BUILDING AND TESTING OF MIDAS INSTRUMENT SUB-ASSEMBLIES

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Abstract

The MIDAS instrument is an atomic force microscope developed by ESTEC to fly on Rosetta. The purpose of the instrument is to sample and characterise cometary dust, which impinges upon a facetted wheel contained within the instrument enclosure. Due to its relative complexity, the long cruise phase of the Rosetta mission and the relatively novel use of piezomotors for all drive requirements the instrument has a number of interesting mechanisms engineering challenges. This paper describes the lubricant selection, EM and FM sub-assembly build and test campaigns carried out by AEA Technology Space in close support of the instrument-level activities which ran in parallel at ESTEC. The paper also identifies some lessons learned, which can be generally applied in other mechanism programmes.

1. Introduction

The MIDAS (Micro-Imaging Dust Analysis System) instrument is an atomic force microscope which will fly on Rosetta and will be used during the 2 year near-nucleus phase of the mission to sample cometary dust particles in the range ~4nm to 5 microns. The instrument will provide information on the dust flux density together with morphological and statistical information on size, shape and texture of the dust population.

Housed within its outer enclosure, the instrument consists of four principal functional units, the microscope itself, a system for collecting and transporting dust grains, a micro-vibration damping unit and the control electronics and computational package.

Dust enters the unit via the funnel, passes through the shutter which is actuated by a piezomotor drive and impinges upon the facets located around the circumference of a wheel. The wheel assembly is driven by a piezomotor such that the AFM tip can be positioned over each facet and sits on a translation stage, which is also driven by a piezomotor. The translation stage provides lateral translation of the wheel. During launch the XY stage is locked against wedge-shaped components. After launch, the approach mechanism is driven to unlock the XY stage and provide a coarse positional adjustment. Fine micro-positioning of the AFM tip is achieved using piezo-devices. All mechanical assemblies are located on a stiff common baseplate which is secured for launch by clam-shell type launch locks and isolated from micro-vibration by damping units. MIDAS is described in more detail in Ref. 1

2. Consultancy and Design Review

The tribological design of all mechanisms within the MIDAS instrument was reviewed by AEA Technology Space. This review included assessments of contact stresses, material surface hardness and treatments, bearing and ballscrew sizing for the application and compliance with the mechanisms standard ECSS-E-30-3. As part of the review contact stresses, stiffness and torque predictions were made for all ball bearings using the CABARET bearing analysis software such that margins could be assessed. The critical –30°C liquid lubricated cold case torque prediction was made using extrapolation of previously published (Ref. 2) AEA Technology Space data.

Given the extended deep space cruise phase of the Rosetta mission and the possibility of liquid lubricant creep, a lubricant selection and trade-off using an attribute scoring system was also included in this part of the programme. The trade-off which is partly subjective considered oils, greases and solid lubricants. Table 1 shows the output scores for various candidate lubricants. It should also be noted that from a practical viewpoint there was a strong preference for use of a single lubricant system in all bearings where possible. The finally selected option was to use the “belt and braces” solution of Braycote 601EF micronic grease applied on top of an ion-plated lead film.

Parameter		**Greases**				**Oils**		**Solids**			
	Wt	Braycote 601	Kluber HX 83-301	Rheolube	MAP	Z-25	Pennzane	Sputtered MoS2	Ion-Plated Lead	Burnished MoS2	PGM Cage
Lifetime/Vapour Press.	2	4	4	4	4	4	4	5	5	1	2
Torque/noise	1	4	4	4	4	5	5	3	3	2	2
Sliding	1	5	5	5	5	5	5	5	1	3	3
Rolling	1	5	5	5	5	5	5	4	5	3	3
Air operation	1	5	5	5	5	5	5	0	3	0	3
Vac operation	2	5	5	4	5	5	4	5	5	2	4
Temperature	1	4	5	4	4	4	4	5	5	5	5
Ease of application	1	5	5	5	5	4	4	1	1	3	4
Flight Heritage	2	5	0	1	1	5	5	5	5	5	0
Price	0.5	5	5	5	5	5	5	2	2	3	4
Availability/Delivery	0.5	4	4	4	4	4	4	2	2	4	3
Storage	1	5	5	5	5	4	4	1	1	1	2
Sealing Required	1	5	5	1	3	4	1	5	5	5	5
TOTAL		**70.5**	**61.5**	**56.5**	**60.5**	**68.5**	**63.5**	**56**	**56**	**41.5**	**42.5**

Table 1 Lubricant Trade-Off Table

This combination has been used in other applications in the past, but for the MIDAS mission it offered the following advantages:

1) a measure of redundancy – if the base oil were entirely lost by creep the lead would remain and provide lubrication without replenishment for the life required.

2) lead provides a barrier to adhesion (in the case of localised base oil creep) and a measure of corrosion protection not provided by the grease alone.

Table 2 below shows the different bearing types and application of the selected lubricant solution taking into account assembly requirements for radial bearings and available cage materials.

Bearing Type	**Lubricant System**
Miniature radial bearings with steel ribbon cage	Raceways and steel ribbon cages were ion-plated lead coated prior to assembly by manufacturer and grease lubrication
Angular contact bearings (phenolic cage)	Raceways ion-plated lead coated, phenolic cages vacuum impregnated with Z25 base oil of grease, bearings greased on assembly.
Hard preloaded miniature ballscrew	Screw ion plated, grease applied
Axial ball bearing (polymeric cage)	Thrust plates ion-plated lead, grease applied on assembly
Linear Schneeberger type crossed roller bearings (steel cage)	Ion-plated lead applied to raceways and steel cage, plus grease.
Cup type miniature needle roller bearings (polymeric cage)	Grease alone as these are on the launch lock assemblies and are activated early in flight

Table 2 Summary of Bearing Types and Lubricant Details

The mechanisms also include a number of small plain shafts (pins); launch lock clamshells and wedge surfaces, which must be protected against adhesion. For these components sputtered MoS_2 was selected.

Finally after reviewing the bearing selections and recommending lubricants and preload values a summary of the main areas of development risk/uncertainty was made, these were:

Use of commercial-off-the-shelf (COTS) ultrasonic piezomotor - despite replacing the bearing with a space-compatible one, the performance in-vacuo of the particular motor type was not fully characterised by the end of the design phase.

Preloading of the linear rails was identified as a challenging task. The manufacturers supply adjustment screw points and for terrestrial applications the parallelism can be set well using these. However for space the preload must be carefully controlled and must be set with in-line load cell and careful adjustment to ensure even torque along the entire length.

3. Procurement and Lubrication Activities

Following the consultancy task, AEA Space was contracted to carry out the procurement, lubrication, sub-assembly build and TV testing of the EQM unit and subsequently also for the FM and FS.

Tribo-component procurement was carried out against a procurement specification, which was developed in-line with Ref. 3.

The long lead items in the procurement were motor - gearheads, ballscrew and miniature radial bearings. The latter were procured un-assembled to permit lead coating of raceways and cages prior to assembly by the bearing manufacturer. This operation proved to be a schedule-driving task.

It should be noted that some radial bearings selected were used in angular contact mode. Due to the relatively limited flexibility over cage material and design choices an obvious lesson learned for future would be to select more readily available angular contact bearings where possible for such applications. This is particularly true where required operational life is long, since in such applications a lead-coated steel ribbon cage may not prove sufficiently durable.

The sub-assemblies built and tested were:

1) *Approach Mechanism* – which consists of a brushed DC motor and gearhead coupled to a plain screw assembly. The motor drives a piston assembly axially within a tube to perform a launch lock/unlock and coarse positioning function. The whole mechanism is hermetically sealed (Figure 1).

Figure 1 Approach Mechanism Assembly

2) *Wheel Assembly* – which consists of a common shaft and wheel with attached facets and a spring preloaded face-face angular contact bearing pair with Codechamps rotary encoder attached (Figure 2).

Figure 2 Wheel Assembly (note a metallic cover protects the wheel facets during build and test)

3) *Translation Stage* – which consists of a baseplate onto which are mounted linear rails and a rotary bearing housing. The carriage which supports the other half of the linear rails and the wheel assembly in the completed instrument is driven via a piezomotor coupled to a hard-preloaded ballscrew supported at one end by hard preloaded face-face angular contact bearings (Figure 3)

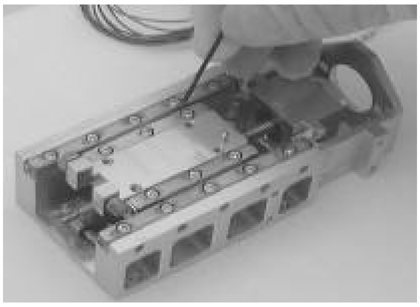

Figure 3 Translation Stage Sub-Assembly

4) Piezomotors

Commercial-off-the-shelf rotary ultrasonic piezomoors were selected. There were manufactured by Shinsei.

3. Mechanism Assembly and Test Activities

The mechanisms were assembled and subjected to in-air characterisation and thermal vacuum testing at AEA Technology Space.

During qualification the EQM Sub-Assemblies were subjected to characterisation in air and under thermal vacuum (TV) conditions. The TV testing consisted of 4 thermal cycles with tests at 70, 22 and -20°C respectively. In order to properly characterise the translation stage torque components it was tested in stages, with the preloaded linear stage being driven first by an external stepper motor with in-line rotary torque transducer, then by the piezomotor itself.

Following characterisation of the sub-assemblies they were integrated into the instrument which was then subjected to unit level vibration, functional and TV testing at ESTEC.

The testing approach used for the FM and FS units was similar except that, the translation stage and its piezomotors (one FM one FS) were subjected only to one thermal cycle with a maximum motor body temperature of 55°C for reasons to be discussed.

4. Test Results

4.1 Approach Mechanism

The approach mechanism motor current was monitored as it was deployed over its 3mm travel against a resisting load provided by a spring assembly. In the case of he EQM the load ranged from 13-23N, however for the FM the load requirement was increased be in the range 50-150N. In order to envelope the unit performance it was characterised in terms of its worst initial peak current at the beginning of deployment and maximum values at subsequent points after the peak for each test condition (Figure 4).

Typical results for the EQM unit are summarised below.

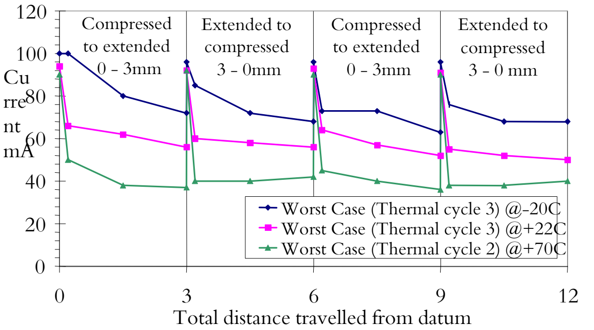

Figure 4 *Summary of Current v Deployment Distance (EQM Unit)*

4.1 Wheel Assembly

In order to test the Wheel Assembly it was mounted with axis vertical on a Kistler table to permit torque measurement and driven by an external stepper motor.

Using CABARET v. 1.08, the predicted mean torque for the wheel bearing pair (ignoring the encoder) was 5-10gcm. The measured values were found to be within this range for both low-temperature (-20°C) and high-temperature (60°C) tests.

4.2 Translation Stage

The EQM Translation Stage was tested prior to vibration by driving the ballscrew via an external stepper motor and in-line torque transducer prior to fitting the piezomotor for final characterisation and completion of the qualification thermal vacuum cycles.. In Figure 5 below the variation in ballscrew drive torque with position of the EQM translation stage is shown as a function of temperature. In this figure positions “0” and “200” are with the linear stage carriage at the closed end of the structure and positon “100” has it at the open end. The graph shows two interesting features, namely:

1. an apparent zero shift on changing direction. This is attributed to a measure of the locked-in-torque when the couplings and external motor/transducer system were attached to the linear stage

2. a trend of increased torque at the closed end of the structure, which is attributed to preload variation and stiffness effects.

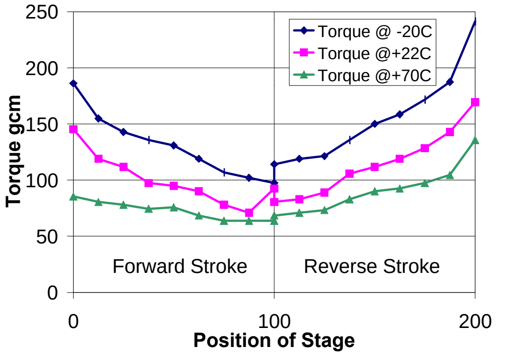

Figure 5 *EQM Translation Stage Drive Torque v Position*

During vibration testing the linear bearings of the EQM translation stage experienced a loss of preload. This was attributed to settling of the screws which define linear rail position and thus preload. In order to prevent this in the subsequent FM unit, a revised preloading procedure was adopted using optical measurements to confirm parallelism of the rails and setting the preload by shimming the linear rail once positioned. In this way any vibration loads would be transferred through the shimmed interface rather than the small set-screws. A stiffening member was also introduced at the open end of the translation stage in order to minimise the torque variation with position of the linear stage.

With these measures the variation in preload and stiffness over the length of travel was minimised for the FM unit. Though a similar pre-characterisation without the piezomotor was not done, the piezomotor current variation was less than ~5% over the translation stage suggesting good parallelism of the rails and similar stiffnesses at each end of travel.

4.3 Piezomotors

During qualification of the EQM sub-assemblies the driving of the Translation Stage using its piezomotor was carried out before full characterisation of the in-vacuo performance of the piezomotor for programme reasons. Though the Translation Stage operations were completed successfully it was obvious that during the test some degradation of the piezomotor performance was occurring. It was subsequently found that the torque output of the piezomotor had decreased from around 900-1000gcm recorded during in-air characterisation before translation stage testing to around 437gcm at the start of its characterisation in-vacuo and 237gcm when the characterisation was complete. This degradation was attributed to thermal changes in the piezomaterial and it was subsequently found that the critical temperature for the onset of these changes was around 65°C. Since the maximum translation stage structural temperature for the test was nominally 70°C and the motor internal temperature must have greatly exceeded this, in retrospect this degradation could have been expected.

Following this observation the in-flight operating environment and regime was reviewed by ESTEC and it was established that the 70°C qualification temperature had been too high. Furthermore since in flight there is considerable time for motor cooling between each operating period, the Translation Stage test had been a considerable over-test.

For the FM and FS units therefore a pre-selection of the COTS motors using flight-standard drive electronics was made in order to choose motors with highest inherent performance characteristics. These motors were then modified by substitution of flight-compatible bearings and addition of creep barriers prior to final characterisation testing. In parallel a successful lifetest was carried out at ESTEC during which motor body temperature was limited to 55°C. Functionally the motor performance was not significantly degraded by the end of the lifetest and only minor changes were observed in the piezomaterial. (Figure 6).

Given the above changes the typical output torque of the FM and FS Translation Stage motors were in the range 1000 to 1200gcm at all test temperatures (up to 55°C).

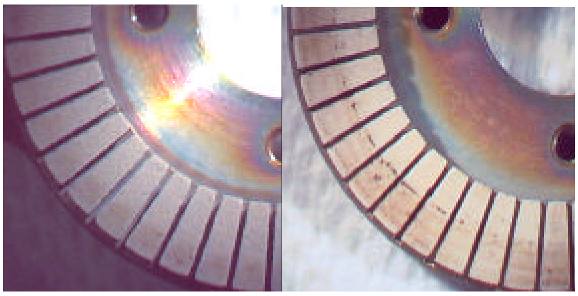

Figure 6 Piezomotor Segment Condition Before (left) And After (right) The Successful Lifetest

5. Lessons Learned

During the EQM test a number of lessons were learned and incorporated into the FM unit, the build of which followed-on only a few weeks behind. The main lessons were:

Translation Stage - preloading of linear bearings was found to be critical and because of their inherent stiffness very challenging. An alignment procedure using precision optical measurement and shimming and more rigidly located bearings was adopted.

Piezomotor Testing - thermal degradation was observed during characterisation testing and had not been anticipated. Fortunately in-flight operation of the motors can be infrequent and of limited duration to minimise internal temperatures and permit equilibrium to be achieved between operations. For testing of the FM, the mechanism temperature was limited to a maximum of 55°C.

6. Conclusions

Though the main conclusion of this paper is that test activities have shown all performance margins to be acceptable in the tested sub-assemblies, it is clear that to permit wider use of piezomotors in flight applications, availability of a piezo-material with wider temperature capability is essential.

Programmatically, early involvement of tribological consultants made tribological design more robust and facilitated integration of solutions into the design and bearing procurement activities. Also it is noted that despite the tight timescale, ESTECs approach of EQM/FM approach was prudent since lessons learned were implemented quickly and with minimum programme impact.

Acknowledgements

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