NIRSPEC WHEEL SUPPORT MECHANISMS´ CENTRAL DUPLEX BEARINGS CRYOGENIC TEST RESULTS

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ABSTRACT

RUAG Aerospace Austria (RAA) has the privilege to develop the Wheel Support Mechanisms for the Filter Wheel and the Grating Wheel of the Near Infrared Spectrograph (NIRSpec) Instrument of the James Webb Space Telescope (JWST).
One of the key components of the wheel support mechanisms is the bearing which shall

1. have highest accuracy,
2. withstand cryogenic operating temperatures of 30K
3. have low friction torque during low temperature operation while
4. withstanding considerable launch loads at ambient temperature

The chosen bearing is a custom-made hard preloaded flanged duplex ball bearing lubricated with sputtered MoS_2 in back to back configuration with a patented thermal off-load device in order to realize the diametrically opposed requirements 3 and 4 above.

Two batches of bearings were procured, and component level testing of the first bearing models was performed. This paper describes the lessons learnt during component level testing, failure recovery, and correlation of the test results with the predictions.

1. DESCRIPTION OF THE BEARING

The bearing is a ball bearing in back to back configuration. It consists of one outer ring with 2 races, 2 rows of balls, and 2 inner rings that are clamped together with 12 bolts of Titanium alloy. Invar segments are placed between the inner rings.

The Invar segments cause an off-loading of the bearing at low operating temperature so that the friction torque is reduced by 90% of the ambient temperature friction torque that applies during launch. This design prevents gapping under launch loads while minimizing friction torque and associated heat dissipation during cryo operation.

Bearing rings and balls are of the same material to prevent thermal impact. Bearing pre-load is applied by clamping the inner ring halves with the bolts. The pre-load is adjusted by modification of the contact area between the inner ring parts. The bearing is of "hard preload" type.

Figure 1 presents a cross-section of the bearing:

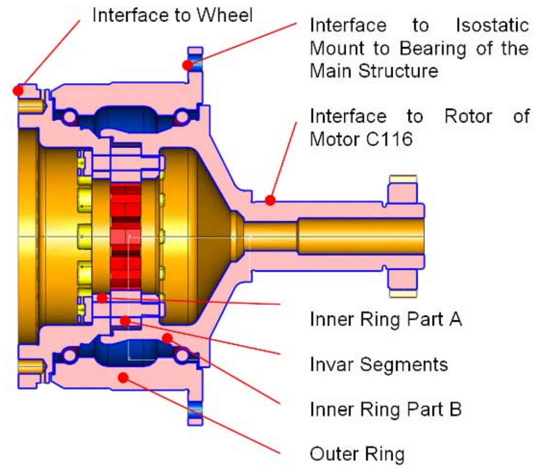

Figure 1. Bearing Cross Section.

The main parameters of the bearing assembly are provided in the table below:

Overall Dimensions	Ø 103 mm x 112 mm
Pitch Circle Diameter	65.1 mm
Center Plane Spacing	31 mm
Quantity and Size of Balls	Ø 4.7625 mm (2 x 33 off)
Ring and Ball Material	AISI 440C
Cage Material	Duroid 5813
Lubricant	Sputtered MoS_2 by ESTL, applied on the races.
Mass	1.480 kg
Part Count	102
Bearing Supplier	ADR

The bearing was developed by RAA together with ADR, S.A.S., manufactured by ADR, S.A.S., cage design and lubrication of the races and the sliding interfaces was performed by ESR Technology Ltd, ambient testing was performed by EADS Astrium GmbH, cryogenic testing was performed by RAA.

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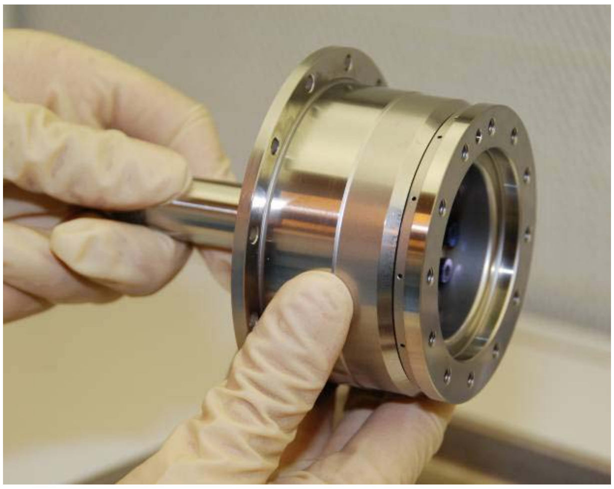

Figure 2. Bearing Assembly.

A detailed description of the bearing design novelties was presented during the 12th ESMATS [1].

2. CAGE GEOMETRY AND DESIGN

Initial friction torque measurements were performed at ambient temperature under vacuum better 10^{-5} mbar.

These initial friction torque measurements showed unexpected friction torque behavior: The initial torque was approx. 2.5 times the predicted value and did not decrease during the test and run-in duration of 1000 revolutions.

The bearing was disassembled after 1000 revs at ambient temperature and after 1000 revs at cryogenic temperature, and the piece-parts were visually inspected.

A photograph of the wear marks on the ball contact areas inside the cage pockets is shown in figure 3.

Figure 3. Wear Marks inside the Cage Pockets.

On the contact points between the balls and the cages the cages showed signs of significant rubbing and wear to quite extensive extent. The substantial contact between balls and cages that caused these wear marks may have led to a significant torque contribution due to interaction between balls and cages.

This was in-line with the rather narrow design clearance between the pocket and the ball at ambient temperature of the initial cage design.

It was concluded, that the initially chosen cage geometry was the reason for this unexpected behavior.

Conical pockets may have lead to situations where the cage forms a wedge between the balls which tries to block the rotation.

So the pocket geometry was changed from a conical pocket design to a pocket design where the contact areas to the balls are now formed by a cylindrical section of the hole. A conical section of the hole is implemented just for assembly reasons. This conical part of these pockets does not touch the balls.

CTE considerations: The high coefficient of thermal expansion of the cage material (Duroid 5813) compared to the CTE of the bearing steel gives two configurations of the cage, one at ambient temperature for on-ground testing and a different one at cryogenic operation temperature of 30K.

To account for the highly different coefficients of thermal expansion by design, at ambient temperature the cage is outer-ring-riding, whereas at 30K the cage is inner-ring-riding. Verification took into account both configurations.

The cage design and analysis was performed by ESR Technology Ltd.

3. VACUUM QUALITY FOR RUN-IN OF THE MoS_2 COATED BEARING

Before run-in the MoS_2 lubrication has higher friction torque which is subsequently reduced by a run-in of the bearing.

For the tested bearing, the friction torque before run-in amounts to approximately twice the average friction torque after run in.

The thermal off-load device of the bearing, formed by the Invar segments between the inner rings [2], causes the bearing to have different contact points between the balls and the races at ambient temperature and at low temperature. A separate run-in for both temperature cases is necessary to account for this specific design.

During the first ambient run-in attempts the friction torque did not decrease as expected. The available facility at this time reached a vacuum quality of 10^{-3} mbar.

It is widely known that on-air friction torque of a MoS_2 coated bearing is much higher than vacuum friction torque at typical TV test vacuum quality of better 10^{-5} mbar. Despite no information was available about the limit of the vacuum quality to attain the expected low friction torque, the run-in was repeated at a facility that allowed bearing operation at a lower vacuum pressure of better 10^{-5} mbar.

At this vacuum pressure the run-in at ambient temperature could be successfully performed.

Surprisingly, it turned out, that once the bearing was run-in, the friction torque measured at 10^{-3} mbar was quite similar to the high vacuum value, in contrast to the on-air value at ambient atmosphere which was significantly higher than the value measured in vacuum.

The run-in duration was originally planned for 1000 revolutions. After approx. 600-700 revs the friction torque did not further decrease, which confirmed the planned run-in duration.

4. FRICTION TORQUE PERFORMANCE COMPARED TO PREDICTION

The average friction torque of the bearing was predicted for the ambient temperature load case with the CABARET software of ESR Technology Ltd.

For the sputtered MoS_2 on the AISI 440C substrate a friction coefficient a value of 0.05 was assumed.

The bearing pre-load was dimensioned based on the prediction results with the following constraints:

- Gapping during launch shall be avoided. In contrast to the usually allowed gapping in the range of 25 µm, for this specific application no gapping was allowed for this bearing to prevent even the most minute deformations and to such maintain highest accuracy. No test data of the impact of gapping on the bearing accuracy could be found for such a high accuracy bearing, and no dedicated tests were possible in the frame of the project, so it was decided to not allow gapping at all.

- The Hertzian Stress of the balls shall never exceed 2360 MPa to prevent a permanent deformation of the balls of more than 0.1 µm to maintain highest accuracy under external load.

- The Hertzian stress of the balls shall not exceed 1500 MPa under pre-load only, target was < 1100 MPa to prevent permanent deformation of the balls and degradation of the MoS_2 lubricant during storage.

The predicted results were compared with the measured friction torque test results.

4.1. Ambient Temperature

During assembly the bearing preload force was measured by ADR S.A.S. with a direct measurement method, and found within tolerance. With this measured preload the prediction model correlated to the measured average bearing friction torque at ambient temperature when using a value of 0.06 for the friction coefficient of the sputtered MoS_2 on the AISI 440C substrate.

The ECSS-allowed reduction of the friction-uncertainty factor in a motorization budget from 3 to 1.5 after testing gives sufficient room for the experienced prediction uncertainties.

4.2. Low Temperature

The low temperature friction torque of this bearing, which is equipped with a thermal offload device, depends on the

- Axial preload, measured at ambient temperature, the
- Coefficient of thermal expansion of the ring, the ball, and the spacer materials, which was measured between ambient temperature and 30K on the material batch used for the rings and the spacers,
- Friction coefficient of the MoS_2 at cryogenic temperature, and on the
- Change of the material properties of the ring and ball material. Typically steels exhibit higher Young's Modules at lower temperatures.

Figure 4 presents the predictions and the measurement results of the average friction torque at ambient and at low temperature.

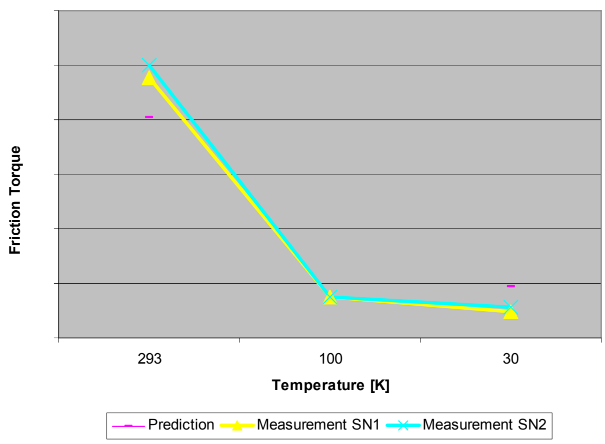

Figure 4. Measured Friction Torques.

The single contributors could not be clearly separated by the performed measurements, but it was clearly shown that the thermal offload device works well, and that the sputtered MoS_2 on the passivated AISI 440C substrate performs well at cryogenic temperatures.

The friction torque reduction between ambient and cryogenic temperature was predicted with 77%. The measured torque reduction amounts to 89%, which is even more than expected, and well within the requirements.

5. DWELL TIME EFFECTS

At ambient, friction torque measurements were repeated after some resting durations up to 2 days.

The measured increase of average friction torque was below 0.2 Nmm for ambient and cryo operations, which can be considered negligible.

6. CRYO CYCLE

The thermal offload device causes the balls to move axially in the bearing, having different points of contact between ball and race at ambient and at low temperature. It should be verified, that running on one track at one temperature does not impair the other track at the other temperature.

Further there is some “cryo-hardening” effect known for certain materials which change their material properties permanently after exposure to cryogenic temperature. Although no confirmed statements about such behaviour on the materials involved were identified, measurements of the bearing performance before and after cryo exposure were performed.

So measurements before and after the thermal cycles were performed to verify that the thermal offload device works repeatable, and to verify the no metallurgical effects change the behaviour of the material.

Friction torque at 30K was compared before and after warming up the bearing from 30K to 100K, operation at 100K, and cool-down to 30K again, and Friction torque at ambient was compared before and after cryogenic operation.

Bearing breadboard testing revealed, that after cryo operation of the bearing the ambient temperature friction torque is 10% higher than average.

After 50 revolutions in inert atmosphere in each direction the bearing reverts to its average friction torque.

It can be concluded that no relevant material parameters changed due to cryo exposure, and that the thermal offload device works in a repeatable manner.

7. STARTUP TORQUE AND PEAK TO AVERAGE RATIO

Startup torques and peak torques were also recorded during the measurements.

The peak to average torque ratio was measured at less than 1.5 at ambient temperature, and less than 2 at cryogenic temperature.

It shall be noted that these measurements were performed on different test setups and may not be directly comparable.

During all measurements the startup torque was lower than the peak torque.

8. CONSIDERATIONS ON THE TEST SETUP

A test setup for measurement of the friction torque at a cryogenic temperature of 30K of the preloaded duplex bearing assembly was developed.

The bearing is driven by an auxiliary motor, and the resistive torque caused by the bearing is measured by a torque transducer.

The bearing is operated at a temperature of 30K, whereas the auxiliary motor and the torque transducer have to operate at ambient temperature. To have low heat intake into the bearing from the auxiliary motor and the torque transducer, small sectioned pipes of stainless steel are transmitting the loads.

For accurate measurement a high stiffness of the setup is required, especially for evaluation of the peak torque results.

High stiffness and low heat intake on the cryo friction test setup are diametrically opposed requirements. Some attempts were necessary to find the finally realized stiffness that was found sufficient for good average friction torque measurements, but also for startup and peak torque measurements while not introducing too much heat into the bearing assembly.

The bearing friction torque at 30K of the pre-loaded bearing assembly could be measured with an accuracy better than 1 mNm.

For the measurement of the cryogenic performance of the bearing the bearing assembly is cooled down to 30K by liquid helium in a cryostat. To prevent deformation of the rings due to thermal stresses, the bearing inner ring and the outer ring are mounted on isostatic mounts. These are attached to the connection shafts, whereas one of these shafts is equipped with a coupling to gravity offload the inner ring, and to prevent thermal stresses due to thermal gradients.

Figure 5 presents the bearing, mounted on the isostatic mount for the outer ring.

Figure 5. Isostatic Bearing Mount for Cryo Testing.

The assembly of the bearing in the isostatic mounts and the temperature regulated enclosure is mounted on the bottom side of a cryostat cover, as shown in figure 6, and inserted into the cryostat as shown in figure 7.

Figure 6. Cryostat Cover with Unit Under Test.

Figure 7. Insertion of the Cryostat Cover with the Unit under Test into the Cryostat.

The temperature is controlled via flow control of liquid Helium while electrical heating of the enclosure of the bearing assembly. Figure 8 shows the test setup during the bearing test activities.

Figure 8. Cryo Testing of the Bearing.

The bearing could successfully be run-in and characterized at a cryogenic temperature of 30K with this setup.

9. STATUS OF BEARING DEVELOPMENT

The bearings were manufactured, coated and assembled, the bearing level tests were concluded successfully.

The bearings could be successfully integrated into the Flight Models of the Wheel Support Mechanisms.

Figure 9 shows the bearing, placed in the main structure of the mechanism support via an isostatic mount of Titanium alloy, as described in [1].

Figure 9. Bearing integrated into Wheel Support Mechanism.

A life test will be performed on assembly level to conclude bearing testing.

10. SUMMARY AND CONCLUSION

A high accuracy bearing for cryogenic operation with thermal offload device could be successfully developed.

The following experiences were made during development:

- Sputtered MoS_2 performs well at cryogenic temperatures.

- The CABARET software delivered good results with assumed friction co-efficient of 0.05, however on the optimistic side. Results correlate with an assumed friction co-efficient of 0.06.

- A run-in of the bearing at a vacuum of better than 10^{-5} mbar is required for proper run-in of a sputtered MoS_2 coated bearing.

- The peak / average ratio at ambient temperature is less than 1.5, at cryogenic temperature less than 2, the startup torque is less than then peak torque.

- The ECSS-allowed reduction of friction-uncertainty factor in a motorization budget from 3 to 1.5 after testing gives sufficient room for the experienced prediction uncertainties.

- The high coefficient of thermal expansion of the cage material compared to the CTE of the bearing steel gives two configurations of the cage at the temperature extremes, both have to be verified.

- Cages with conical pockets may lead to situations where the cage forms a wedge between the balls which tries to block the rotation which could be avoided by cylindrically shaped pockets.

- A test setup for measurement of the friction torque of the preloaded duplex bearing assembly at a cryogenic temperature of 30 K could be developed. The bearing friction torque at 30K of the pre-loaded assembly could be measured with an accuracy better than 1 mNm.

11. REFERENCES

1. Neugebauer C. Et. Al.: „High Precision Duplex Bearing with Thermal Off-Load Device for the NIRSpec Wheel Support Mechanisms“; Proceedings of the 12th European Space Mechanisms and Tribology Symposium, 2007.
2. Neugebauer C., Falkner M.: “Wälzlager mit temperaturgesteuerter Vorspannungsverstellung für Raumfahrtanwendungen”, Austrian Patent Application A 2046 / 2005.
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12. REMARK & ACKNOWLEDGEMENT

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