DEVELOPMENT OF AN ADJUSTABLE BEARING PRELOAD ENABLED - OPTICAL TERMINAL

S.D. Lewis(1), G. Munro(1), M.E. Humphries(2), G. Székely (3)

(1)ESTL, ESR Technology Ltd., Whittle House, 410 The Quadrant, Birchwood Park, Warrington, WA3 6TN, U.K.
Email:simon.lewis@esrtechnology.com, grant.munro@esrtechnology.com
(2)Sula Systems Ltd. Sula Systems Ltd, Old Crown House, Market Street, Wotton-Under-Edge, Gloucestershire GL12 7AE, U.K. Email:mhumphries@sula.co.uk
(3)Oerlikon Space AG, Schaffhauserstrasse 580, 8052 Zürich, Switzerland Email:gerhard.szekely@oerlikon.com

ABSTRACT

The Bearing Active Preload System (BAPS) is a generic ball bearing preload adjustment device which is scalable and customisable to a range of bearing sizes, preload ranges and applications.

This paper provides an insight into the design customisation carried out in order to realise a bespoke, fully optimised high performance BAPS solution for an optical coarse pointing assembly (CPA) for use on an inter-satellite laser communications link.

The paper not only describes some of the main challenges overcome during the customisation of the BAPS technology for its first flight application, but also highlights some near future developments which will enhance the capability of the BAPS system for the CPA and for other applications such as reaction/momentum wheels, scan mechanisms, radiometers or other instruments where bearing life, torque noise system stiffness and sensitivity to thermal strains are critical.

1. BACKGROUND

1.1 Application Introduction

Optical terminals for use on inter-satellite laser communications systems represent a particularly demanding application for ball bearings. In optimal architectures a large diameter, thin section bearing is used in order to permit optical beam access to the telescope but extremely low bearing mean torque and torque noise are required from the bearing system which supports both a mirror and, typically, also a high precision encoder system. Pointing requirements for optical terminals are very demanding, typically a few micro-radians or less and to achieve this torque noise must be absolutely minimised. These requirements are bordering on the limitations of present mechanical technologies.

Oerlikon Space successfully developed an earlier generation of optical terminal Coarse Pointing Assembly (CPA)[1] employing a gimballed mirror geometry some years ago and one key performance issue in this application and others where large thin section bearings are used is to engineer the system to provide low and stable bearing torque in the presence of positive or negative thermal gradients between shaft and housing. A clear design driver for the next generation CPA was to manage and optimise this performance aspect.

In an un-related programme, commenced about the same time as the first CPA at Oerlikon Space AG the European Space Tribology Laboratory (ESTL) proposed and with ESA support commenced development of a Bearing Active Preload System (BAPS) which is a generic device which can be used to actively adjust the preload on a ball bearing system so providing high and stiff preload to bearings for launch and low, and very compliant preload for on-orbit operations. At the time of its initial development the BAPS was envisaged for use in many types of bearing system [2] and due to its operating principle can be customised for a range of bearing sizes. However it was envisaged that it would mainly be adopted in applications where life, mean torque or torque noise and micro-vibrational noise or susceptibility to thermal strains were dominant concerns [3]. Applications such as radiometers, scan mechanisms, reaction wheels and optical pointing and tracking systems were all highlighted by early studies as being most likely to benefit from BAPS technology.

In this paper we discuss how the early adoption of the BAPS, a relatively new technology in its latest generation optical terminal CPA has enabled Oerlikon Space to fulfil an extremely demanding set of requirements to deliver a product for a flight programme (likely the first BAPS flight) which demands extremely high performance.

Having discussed the specific implementation and advantages of use of this technology in the present generation of CPA we also identify how a further parallel development of the BAPS might be used for

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future devices which combine high pointing accuracy with large thermal gradients and for other demanding bearing applications such as scan mechanisms, radiometers or reaction wheels.

1.2 BAPS Conceptual Basis

In this section we briefly describe the BAPS concept which is more fully described elsewhere [2], [3].

In its basic conceptual form, the BAPS can be considered to be a bearing housing consisting of a monolithic titanium structure of three coaxial rings which are joined by pairs of thin, blade-like flex-struts as shown in Fig. 1. The upper and lower rings are interfaced to the bearings to be preloaded whereas the middle, 'synchro-ring' can be rotated though a small angle (typically ~10-15mrad), thus deforming the flex-struts and axially displacing the upper ring with respect to the lower (typically by 30-100µm) so changing preload whilst retaining tight control of the bearing ring planarity.

The axial displacement of the structure (hence preload) is sensed by strain gauges attached to 'suspension beam' features which also increase lateral stability of the structure and prevent relative rotation of upper and lower structural rings as the synchro-ring is rotated.

Whilst the flex-strut geometry itself is essentially optimised, the number of flex-strut pairs can be modified to accommodate the load requirements for different applications. Structures have so far been manufactured with 24 or 48 flex-strut pairs (i.e. up to 96 flex-struts) arranged in groups of 3 and providing in the latter case a load capacity >11kN.

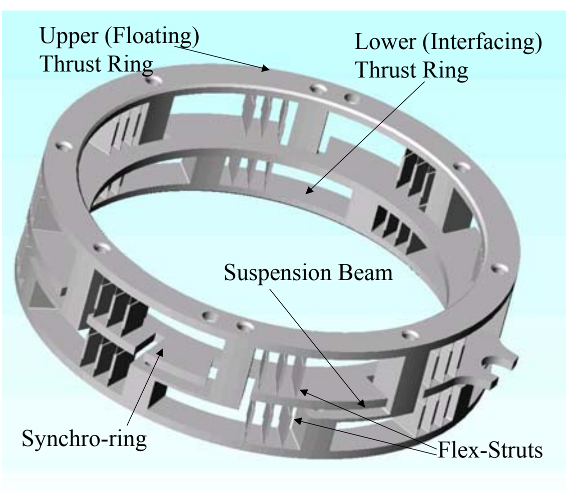

Figure 1. BAPS Structural Concept

In the high preload state for launch the flex-struts are slightly deformed from the nominal as-manufactured fully straight 'Top Dead Centre' (TDC) position as shown in Fig 2. In order to actuate the device a torque or tangential force is applied to the synchro-ring causing its rotational displacement past the straight strut position "Top Dead Centre" (TDC) initially to low-preload balance point (which is optimally low preload stiffness since the synchro-ring is un-restrained) at which point the residual preload in the bearing system is balanced by the elasticity of the flex-struts in bending. Application of further synchro-ring force will displace the synchro-ring to the ultimate low-preload state, which is itself the dimensioning state for the flex-strut stresses.

The BAPS structure is inherently stiff and stable in the high preload state for launch when the flex-struts are relatively lightly stressed even by launch vibration loads. The struts also serve to synchronise the motion so that the parallelism of the axial motion of the rings is extremely high.

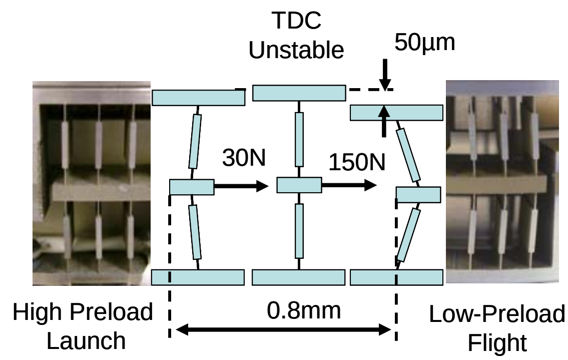

Figure 2. BAPS Flex-Strut/Synchro-Ring Function Showing High Preload, TDC and Low-Preload Positions, Typical Forces and Displacements and Flex-Strut Appearances

2. KEY MECHANICAL REQUIREMENTS OF BAPS FOR A CPA

Ideally the CPA bearing system would provide extremely high preload and stiffness for launch in order to prevent bearing gapping, a concern for bearings of the highest surface finish, and protect the close clearance high precision encoders used for motor control against contact. But on-orbit the ideal situation would be to have extremely low stiffness, target <5N/µm, and preload in order to provide very low inherent sensitivity to thermal strains, and low torque noise in absolute terms, a major driver for the design. Given this, it is clear that a bearing preload system having either a fixed, hard high-preload or fixed compliant low preload using conventional technologies would be non-optimal for one or other part of the mission.

However the BAPS provides a solution approaching ideal for the application, and removes the compromise required with a passive system. This kind of preload switchable BAPS device is known as 'S-BAPS'

Typical CPA specified parameters are shown in Tab. 1 below.

Table 1. BAPS Derived Specification for Non-Operating Launch Cases

Parameter	Value
Maximum High Preload	~ 4000N
Min Low Preload	~ 350N
Quasi-Static Launch Loads	5650N
Quasi-Static Bending Moments	770Nm
Quasi-Static Angular accelerations around rot. axis	2500 rad/s^2

The targeted preload ratio for the CPA actuation is ~6.

3. OPTIMISATION OF BAPS FOR THE CPA APPLICATION

Due to very stringent space requirements, the CPA motor is placed within the bearings and surrounded by the BAPS structure. Also the encoder is then directly attached close to the bearings for high precision support reasons. Essentially, thus a highly mass/volume optimised Drive Unit is obtained, that incorporates the BAPS.

Key engineering challenges overcome were:

Bearing Selection: A dissimilar thin section bearings were paired to enable assembly of the motor within the structure between the bearings. In practice the load deflection curves for the bearings were found to be much less linear than expected based on manufacturer's data, particularly when deflection at very low preload was considered. Since this relationship is an essential input to the BAPS design process and prediction of high and low-preloads achievable it was found necessary to measure this data experimentally rather than to rely on manufacturer's data. It should be noted that the preload range achievable is a direct function of the bearing stiffness, and in principle because the BAPS inputs a displacement various combinations of high and low preload can be set using the same structure and bearings.

Bearing Gapping: One major lesson learned during this process was the importance of ALL of the stiffness elements within the preload chain in defining the gapping response of the bearings. In general the gapping will be asymmetric with load sense and point of load application with respect to the stiffness elements of the system (bearings structure, shaft spacers etc). In fact this is true of all preload systems and for conventional stiff housings, but because the BAPS structure is optimal in the sense that it typically has similar stiffness to the bearings it houses the effect is more noticeable. It should be noted that to maximise the loads which can be sustained before the onset of bearing gapping in both directions the shaft and housing stiffnesses should be equalised for the configuration used here.

Envelope: The very close proximity of a cable wrap permitted only a thin annular volume surrounding the bearings for BAPS structure and actuator. This, together with the simple timed power supply interface and operational temperature range requirements necessitated the selection of a 'two-way trained' shape memory alloy (SMA) actuator. The selected actuator was a 'bender' in which strain is induced in a cantilevered bar of SMA due to a phase change when the bar is heated by redundant electric heaters fixed to an adjacent heater plate. Contact between the 'SMA Contact' and the BAPS synchro-ring transmits force to drive the synchro-ring so changing the preload and on cooling the SMA returns to its original form. The actuator was manufactured in-house at ESTL using SMA material from a European source and is shown Fig 3 below. As with other SMA actuator programmes known from open literature references, development, though ultimately successful, proved less straightforward than had originally been expected.

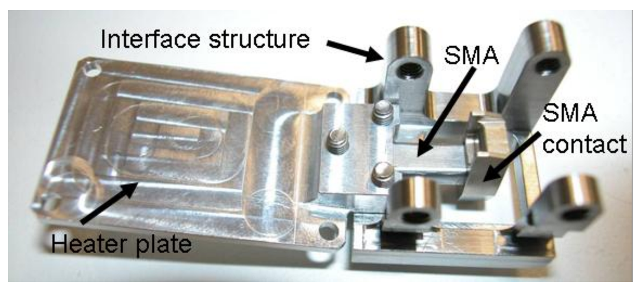

Figure 3. SMA Actuator Assembly
(Prior to bonding of heaters to the heater plate)

Local Angular Accelerations: The geometry of the CPA in launch configuration resulted in unexpectedly high local angular accelerations around the BAPS rotation axis applied to the synchro-ring. In a worst case these could theoretically release the BAPS, hence provision was made for adoption of magnetic latches to provide suitable release margins.

Stiffness: It emerged that the stiffness of the entire preload loop was not fully understood early in the programme. This lack of detailed understanding resulted in some difficulties in preloading the BAPS to the required value during the initial build and emphasises the importance of systematically building up analysis models, to correlate stiffness values with measured data and in particular to cover all load cases and flown down requirements. Once these stiffnesses were understood, the behaviour of the BAPS was entirely as expected and target preload values were achieved.

Thermal Strains: Since the BAPS housing stiffness changes from around 140N/µm in the high preload state to <5N/µm in low-preload (a stiffness factor >20) the sensitivity of the bearings to thermal gradients within the 'preload loop' is drastically reduced and in line with the demanding target proposed. However, despite this, the bearing system stiffness (shaft relative to housing) remains relatively high so long as the preload is maintained.

Structure Manufacture: Initial units had integral instrumented suspension beams within the monolithic structure, which forced the strain gauging operation onto the project critical path. In order to facilitate production for later flight models 4 of the suspension beams within the structure were designed as removable 'strain gauge elements', which could be separately machined, strain gauged, tested as appropriate and installed (also if necessary removed and replaced), thus removing the strain gauge activities from the project critical path.

The BAPS bearing unit is delivered to Oerlikon in an agreed sub-assembly form as typified in Fig 4 below for integration into the complete CPA unit.

Figure 4. Completed CPA Motorised Bearing Module (actuator to rear)

4. BAPS PERFORMANCE

During acceptance testing the BAPS has been shown to perform acceptably in thermal vacuum (in terms of actuation and non-actuation temperatures). A factor >20 is possible between high and low preload stiffness and the device introduces very low misalignment (much less than the misalignment of ABEC 7 bearing raceway groove to face) during operation. Typical headline parameters are shown below in Tab. 2 below.

Table 2. Typical BAPS Performance

Parameter	Value
Misalignment Introduced by BAPS Operation (High-to-Low Preload Operation)	<10µrad
High Preload System Stiffness	> 150 N/µm
Low Preload System Stiffness	~ 65 N/µm
High Preload	~ 4000 N
Low Preload	~ 500 N
Jitter Performance	Low
Allowable Thermal Gradients across bearings in operating range	$-11°C < \Delta T < 11°C$

Furthermore it is clear that the elastic nature of the BAPS in its low preload state provides optimally low torque noise and low sensitivity of torque to thermal strain, thus meeting some of the more challenging requirements of the application.

At CPA level the BAPS has successfully completed vibration testing up to Qualification level.

5. FUTURE DIRECTION FOR BAPS AND CPA

In parallel to the S-BAPS CPA development, a fully variable BAPS device (known as 'V-BAPS') is under development, which has a single fixed high preload setting and permits variation of low preload over a wide range together with the ability for on-orbit/remote high preload reset.

A breadboard model of a suitable drive for the fully-variable BAPS has been produced (Fig 5). This features a fully redundant miniature differential worm drive driven by miniature motor. The motor can be a stepper motor, brushless or brushed DC motor dependent on the available electrical interface and degree of sophistication required by the application.

Figure 5. Breadboard Model of Differential Worm Drive

An Engineering Model (EM) standard fully variable BAPS unit is currently undergoing a comprehensive test programme.

Such a system has potential benefits for future high precision applications (such as the CPA) by enabling the unit to operate under still more adverse thermal gradients if necessary. In principle such a device would permit tuning of on-orbit bearing performance to fully optimise pointing accuracy/bearing noise given an imposed thermal environment.

6. CONCLUDING REMARKS

This paper has demonstrated some of the issues to be resolved if a generic device is to be customised and optimised for a specific space application. Future adaptations to other applications will certainly benefit both programmatically and technically from the lessons learned on the CPA programme.

7. REFERENCES

1. Mussett D., et al. (2003) Contraves Optical Terminal – Coarse Pointing Assembly (CPA). *In Proc. 10th European Space Mechanisms and Tribology Symposium (San Sebastian).* (Ed. R.A. Harris) ESA SP524, ESA Publications Division, European Space Agency, Noordwijk, The Netherlands, pp 81-88
2. Lewis S.D .& Humphries M.E. (2005). An Introduction to Bearing Active Preload Systems - Technology and Performance Benefits. In *Proc. 11th European Space Mechanisms and Tribology Symposium (Lucerne)* (Ed. B. Warmbein), ESA SP591, ESA Publications Division, European Space Agency, Noordwijk, The Netherlands, pp 261-269
3. Lewis S.D. & Humphries M.E. (2006). Development, Pre-qualification and Application of an Active Bearing Preload System. In *Proc 38th Aerospace Mechanisms Symposium (NASA Langley Research Centre, Williamsburg V.A.)* (Ed. A. Boesiger), NASA/CP-2006-214290, pp133-140