Development, Pre-qualification and Application of an Active Bearing Preload System

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Abstract

This paper describes the development to pre-qualification status of a novel and widely applicable technology development known as a Bearing Active Preload System (BAPS). The BAPS can be thought of as a "smart bearing housing" which replaces a conventional bearing or mechanism housing and whose function is to permit ball bearing preload variation on command. An overview of typical BAPS requirements, its design, the range of actuation options and some performance data are provided. A number of historical and recent bearing applications are reviewed and the benefits realizable by a capability to vary preload are highlighted. These can include order of magnitude improvements in lubricant lifetime, reductions in bearing torque, mechanism mass, cost and complexity.

Introduction

Ball bearings are preloaded to provide adequate rotor location and bearing stiffness, as well as to protect the bearings themselves from damage due to "hammering" during launch. However, increased preload also has some undesirable effects discussed below.

Grease- or oil-lubricated bearings have essentially two main torque components, namely a speed and temperature dependent "Viscous" component and a load dependent "Coulombic" torque component. At low- to moderate-speeds, the Coulombic component can be dominant, such that mean bearing torque is approximately proportional to $preload^{4/3}$. This relationship is also true at all speeds for solid- and self-lubricated bearings. Furthermore, peak Hertzian ball-raceway contact stress is proportional to $preload^{1/3}$ [1].

In ESTL much work has been done in the past concerned with characterization of bearing torque and lifetime, particularly for self-lubricating (e.g., Duroid or PGM-HT) and solid-lubricated (e.g., thin films of MoS_2 or lead) bearings. A review of some of the highlights of this experimental work [2-5] demonstrates that preload (or peak Hertzian contact stress) has a very significant effect, both on film lifetime for solid lubricated bearings, and on separator (cage) wear for self-lubricating bearings as shown in Figure 1. For liquid lubricated bearings too (especially PFPE-based oils and greases), though the lifetime may be often be longer, ultimately lubricant degradation due to shear or chemical reaction at ball/raceway asperities and separator stability/wear issues are aggravated by high bearing preload.

In summary, the use of a high preload throughout life not only increases the Coulombic torque and therefore motor mass/power requirements for the bearing, but also decreases the potential operational lifetime significantly. Furthermore, since in most applications the high bearing stiffness required for launch is no-longer essential once in-flight, the capability to operate in-flight at relatively low preload is highly desirable, particularly in long-lifetime applications and those with challenging thermal requirements (e.g., those having a particularly wide operational temperature range, large or adverse thermal gradients).

Historically bearing "off-load devices" or "launch-locks" have been used to protect bearings during launch by providing an alternative load path in those relatively few applications where the launch loads necessarily exceed the capacity of the bearings, or more often where the low-torque or long-life requirement dictated a moderate to low preload should be selected (e.g., Giotto de-spin bearings [6]). However, bearing off-load devices are relatively mass inefficient and need to be tailored to the application.

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The BAPS concept provides a bearing cartridge structure that is of appropriate stiffness and load capacity to enable the maximum loads (combination of preload and externally applied launch loads) for the particular bearing size to be applied and a factor of approximately 10 high/low preload ratio. This ratio permits at least a halving of Hertzian contact stress, with commensurate bearing torque and life benefits.

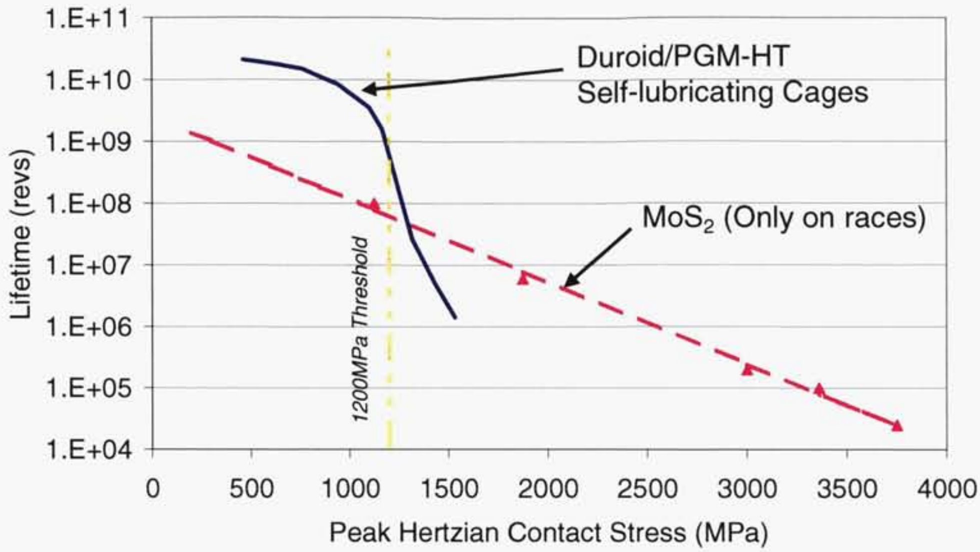

Figure 1. Lifetime v Contact Stress for Bearings Lubricated by Duroid/PGM-HT or MoS_2

BAPS Requirements

The BAPS device requirements were determined via a comprehensive Market Survey of current or near term applications in which more than 34 space companies were contacted. Responses to the questionnaire indicated that over 20 applications could benefit from BAPS technology, for example deployment hinges, steering devices, APM's, various instruments, actuators, reaction/momentum wheels, CMG's, solar array drives and scan mechanisms for microwave sounding and radiometry. Design drivers from the Survey were ranked in order or priority as Reliability, Envelope, Mass and Cost.

The Survey suggested most potential users would require a bi-stable BAPS device capable of switching from a single high-preload (State 1) to a single low-preload (State 2), however a significant minority of respondents also foresaw applications where the ability to continually vary preload could be valuable. A wide range of bearing sizes was identified, from 25-190 mm bore, but the most popular size range was 50-100 mm bore. The number of operations required of a bi-stable BAPS (assumed to exclude qualification margins) was enveloped as <20 on ground and 1 in-flight. For a variable type device, up to 2 million operations were envisaged.

Envelope constraints were also deduced from the Survey, together with thermal requirements. Excluding the relatively infrequent cryogenic or high-temperature applications, the majority of applications were enveloped by an operational temperature range of –40°C to +80°C.

BAPS Concept Derivation and Description

By combining the results of the Market Survey and the experience of the team, a generic requirements specification was generated together with a number of concepts potentially capable of meeting these requirements. The concepts were subjected to an initial filtering using "killer criteria" (i.e., criteria which all viable concepts MUST meet) after which surviving concepts were then subjected to a formal trade-off against criteria again reflecting the aspirations/concerns expressed in the Market Survey returns ranked using a rigorous paired comparison method.

As part of the trade-off process an assessment was made of the flexibility of each candidate design for adoption with 4 candidate design cases ranging from small (25-mm bore ISO 10 section, e.g., SNFA EX25 with State 1 preload of 200 N), to medium (50-100 mm bore, thin section) and large (>150 mm bore thin section, e.g., Kaydon KA075ARO, with State 1 preload of 3000 N) bearing envelopes. From these design cases, a single so-called "enveloping design case" was established as a most-challenging case for the Breadboard Model (BBM). The enveloping case was based on the thin-section SNFA SEA55 (7CE3) bearing, having a preload ratio of 3000 N (State 1) / 200 N (State 2) generating a peak bearing Hertzian contact stress ratio of approximately 2000 MPa / 850 MPa.

In the trade-off winning concept, which is based on the monolithic titanium structure shown in Figure 2 below, the bearings (not shown) are located by upper (floating) and lower (interfacing) thrust rings. These rings are linked via a series of "suspension beams" which provide the required structural stiffness characteristics for launch. By monitoring the strains induced in these features due to changing relative axial displacements of the two rings the bearing preload can be determined.

Rotation of a central "synchro-ring" by a few degrees adjusts the spacing of the upper and lower rings by some microns and so modifies bearing preload. The upper and lower rings remain parallel despite the rotation of the synchro-ring because they are linked through a series of flex-struts to the upper and lower rings preventing misalignment. These features also provide an over-center toggle action such that the preload is stable un-powered in two synchro-ring positions. For the high preload state the central synchro-ring is retained just away from top-dead-center (TDC) in a stable configuration (in contact with an end-stop). To set the bearings to low preload, a "Self-Release" force is applied to displace the synchro-ring such that the flex-struts are pushed over TDC and to a stable low-preload position used for flight. This position is maintained by application of a "Holding Force". For the BBM, the high (3000 N) preload state is at a synchro-ring position of +100 µm, and low (200 N) preload at –600 µm as shown in Figure 3. A maximum "Reset Force", around 100 N on the BBM must be applied.

Figure 2. Monolithic Titanium Alloy Structure Concept and Hardware (includes liners to interface with bearings)

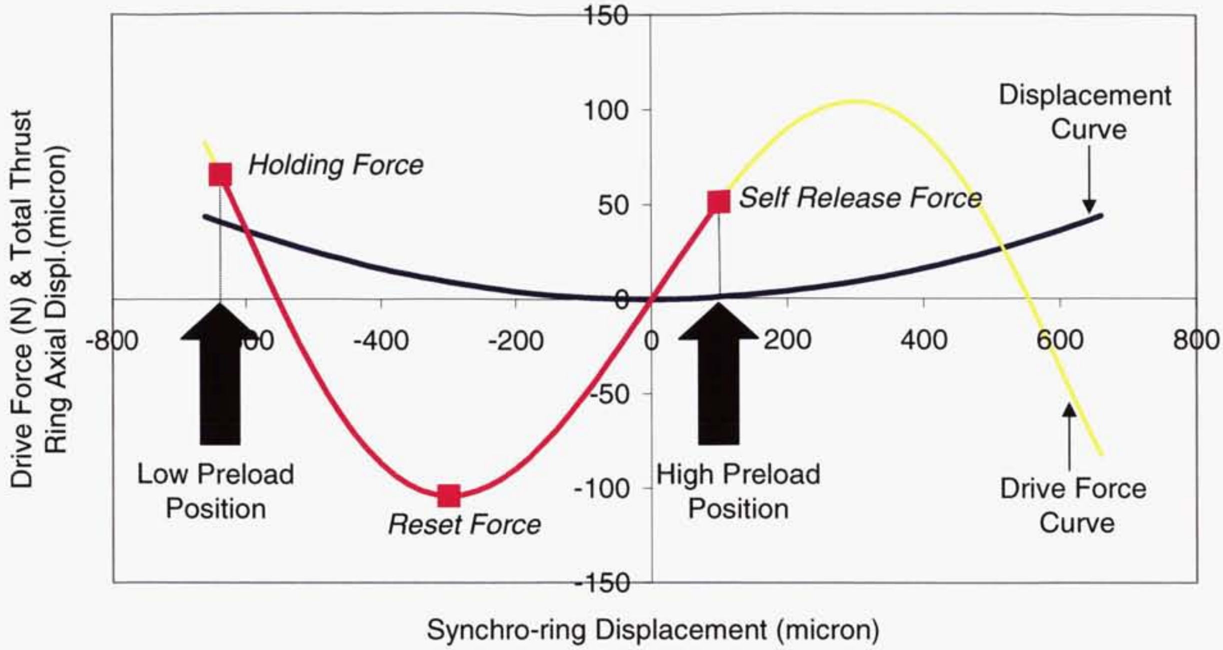

Figure 3. Predicted Drive Force and Thrust Ring Displacement Curves for SEA55 BAPS

Practical Experience with Hardware

Highlights of the performance of the breadboard model (BBM) BAPS, which contains bearings lubricated by a PFPE-based grease thickened by PTFE particles are provided below.

Dimensional inspection showed the BBM to have been manufactured to tolerances in-line with requirements, especially when considering bearing seating tolerances. No significant misalignment of the bearings on assembly or during BAPS operation was measurable. On assembly the BBM structure introduced <100 μrad of angular misalignment and when operated at most a further 20 μrad. These values are well within even the permissible groove-face misalignment for the bearings themselves (e.g., for ABEC 9 grade bearings of this size, 200 μrad PER BEARING is allowed). This figure is also much less than the known face-face target misalignment for good performance of solid-lubricated bearings, which is around 300 μrad.

As expected, because the BAPS is a purely elastic system, the strain gauges used to monitor displacement of the suspension beams were found to be very linear (sensitivity typically 20 με/μm of BAPS total axial displacement) and repeatable (within 1-2 με when BAPS is repeatedly switched from high- to low-preload), demonstrating accurate, repeatable preload switching even after vibration.

The target preload ratio of 3000 N (State 1) / 200 N (State 2) which would have provided bearing mean torques at room temperature of 1400 gcm and 110 gcm respectively was not quite reached due to the effects of elastic strain in the bearing seats. The achieved preload values were 2500 N and 300 N for which the measured torques were around 1100 gcm and 200 gcm (Figure 4).

However a positive effect of this bearing seat elasticity was that because strain energy is stored in the BAPS, bearings AND the bearing seats, on switching from high to low preload much less force is needed to hold the device in against the low-preload end-stop position than is predicted based on a model which excludes bearing seat effects, as can be seen in Figure 4.

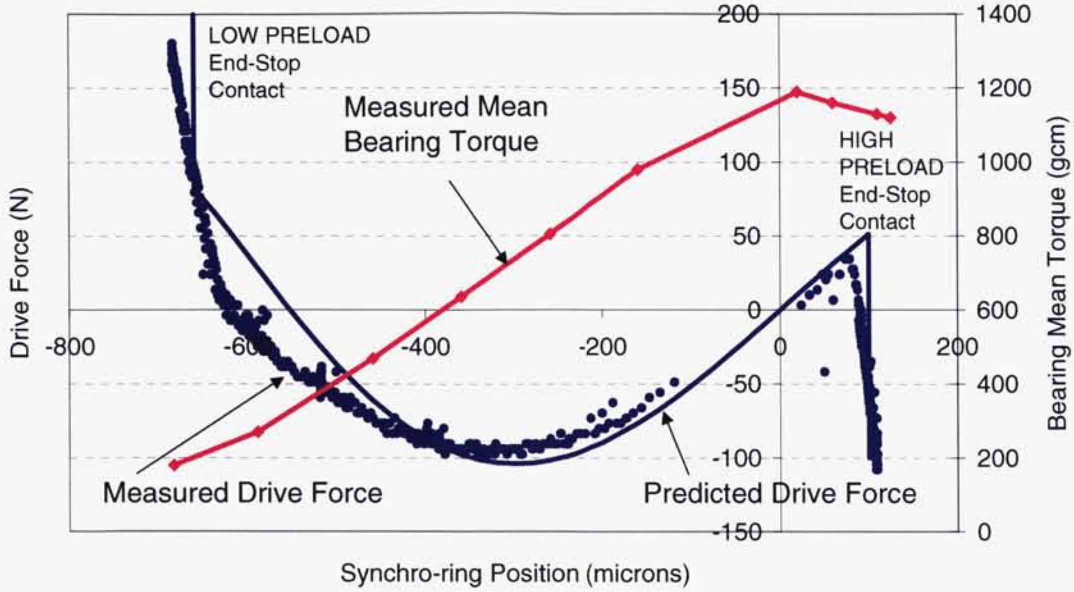

Figure 4. Measured torque and Drive Force Performance of BBM BAPS Unit

Actuation Options

The BAPS can be actuated by several means depending on the application. Most commonly a direct linear actuation will be used for which, all that is required is to provide up to around 60-70 N force and around 700 μm of total linear displacement. For the majority of applications where a typical operational temperature range of –40 to +80°C is demanded, then actuation will be via a Shape Memory Bender or High Output Paraffin Actuator. Both devices have the advantage of reset-ability and ease of redundant implementation. However, the BAPS can also be entirely passively actuated, for example by exploiting differential thermal expansion for applications that have high or low temperature requirements, or indeed implemented in a fully-variable form. In the latter case, use of a rotary piezomotor is an attractive option.

How Designs Could Change Post-BAPS

A number of historical and more recent applications are reviewed (and summarized in Table 1). For each we identify some of the main potential design changes and resulting engineering benefits of use of a BAPS device in similar future applications.

Optical Pointing and Tracking (e.g., GOMOS SFA on ENVISAT)

The GOMOS Steering Front Assembly (SFA), currently flying on ENVISAT, is an optical acquisition and tracking mechanism for stars. The mechanism includes a coarse pointing azimuth stage that provides a wide pointing range by allowing a mirror and turntable to rotate. The bearing configuration would ideally support the mirror and turntable during launch. However, given the need for low torque noise emission and reliable operation the bearings required a soft, low preload, and a relatively small outside diameter. However, high strength and stiffness were required during launch, and these conflicting demands could only be met by use of a massive and complex motorized launch protection system (bearing offload device or BOLD).

Using BAPS, a more elegant design using large, thin-section bearings could have been adopted, capable of meeting the launch design case, yet also providing low and soft bearing preload on-orbit. Preliminary analysis suggests that a pair of back-to-back thin-section bearings having a bore of 200 mm could have met the launch load and stiffness requirements. This approach would have yielded very significant savings in mass, cost and complexity.

Table 1. Summary Historic/Recent Application Details

Application	Back-Back: BB Face-Face:FF	Size (Type or Bore Dia.)	Supported Load and Offset	Launch Frequency or Stiffness/Preload Used	Special Constraints
GOMOS SFA	BB & Diaphragm	SEA60 /SEA55	16 kg / 100 mm	>100 Hz / 250 N	BOLD used
Giotto De-Spin	BB & Diaphragm	SEA55	5 kg / 150 mm	>100 Hz / >100 N	BOLD used
Optical Terminal	FF/BB	KA075	2 kg / 120 mm	>160 Hz / Minimize (e.g., 30-300 N)	Large bore, severe mass/power constraints
APM with RF Feedthrough (Bepi-Colombo)	BB or Super-Duplex	~50-85 mm	10-14 kg cantilevered – but with 3rd hold-down points (Launch loads ~ 1.5-3 kN plus 102 Nm)	> 5.4×10^5 Nm/rad / 1200 N (min) for launch stiffness	Bore to accommodate RF joint High launch loads and moments
SADM (BAPTA)	BB & Diaphragm	25 mm	Unknown	>100 Hz / 45 N in flight	BOLD used, released on-orbit stiffness must support solar array
Reaction/Momentum Wheel/CMG	BB or FF & Spring/Diaphragm	20 mm (typ.)	Up to 1-2 kg	>100-150 Hz	Life target 5×10^{10} revs
Swash Plate APM	4 Pt Contact BB Hard Preload	177 mm	Unknown	>100 Hz / 1500 N	Stiffness on-orbit adequate for payload
Push-Broom Scanner (EGPM)	BB	>100 mm	>60 kg	>70 Hz	6×10^5 Nm/rad. On orbit

Despin Mechanism (e.g., GIOTTO De-spin)

In common with many deep space missions, GIOTTO the last European deep space mission using a spin stabilized spacecraft, required a de-spun antenna to maintain a high-data-rate communications link to Earth. The key issues for this type of mechanism are to support the antenna during launch yet provide long life, low friction and reliable operation in adverse thermal conditions (e.g., with wide fluctuations in temperatures and temperature gradients).

To maximize bearing/lubricant life while maintaining insensitivity to adverse thermal gradients a low preload was required and applied by means of compliant diaphragm. But launch loads and frequency constraints for the application could only be met by employing a separate bearing off-load device (BOLD).

Had BAPS technology been available this application could have avoided the need for the BOLD even if a bearing pair with virtually the same diameter were selected.

Optical Communications

Laser Communications Terminals for inter-satellite communications links are a major application for pointing mechanisms. One device currently under development is a Course Pointing Assembly. This device is required to gimbal a high precision mirror through large angles. The bearing must be almost free of stick-slip effects and must provide a through-bore sufficiently large to allow the passage of an optical beam (typically 15-mm dia.) through the azimuth gimbal. To achieve both of these requirements in a mass- and cost-effective manner ideally requires high bearing preloads during launch and very low preloads once on-orbit.

A preliminary assessment suggests that launch requirements could be fully met at low risk if launch preload could be set at 2000 N, provided preload is released to less than 200 N once on orbit. The use of BAPS could provide an even larger range than this and would provide a lower risk solution than the use of a fundamentally lower fixed preload and snubbers to limit rotor motion during launch vibration. The latter conventional approach allows hammer like contact at the bearing and drive gear contacts which increase risk of degraded life-time and in-orbit performance.

Two Axis Antenna Pointing Mechanisms (APM's) with RF Feedthrough

There are a number of current/near future applications for two-axis APMs that require integrated R/F rotary joints within their azimuth actuators. The applications cover both commercial LEO constellations through to dedicated science missions such as the Bepi-Colombo mission to Mercury. These applications need to accommodate internally mounted rotary RF joints that call for high precision and repeatable co-alignment of R.F. choke faces. The bearings themselves are required to be stiff during launch to support the antenna but must provide low friction torques once on-orbit even when subjected to inverted temperature gradients caused both by R.F. losses at the shaft and in some cases by the operational environment.

The major risks associated with these mechanisms are their sensitivity to thermal gradients and installation tolerances given the lack of elastic preloading. In the unique Bepi-Colombo case, an operational temperature range of +50°C to +250°C is envisaged with 70% of the expected life at the hot case and with adverse temperature gradients which could be up to 30°C across the bearings.

It is foreseen that the use of a BAPS for these applications would significantly enhance performance and reduce risk. It may be an advantage for applications to control bearing stiffness at actuator level in order to maximize the overall structural efficiency of the combined APM and Antenna Launch Configuration, with the Antenna in its stowed configuration. To implement BAPS in for example the Bepi-Colombo application, a pair of angular contact bearings would replace the baselined hard-preloaded super-duplex bearings (without significant impact on radial envelope) and titanium housing. For launch, the BAPS could be set to provide a high-preload in excess of the currently specified 1200 N (enhancing launch stiffness, eliminating bearing gapping during launch and further minimizing risks of fretting damage to gears). On-orbit the preload could be reduced, and more importantly the preload-stiffness achievable with BAPS is low, compared to a conventional hard-preloaded system thus rendering the bearings much less sensitive to the significant and adverse thermal environment.

Medium Power SADM (BAPTA)

The BAPTA was developed for early satellite programs, e.g., OTS, ECS, Marecs. It became the baseline SADM for a later series of defense satellites transferring up to 900 W of array power and associated signal lines.

The SADM design uses a pyrotechnically released internal bearing off-load system providing bearing protection and adequate launch stiffness to the solar array. In orbit, the bearings are compliantly preloaded.

Use of a BAPS for this type of SADM would replace a complicated system of compliant preloading, hard bearing-offload and pyrotechnic release mechanisms. Final preload could be set on station for required torque performance and maximum power efficiency. Such a device would be suitable for small to medium mass arrays on small satellites.

Reaction/Momentum Wheel/Control Moment Gyros

Reaction/momentum wheels and Control Moment Gyros run continuously and allow transfer of momentum/torque as required by the orbital control system. Ideally the operating case requires a minimum of bearing preload to minimize power loss, torque disturbances and motor mass/volume. The rotating elements supported on bearings have significant mass and require correspondingly high stiffness, both to prevent damage during launch and in the case of the CMG to provide structural efficiency during slew maneuvers. Cage instability and wheel whirling instability are also factors to be considered.

Use of BAPS for wheels would prevent gapping on launch yet allow minimum preload and hence torque loss value for in-orbit operation thus improving power consumption and wheel performance per unit mass. Such a capability is particularly important for solid-lubricated wheels sometimes used in Smallsat and Microsat applications for which life benefits may be significant. With a variable type BAPS, preload could be varied to alleviate cage or resonant frequency problems in reaction/momentum wheels or to permit tuning of CMG stiffness characteristics and energy dissipations.

Push-broom Earth Scanner (e.g., EGPM)
The now postponed EGPM mission requires an earth-scanner using the push broom scan approach. The main instrument rotor and reflector (mass >70 kg) rotate at a constant speed up to 32 revs per minute over a nominal 15 year mission, resulting in >250 million revolutions. The instrument rotor must be supported rigidly during launch and rotated about a precise axis in-flight.

The main issue is related to the high instrument rotor mass and the relatively large C of G offset of the instrument rotor in relation to the scan mechanism. This leads to combination of high lateral and axial forces and very high moment loading during launch. Therefore the current instrument configuration incorporates a dedicated hold-down system that supports the rotor at its outer extremities at four locations for launch. These are released once on-orbit and then the instrument rotor is supported purely by the scan mechanism. While the primary launch protection is able to rigidly secure the bulk instrument structure, due to the size and supported mass of the instrument equipments mounted within the instrument there are also local panel modes between the scan mechanism interfaces with the instrument lower panel and the spacecraft side wall. It is not possible to accommodate these modes by allowing relative internal movements within the mechanism due to a number of critical internal operating gaps (e.g. at the motors, sensors and power/signal transfer devices) Therefore the scan mechanism must react the local forces and moments associated with constraining these local modes, which leads to significant local forces and moments across the mechanism. The bearings of the scan mechanism are required to have a bore of greater than 100 mm due to internal design constraints and so in principle the mechanism is capable of reacting significant loads. The use of BAPS technology allows the bearings to react these launch loads without introducing any significant internal movements and provides a relatively stiff fifth hold down point at a location where it is most mass effective. This is done without compromising the mechanism's on orbit performance, in particular the long life and the critical on orbit nodding frequency.

Note that although a bi-stable BAPS is currently base-lined, there would be some benefits in this application in the use of a fully variable BAPS that would enable on-orbit tuning of instrument rotor preload in order to achieve an ideal rotor stiffness.

Conclusions

This paper demonstrates that the novel BAPS device can be used in a wide variety of the more demanding spacecraft mechanism applications to improve both system level and mechanism performance and lifetime. The examples used demonstrate that for maximum benefit, the BAPS concept needs to be incorporated within the design from an early stage in the system development.

The BAPS is currently at the pre-Qualification stage of development, but it is expected that it will be Qualified during 2006.

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