DEVELOPMENT OF AN EUROPEAN EDDY CURRENT DAMPER (ECD-100)

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1 ABSTRACT

Oerlikon Space have been designing high efficiency magnetic damping elements for a number of years to support specialised applications. These applications include the use of eddy current dampers for providing critically damped step responses and to help isolate micro-vibrations.
Oerlikon Space now have the capability for large scale low cost production and this can now be combined with the design capability to enable the production of batches of low cost Eddy Current Damper (ECD) units.

This capability has been recognised by our Customers and being a major user of ECDs they have encouraged and supported this development.

To mitigate risk and allow provisional costing to be consolidated Oerlikon Space have initiated the design process with a hardware/test oriented approach. The design has been based on using engineering experience supported by early hardware implementation and test. This approach was possible due to the availability of relevant experience and the basic simplicity of the devices mechanical design. The ECD-100 is designed to fulfil a wide range of applications on satellites in LEO and GEO orbit that are used for scientific or telecommunications purposes by using a standard product to minimize costs on system level.

The ECD is a passive device, fully space qualified in accordance with ECSS and ITAR free. This paper describes the concept, the verification programme and the performance of the qualified damper.

2 CONCEPT

The Eddy Current Damper shown in Fig. 1.1 consists of three basic modules.

There is a damper unit which provide the damping function a torque multiplication is needed and this is provided by a gear system that consists of an intermediate gear head and an input stage.

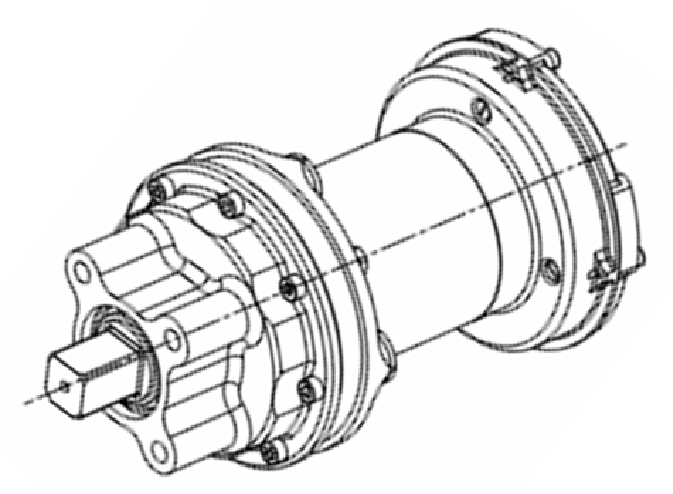

Figure 1.1: Eddy Current Damper

2.1 Damper Unit

The core element of the concept is a high efficient magnet circuit design. The damping is generated with a high purity copper disc rotating within a highly concentrated magnetic field.

The field is provided by 12 pairs of samarium-cobalt magnets with alternate north and south orientation. Figure 2.1 illustrate the described configuration.

The maximum damping rate is achieved by orientating magnetic pairs to have directly facing north and south poles. By rotating the outboard magnet set so that poles are facing one-another one can achieve a very low damping rate.

It has been decided that this core element that provide the damping function should designed as a self contained module with its own shaft supported by its own set of bearings.

The efficiency of this damper module enabled to fulfil the following critical requirements.

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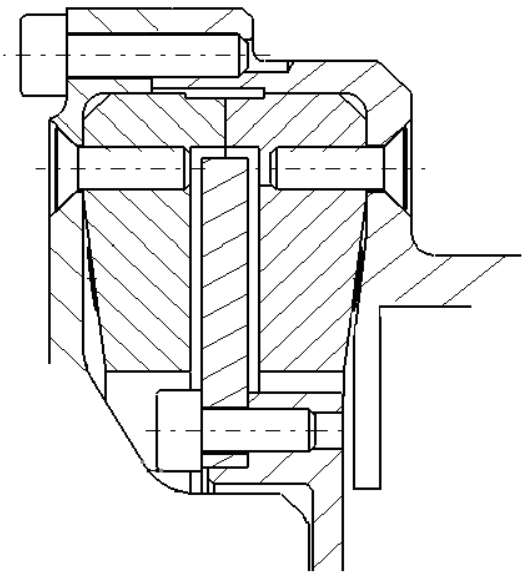

Figure 2.1: Damper module drive

Envelop

As damping is proportional to the cube of the diameter i.e. d^3 it is particularly important to maximise this dimension. But the allowed space at existing applications limited it. For a compact design it is essential to use magnets with high magnetic properties like samarium cobalt magnets.

Damping Rate

The aimed damping rate at ambient conditions is a maximum of 1000Nmsec/rad. To provide such a high damping either a high reduction ration is needed which has adversely effects to friction torque and life or a very efficient magnetic circuit design. Latter was the preferred approach for a good relations regarding mass and envelop.

Maximum Start Torque

The specified maximum stiction torque is 1.24 Nm. This means that the friction must be minimised. To achieve that the overall gear ratio has to be minimised.

Temperature

The operating temperature range was the most significant design driver and particular the lower temperature of -55°C. That means that the design must be insensitive to thermal effects. That means the overall gear ration between input and damper needs to be minimised because wet lubrication exhibit higher coulomb friction and viscous drag that increase damping and start up torque. Also to consider in this context is the temperature influence of the magnets material. The chosen samarium cobalt magnet has an outstanding thermal stability.

2.2 Gear Head

Another important target was to build a well-priced serial product. This is ensured by minimising the recurrent cost not only for machine parts also for off the shelf parts, assembly and testing.

It was particularly implemented by the intermediate gear-head. This unit provide the first stage of torque amplification.

A commercial gear-head was selected and adapted for high vacuum applications. This was essentially done by changing the lubrication system within the unit. To further optimisation the grease quantity was defined to achieve low viscous drag in due consideration with the expected life time. Then the unit's frictional performance was verified by tests.

A further advantage of this commercial gear-head is that by selecting from a range of existing gear-head ratios the maximum level of damping range can be set. That means this concept can be adapted to provide an extremely wide range of damping with no impact on mass and geometric envelop. Fig. 2.2 shows the selected gear head.

Figure 2.2: Commercial gear head

2.3 Input Stage

The maximum input torque applied at the ECD input stage is 75.2Nm. This is an impulse torque but is still high for a compact design as foreseen. It means that the input gear stage must be optimised with response to torque and it precludes the use of conventional commercial gear-heads for this element of the design. Also the high torque input stage provides a custom designed interface. For highest torque capacity a planetary system is used similar to commercial gear-heads. The capacity is further enhanced by the use of 4 planets within the sun gear. The gear configuration is shown below in figure 2.3

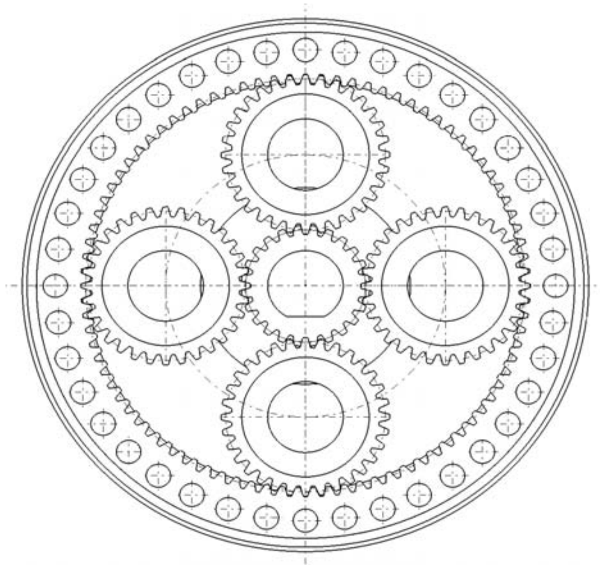

Figure 2.3: Gear Configuration

All of the gear components manufacturing from a high strength stainless steel with is used for many other space applications. To minimise starting torque each of the planets are lined with internal plain bushes which act as plain bearings and thereby support the planets on the drive pins. The section below shows planets and plain bushes.
Also shown is a section of the main shaft. The shaft has four machined legs which are used to support the planet support pin. The shaft is supported by a pair of thin section deep groove bearings. These dry lubricated bearings are preloaded by a wave washer.

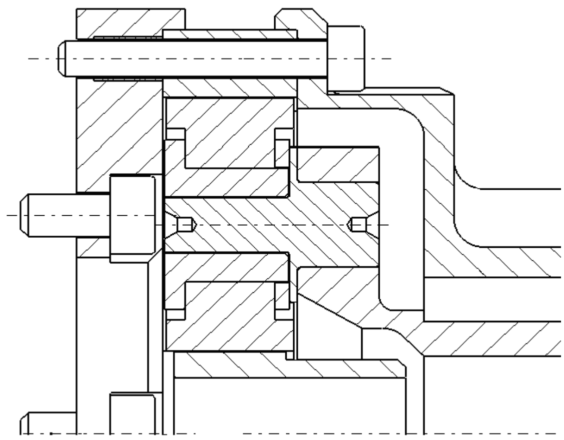

Figure 2.4: Section showing planets and plain bushes

3 VERIFICATION PROGRAMME

After extensive bread-board (BBM) tests a qualification model (QM) was built and the modification identified during BBM testing was implemented. In accordance to a current satellite solar array programme a suitable acceptance test programme was defined. The qualification testing comprised dimension and mass measurement, grounding check, performance at ambient, play test, strength and shock test, sine & random vibration , thermal vacuum cycling and performance under TV, life test and post life performance at ambient. After each test a functional test was performed to confirm the performance of the damper has not changed.

The following paragraphs characterize the performed qualification tests.

3.1 Dimension and Mass

The dimension and mass measurement comprised the control of functional and main interface dimension. The unit mass had to be less than 750g. The actual mass is approximately 740g.

3.2 Damping Rate

The most important requirement was the damping rate. To measure it a damper characterisation test bench (CTB) was used to drive the ECD at different speeds and monitor resistance torque. The main parts of the CTB were a brushless DC motor, gear-head, two torque sensors a reactive torque transducer directly mounted on the ECD and a reference torque transducer to measure drifts generates by temperature variation. Also important were several flexible couplings which absorb thermal expansion and contraction. A motor controller controls input speeds. A data acquisition system was used to record all measured values.

Fig. 3.1 shows typical test results measured during a damping rate test. The V200 is equal to 200 revolutions per minute of the motor before the gearbox (2548:1), therefore the ECD will take approximately 12 minutes for 1 complete revolution.
Fig 3.2 shows the arrangement of the ECD unit on the CTB.

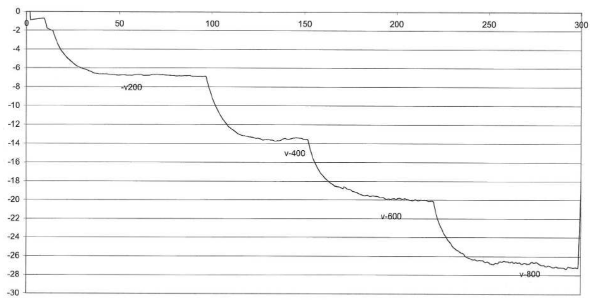

Figure 3.1: Damping rate test at ambient condition (+22°C) and different speed of rotation.

Figure 3.2: Damper TV Characterisation Test Bench

3.3 Stiction Torque

Another important requirement was the stiction torque (ST). The stiction torque test was also performed on the CTB. Only 4% on the damping is applied as the ST. When 30Nm is applied on the input shaft of the damper the max effect of the stiction torque would be 1.24Nm. To measure this quasi-static torque a very slow movement is required. So the applied speed was V10 that means approximately four hours for one revolution.

Fig. 3.3 shows typical test results of a Stiction Torque test at ambient condition at +22°C with velocity V10.

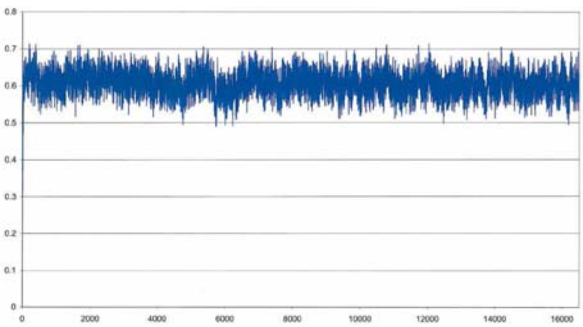

Figure 3.3: Stiction Torque test at ambient condition (+22°C) at V10.

3.4 Strength Test

To prove the strength of the qualification model it was tested during one revolution in both CW and CCW direction at the maximum load of 105Nm. The torque was generated over a pulley. The pulley diameter was 200mm and a mass of about 105 kg was applied on it. The 105 kg weight was supported on a crane, and then the crane was lowered quickly to transfer the weight onto the damper. As you see in Fig. 3.4 a massive structural steelwork was needed to perform the test. Figure 3.5 shows the response of the damper after applied the 105 kg.

The post functional test confirmed that the unit passed the strength test without any damage or decrease in performance.

Figure 3.4: Strength Test Setup

Fig. 3.5 shows a constant 105Nm applied to Damper for 1 complete revolution.

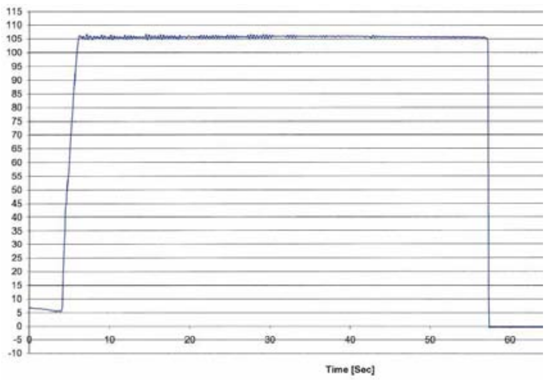

Figure 3.5: Strength Test result

3.5 Shock Test

The maximum deployment induced start-up shock load on the damper (occurring at start of solar array deployment) is 75.2Nm. The test set up used a dead weight system to enable known and controlled torque impulses to be applied to the damper input shaft. The set up still uses the general purpose test bench which includes the reactive torque transducer used in previous tests. The shock test was performed in ambient condition. 100 kick off shocks were applied on the damper.

The test performed in the following way. In a first step the beam was put in the horizontal position. Thereafter it was released and after approximately 6 degrees off the horizontal position the weight hits the end stop. Figure 3.6 illustrates the used test rig.

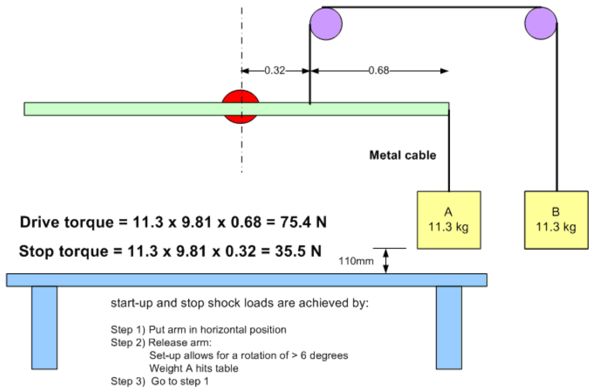

Figure 3.6: Eddy Current Damper start-up and stop load shock test set-up

At the beginning it was not clear which is the best way to test this requirement? At a first approach the load was applied by hand. But the different velocities and periods that the torque was applied was not adequate to perform the test properly. So the test setup as above was realized. Typical start-up shock test results could you see in Fig. 3.7.

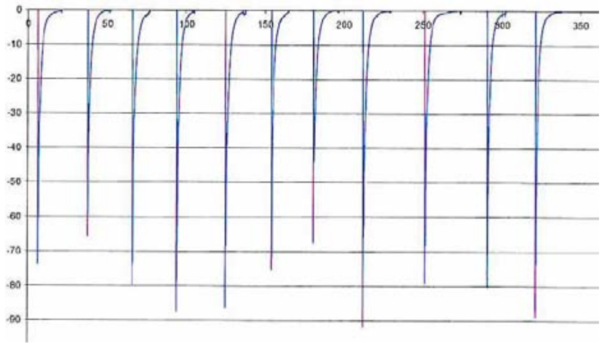

Figure 3.7: Eddy Current Damper start-up and stop load shock test results

The unit released without anomalies. So the test affirm that the unit is resistant again such kind of variation in stress.

3.6 Random Vibration

The unit was subjected to a sine & random vibration test. The Eddy Current Damper was tested along a lateral (Y) and the vertical axis (Z). The test comprised the following sequence:

- Low Level Sine
- Random

The response was recorded by one tri-axial and three uni axial measurement accelerometers attached to the unit housing.

The following test runs were performed

Table 3.1: Test run

Run No.	Description / Piloting	Frequency Range [Hz]	Input Level	Sweep Rate / Duration
1y	**Low Level Sine** *Maximum P1 + P2*	10 - 2000 Hz	0.5 g	2 oct/min
2y	**Random 0dB** *Average P1 + P2*	10 - 80 Hz 80 - 400 Hz 420 - 620 Hz 640 Hz 1000 Hz 1500 - 2000 Hz	+6dB/oct 0.6 g^2/Hz 0.1 g^2/Hz 0.2351 g^2/Hz 0.0966 g^2/Hz 0.0001 g^2/Hz	120 sec
		Overall level: 17.3 g_{rms}		
3y	**Low Level Sine** *Maximum P1 + P2*	10 - 2000 Hz	0.5 g	2 oct/min
4z	**Low Level Sine** *Maximum P1 + P2*	10 - 2000 Hz	0.5 g	2 oct/min
5z	**Random 0dB** *Average P1 + P2*	10 - 80 Hz 80 - 400 Hz 400 -1000 Hz 1500 - 2000 Hz	+6dB/oct 0.6 g^2/Hz -6dB/oct 0.0005 g^2/Hz	120 sec
		Overall level: 19 g_{rms}		
6z	**Low Level Sine** *Maximum P1 + P2*	10 - 2000 Hz	0.5 g	2 oct/min

During qualification vibration the lowest fundamental frequency of the ECD reduced from 535Hz to 485Hz. The drop in frequency was first observed in the 3rd run. The shift in frequency attributed to the fact that this lowest mode is a bending mode is due to the mass of the damper module and the gear-head is mounted to the gear-head adaptor plate. This is made of aluminium alloy and is clamped to the steel gear-head by four bolts. The stiffness of this interface is likely sensitive to such interface load.

Fig. 3.9 shows a typical response spectrum of the ECD during random vibration run. Fig. 3.10 shows the arrangement of the QM on the shaker table.

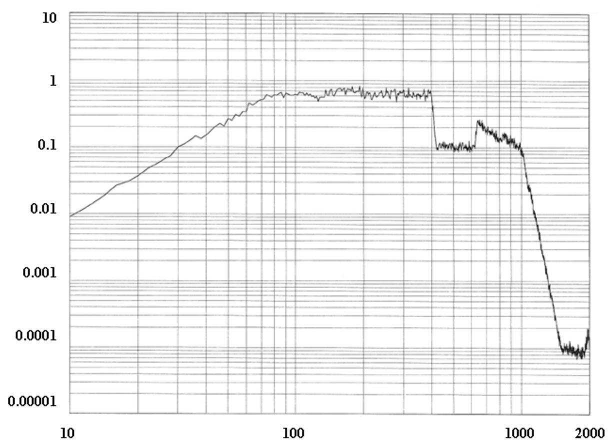

Figure 3.9: Random qualification test

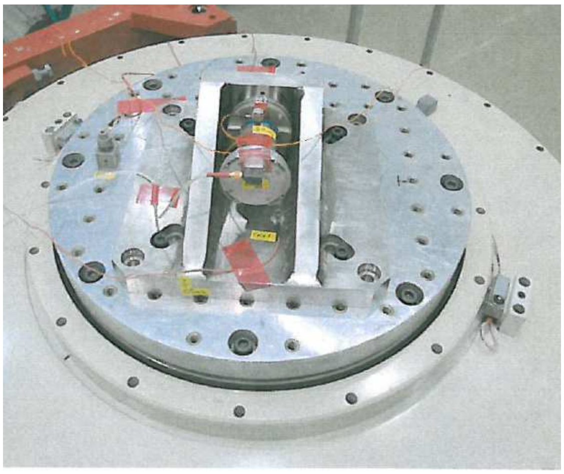

Figure 3.10: Arrangement of ECD on shaker table

3.7 Thermal Cycling

The purpose of this test was to verify the damping rate and stiction torque under thermal vacuum conditions. The unit was installed in the TV chamber after a functional test was performed.

Environment during cycling

Pressure	≤ 10^{-5} mbar to atmospheric
High temperature	
Stowed	+110°C
Operational	+100°C
Cold temperature	
Stowed	-65°C
Operational	-55°C

The temperatures were controlled via five thermocouples these was place at the following location: on the damper module (1), Gearbox (2), front end gearbox (3), torque transducer interface (4) and on the torque transducer (5). See picture below

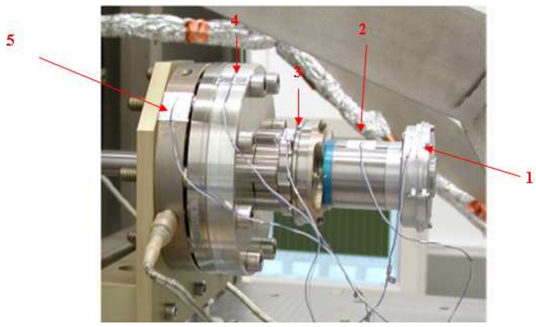

Figure 3.11: Thermocouple Measurement Positions

During the TV-cycling phase the recorded damping rate at high temperature was below the requirement of 600Nmsec/rad. It was decided to change the damper setting from position 6 to 7. This significantly improved the results.

3.8 Life test

The life test was the last test to pass. The damper had to perform 50 full rotations in each direction. The requirement was that the damper had to perform within its specification and show no failures and damages after the life time requirements
After the test an additional functional test was performed this was passing without any anomalies.

3.9 Conclusion

The Eddy Current Damper mechanism fulfils all the requirements,. Except for damping requirement at +100°C, measure values are 570Nmsec/rad, the specification is 600Nmsec/rad.
Stiction measurements are significantly lower than any of our competitors.

4 PERFORMANCE OF QM ON MAXIMUM SETTING

Finally below a table that shows the performance of the qualification model on maximum damping setting.

The damping rate range was within the given temperatures 570Nmsec/rad - 1660Nmsec/rad.

The stiction torque test showed that the damper has a high-margin in respect of the stiction torque requirement of 1.24Nm.

The damper withstands the maximum torque of 105Nm without any decrease in performance or anomalies.

The vibration test showed that the design is sensitive within the lower fundamental frequencies.

The mass had to be less than 750g. The actual mass of the QM is 737g.

Table 4.1: Summary of qualification model performance on maximum damping setting

Damping	Performance
+22°C +100°C -55°C	850 Nms / Rad 570 Nms / Rad 1660 Nms / Rad
Stiction	
+22°C +100°C -55°C	0.4Nm 0.26Nm 0.7Nm
Temperature Operating range	+100 / -65°C
Maximum Torque	105Nm
Random Vibration	19Grms
Mass	<740g