	*MAPLUB PF100*	500 N – (170 hb)
MPB	W137 – 803	Si3N4	*MELDIN 2030 PTFE FILLED*	AISI 440C	No lub.	500 N (240 hb)
MPB	W137 – 804	Si3N4	*Lead/Bronze (EMS 230)*	AISI 440C	No lub.	500 N (200 hb)
MPB	W137 – 800	Si3N4	Phenolic	AISI 440C	No lub.	500 N (200 hb)
MPB	W137 – 802	Si3N4	*Bronze-Al (EMS 284)*	AISI 440C	No lub.	500 N (200 hb)
FAG	HC71905C	Si3N4	Phenolic	*CRONIDUR 30*	No lub.	500 N (220 hb)

Table 7.: The test samples

5 THE TEST RESULTS

In order to avoid a tedious list of all results, these have been sorted out according to success criteria, to point out what is important for obtaining the best performances.

5.1 Failures

Three failure cases have been observed, which means test interruption after the run-in because of an increase of friction torque 5 to 10 times the initial values (0.1 to 0.2 N.m). This was due to the generation of debris by the cage or the separators, and observed with PTFE separators, and metallic bronze cages.

The figure 8 plot shows the friction increase of the bearing mounted with PTFE separators.

The figure 9 shows a big lead-bronze cage particle.

A no load run-in tentative has been conducted on a bearing with bronze cages, in order to see if an initial lead deposit on the rings could prevent from damaging when the bearing is operated in dry conditions, with high preload, but this did not improve the performances.

These results are in accordance with manufacturer technical forecast

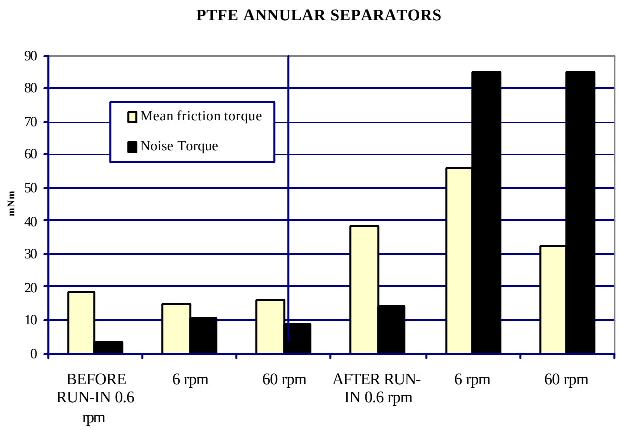
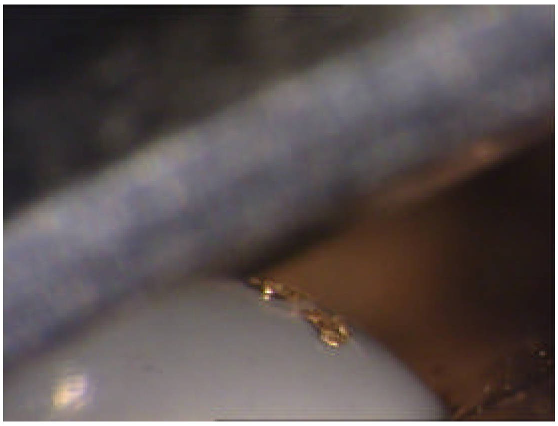


Figure 8.: PTFE separators: *left: 3 measurements before run-in (mean torque and noise torque)*

The three measurements in the right part of the figure correspond to the same conditions, after 10000 run-in rotations.



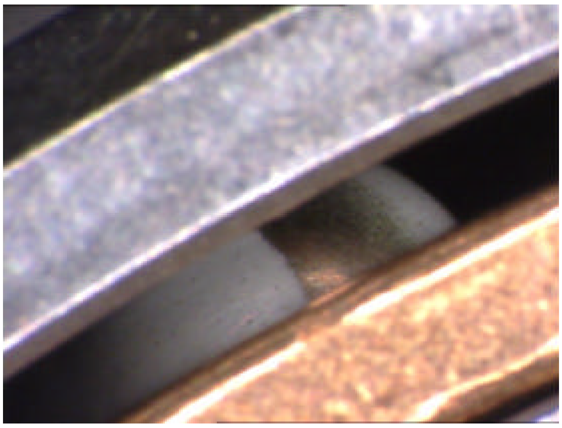


Figure 9. cage particle and traces of cage material on balls (bronze cages)

5.2 Dry bearings, non-metallic cages

Whatever the number of life test cycles was, no wear process of ball or rings was observed during these tests, except sometimes a slight marking of rings due to balls take off during vibrations. Nevertheless, this did not generate abnormal bearing failure, just a degradation of the torque measurement.

The performances degradation is due to the accumulation of cage particles. This is clearly visible when looking hysteresis cycles (torque versus angular position) during life test. The torque value increases at the extremities of the cycle (change of rotation direction), where the particles accumulate.

Fig.10 shows a typical hysteresis cycle obtained with phenolic resin cages: the plot extremities distortion increases with the number of cycles. Fig.11 shows the same result with similar bearings, but lubricated: the cycle remains flat.

The longest life tests were carried out with the phenolic resin cages, which was unexpected because this material is designed to be impregnated. The bearings with polyimid cages (MELDIN 2030) showed a greater, but non dramatic, degradation of the performances.

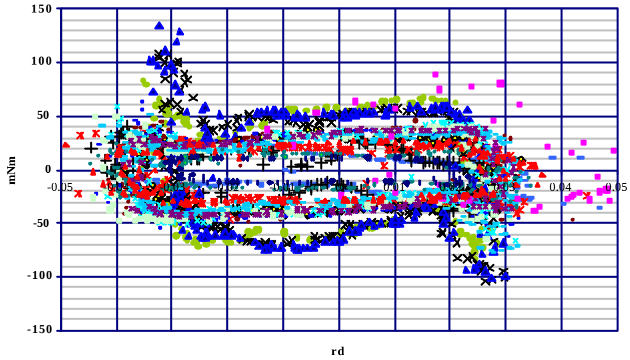


Figure 10. hysteresis cycles distortion due to particle accumulation

These particles degrade the noise torque, while the mean friction torque does not increase significantly. A few tens of constant speed rotation are in this case sufficient to sweep out the particles, and to bring the bearing performance back to nearly its "begin of life" state, as shown in fig.12.

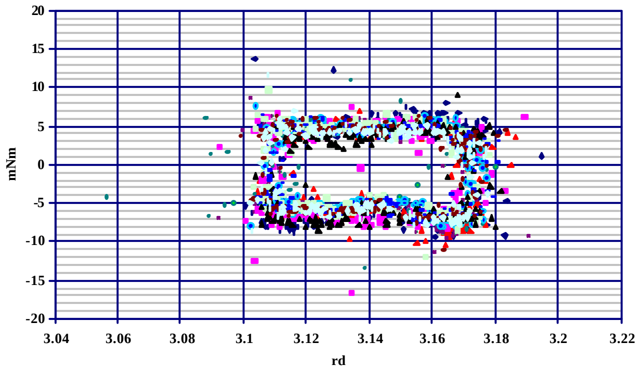


Figure 11. The cycle remains "flat" if the bearing is lubricated

Among the bearings tested, no combination totally insensitive to absence of lubrication has been found. Some possibilities have however not been yet tested, such as "hard" metallic cages like steel cages, or bearings without cages or separators (but in this case a torque instability due to the lack of guidance of balls is suspected).

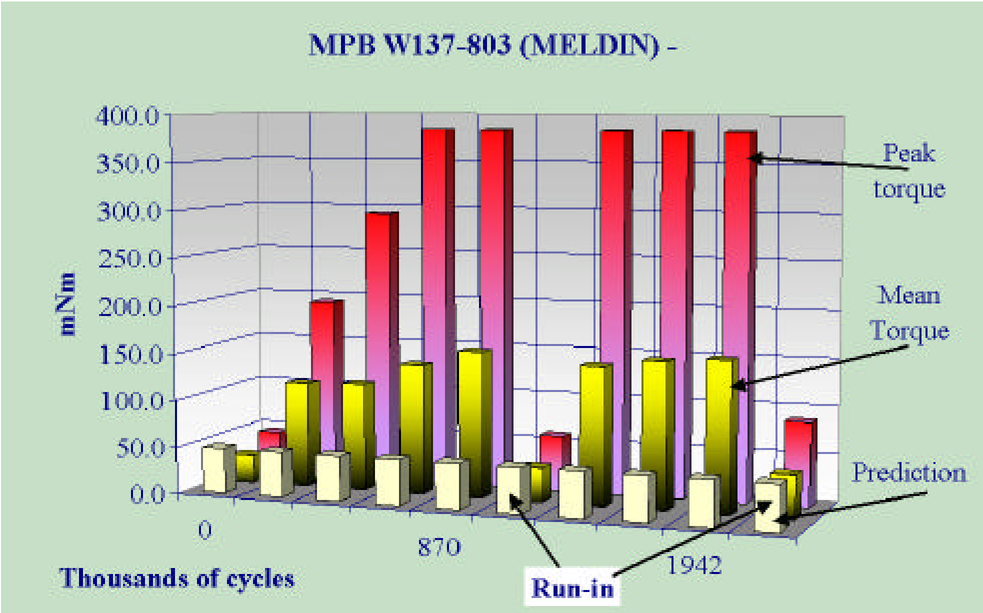


Figure 12. Effect of run-in to improve performances

5.3 Other results

The CRONIDUR 30 alloy cannot be fully evaluated, because the rings were marked due to an unexpected resonance during vibration test, and needs to be re-tested in another campaign.

The hybrid or full ceramic bearings lubricated with fluoric grease did not show any degradation. Thus no chemical effect has been pointed out at this stage.

6 CONCLUSION

The test data gathered during these two campaigns shows that the performances degradation comes from cage material wear when hybrid or ceramic bearings are operated in dry conditions for pointing applications. This is not surprising because standard cages are designed to work with a fluid lubricant. The effect of this degradation is mainly an increase of the noise torque, and this degradation is mostly reversible, as a few tens or hundreds of rotations can sweep the particles and bring performances to initial values.

These results have to be weighted by the test conditions: high preload maintained during all life, with contact pressures of about 200hbar. With this context, one can say that the life expectancy of similar bearing with a standard dry lubricant has been far improved.

The tests confirm then the interest of this application when fluid lubricant is forbidden, and large lifetime associated with extreme conditions, is required.

There is however still lot to do prior obtaining a configuration ready to be qualified and proposed for a space mechanism development. This will be the scope of the next step of this work, to start in the second half of year 2001:

- Test influence of temperature, especially cold environments.
- Selection of an adequate cage, or test the behaviour of a bearing with no separation between balls.
- Quantify the effect of gapping during launch: improve our prediction tools, validate them by tests and derive a dimensioning rule (today rules are derived from abacus strictly applicable to stainless steel).
- Qualify the "reference " design solution
- Complete some tests: e.g. re-test a CRONIDUR 30 bearing.

7 REFERENCES

Please contact the authors to get the complete list.

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