Thermal Vacuum Performance of Cycloid and Harmonic Gearboxes with Solid (MoS_2) and Liquid (Braycote 601) Lubrication

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ABSTRACT

The use of high power to weight ratio low backlash gearboxes, such as Harmonic Drives or the Cycloid gearbox, in spacecraft applications is highly desirable. The tribological performance of such gearboxes in space has not been well documented however. This paper reports on testing performed at ESTL to research the efficiency of such gearboxes in-vacuo when both dry and grease lubricated. Although the Harmonic Drive has shown itself to be superior in terms of efficiency over the Cycloid gearbox, wear of the gear teeth was evident after only a short test duration, whether grease or dry-lubricated.

Keywords: Gearboxes, Lubrication, Efficiency, Vacuum.

1. INTRODUCTION

The requirement for high torque-capacity gearboxes on current ESA projects, e.g. in the actuators for the HERMES robotic arm (HERA), has focussed on the use of either Harmonic Drives or Cycloid gearboxes. These were chosen as candidates for their high power-to-weight ratios. However, little data is available to assess the likely performance (i.e. efficiency and back drivability) of these gearboxes in the space environment. The comparison of these gearboxes in-vacuo whilst incorporating different lubrication techniques requires a facility with a capacity for high torque measurement.

ESTL has designed and built a high torque capacity (up to 500Nm), in-vacuo gearbox test facility. The facility currently has interfaces to suit both of the Harmonic Drive types HDUC50 and HDUC40 and the Cycloid gearbox type FA15. The objectives of this paper are first to describe the ESTL test facility. Secondly the paper will report on investigations into the in-vacuo efficiency levels of Harmonic Drives and Cycloid gearboxes when either solid or liquid lubricated. The grease used for these tests was Braycote 601, whilst spray-bonded MoS_2 was used as the dry lubricant. The tests were conceived to investigate efficiency levels over short time periods, and not to optimize the lubricant choice. Finally the current investigative programme at ESTL will be discussed.

2. ESTL Test Facility Description

Figure 1 is a schematic layout of the facility. The test facility comprises three main elements - the input shaft stage, the vacuum chamber with test gearbox and the output shaft stage.

The input shaft stage comprises a pulse-width-modulated amplifier controlled drive motor, with integral tachometer and speed reduction gearbox, along with an in-line rotary torque transducer. These items are mounted on an overhung support bracket, with integral support bearings and rigid two-piece jaw couplings.

The input torque is transmitted into the chamber by a shaft which passes through a rotary feedthrough, and is supported by a pair of preloaded radial ball bearings. A flexible coupling, for thermal and alignment considerations, transmits the torque to the gearbox input shaft. In the case of the Harmonic Drive only, the input shaft is supported by a pair of preloaded radial ball bearings set into a housing. The test gearbox is mounted on the end flange of a support housing. This main support housing, incorporating a fluid channel for thermal control, is rigidly bolted to the internal end of the bearing housing which in turn is connected to the vacuum chamber.

The output from the test gearbox is bolted to a large diameter hub which is locked to the main output shaft by a self-centering tapered block friction locking assembly. The output shaft, supported by a further pair of preloaded radial ball bearings, leaves the chamber via another rotary feedthrough.

Output torque is monitored by a high capacity torque transducer, which is carried between two flexible

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couplings. A step-up gearbox reduces the torque which is transmitted to a powder brake, which controls torque levels in the system. The reaction torques produced by the gearbox and brake are transmitted back to the chamber by a long outrigger.

Two-piece jaw couplers are used to provide misalignment capability where necessary external to the chamber. This also allows the position of motor and powder brake to be simply reversed, and thus the gearbox under test can be back-driven.

Testing was performed with the facility evacuated to vacuum levels between 10^{-4} and 10^{-6} torr.

3. Cycloid Gearbox Testing

The gearboxes tested were of type FA15-59, and were of standard supply. Their ratios are 59:1, they have a mass of 2.7 kg, and a quoted accuracy of 3 minutes of arc. They are rated for 132 Nm @ 2250 rpm.

3.1 Lubrication

All parts of the Cycloid gearbox were ultrasonically cleaned, with the exception of the two support radial ball bearings. These had their shields removed, and were thoroughly cleaned by spray rinsing with Arklone P.

For the grease lubrication tests, Braycote 601 was applied to all working surfaces as the gearbox was reassembled. The amounts of grease applied were not excessive, and in total amounted to about 0.8ml.

Dry lubrication of the cycloid gearbox was done using MS16 Solid Film Lubricant from Lubeco. Each item was sprayed in accordance with manufacturers instructions, and allowed to dry in air. The film thickness was estimated to be 30 microns.

Assembly of this gearbox dry-lubricated was more difficult than when grease lubricated, since the grease acts as an assembly aid by holding the many rollers in position. The gearbox also felt less "smooth" when rotated by hand, showing the need for a run-in period when in vacuum.

The grease lubricated cycloid gearbox was run in during a 20 minute test at 100 rpm in air, which ascertained efficiency against loads up to 400 Nm. The MoS_2-lubricated Cycloid gearbox was run in for 30 minutes at 100 rpm in vacuum with only rig parasitic torque loads applied. The required input torque was seen to reduce by 35% over the first 1500 revolutions, and was constant thereafter.

3.2 Cycloid Gearbox Efficiency Levels

A set of graphs pertaining to the measured efficiency levels of the Cycloid gearbox are shown as Figures 2-5. With grease lubrication - Figures 2 & 4 - the efficiency is around 80% when forward driven, for output torque levels above 100Nm. There is little variation due to change in temperature. When back driven the efficiencies tend towards 70% at input torques above 150Nm, there is however a reduction to around 60% when the temperature is reduced to -40 degrees C. At these relatively low speeds, efficiency levels are seen to increase with speed.

The dry-lubricated Cycloid gearbox has an efficiency level of about 75% when both normally driven and back driven for torque levels above 125 Nm, Figures 3 & 5. There is no apparent sensitivity to speed or temperature. It is interesting to note however that the dry-lubricated Cycloid gearbox, tends towards reduced performance with increasing speed as the temperature is increased.

3.3 Cycloid Gearbox Condition

Following the testing of the Cycloid gearboxes, all the components were removed for visual inspection.

In the Braycote 601 lubricated gearbox the lubricant was discoloured throughout the gearbox. The annular rollers which accommodate relative motion between the cycloid plates and the output hub pins, showed light burnishing marks where the plates had been in contact (Figure 6). Most rollers rotate freely on the pins, however a few required freeing.

The cycloid plates had lubricant remaining in all regions. Although the loaded portion of the tooth was highlighted by two lines of discoloured lubricant, on removal there were no obvious wear scars at this juncture, Figure 7. These components were typical of the component condition throughout this gearbox.

Figures 8-9 show similar details from the dry-lubricated MoS_2 gearbox.

The annular rollers, Figure 8, were heavily banded whilst still maintaining a light transfer film of MoS_2. On dismantling it was not easy to rotate any of these rollers on the hub pins, and a number of them were stuck. Despite the heavy banding marks, no heavy wear had taken place.

Figure 9 shows the condition of the cycloid-profiled plates. Where the teeth were in contact with the rollers, there was a well compacted film of MoS_2. On removal of this film there were no signs of any wear. Again these components illustrate the general condition of all the many components in the gearbox.

The overall condition of the tested Cycloid gearboxes was very encouraging, no signs of appreciable wear damage were in evidence. Most concern was registered over the inability of all the annular rollers on the output hub to rotate freely, especially in the dry-lubricated gearbox.

4. Harmonic Drive Testing

The gearbox tested was of type HDUC50-100, and was of standard supply. The gearbox ratio is 100:1, with a mass of 3.9 kg, and a quoted accuracy of 9 minutes of arc. It is rated for 480 Nm @ 2000 rpm.

4.1 Harmonic Drive Lubrication

Grease lubrication of the Harmonic Drive was relatively simple. Braycote 601 was applied to all the balls and raceways of the wave generator. On assembly into the rig, grease was applied to the teeth of both the flexspline and circular spline. The final assembly operation was to insert the wave generator into the flexspline, and prior to this, grease was applied to the relevant bore and O.D. Grease was applied with a syringe, and in total about 2ml of grease was used.

Dry lubrication of the Harmonic Drive was more complicated however. The circular spline was sputter-deposited with MoS_2 to standard ESTL procedures (ESTL/QP/061). The flexspline was spray-bonded with MoS_2, both on the external gear teeth and on the internal bore where the wave generator is in contact, with ROCOL DFSM Inorganic Anti-Scuffing Spray. The spray coating used for the wave generator was MS16 Solid Film Lubricant from Lubeco. These lubricants were applied in accordance with the manufacturers instructions, with an estimated film thickness of 30 microns, and allowed to dry in air.

The grease lubricated harmonic drive was run in for 30 minutes at 200 rpm against a load of 150 Nm in vacuum. No discernible change in efficiency was observed. When MoS_2 lubricated, the Harmonic Drive was <u>not</u> run in, and <u>all</u> running was performed under vacuum.

4.2 Harmonic Drive Efficiency Levels

The Harmonic Drive efficiencies when lubricated with Braycote 601 were as shown in Figures 10 & 12. When driven normally the efficiency tends towards values in excess of 85% at ambient in-vacuo, when at higher torque levels (>200 Nm). The effect of lubricant viscosity is however quite marked with a reduction to around 70% at -40 degrees C, and efficiencies in the order of 90% at 82 degrees C.

When back driven the trends are similar, but with a reduction of a few percentage points. Higher speeds tend to give an improved efficiency performance when driven in either manner.

When dry lubricated with MoS_2 the Harmonic Drive behaves in a different manner as recorded by Figures 11 & 13. The efficiencies when forward driven have been reduced by less than 5%, however the effect of temperature is now very slight with no apparent loss of efficiency at low temperature.

When back driven the reduction of efficiency is only marginal, in the order of 1% or 2%. Note however that the speed effect is markedly higher when temperature is moved away from ambient, and also that there are signs of a reversal in the trend towards increasing efficiency with increasing speed.

4.3 Harmonic Drive Condition

Only one Harmonic Drive was purchased for this series of tests, with running performed in opposite directions for the grease and dry-lubricated tests.

Figures 14 & 16 show the condition of the harmonic drive following testing whilst lubricated with Braycote 601. Figure 14 shows the circular spline after cleaning away of the discoloured grease. A wear and deformation zone is visible on <u>every</u> tooth around the circumference, coinciding with the position of a similar zone on the edge of the flexspline teeth (Figure 16). A less well defined scar on the circular spline, slightly inboard, is in the position of the outermost edge of the wave generator. Inside the flexspline, in the area where the wave generator was in contact, there was a light burnishing of the surface.

Figures 16 & 17 highlight features of the Harmonic Drive following the tests whilst dry-lubricated with MoS_2. A view of the circular spline in Figure 16 clearly shows the tooth profile of the leading edge and the degree of engagement of the mating wave generator by the transfer of bonded lubricant. Visual inspection showed that the same regular wear and deformation pattern exists at the point where contact with the flexspline is first made. A similar mark was also evident on the flexspline. The wave generator showed no signs of distress, and the balls have a healthy transferred film, Figure 17. Visual inspection of the interface between the wave generator and the flexspline showed the wave generator to have a thin sheen of MoS_2 all around, whilst the inner bore of the flexspline showed a zone of densely compacted MoS_2, which was well bonded to the surface.

5. Current Investigations

With the wear marks so obvious on the Harmonic Drive after only a few hundred revolutions of the output shaft (180 in the case of the dry-lubricated test), ESTL are currently engaged in the performance of a simulated life test on a dry-lubricated Harmonic Drive gearbox to prove the viability of such an approach.

The gearbox is of the HDUC40-120IH type, rated for 294 Nm at 2000 rpm input speed and of mass 2.3 kg. The newly developed IH tooth profile ensures that more teeth are in contact and as a consequence the torsional stiffness of the gearbox is improved and the backlash is quoted as being practically zero.

ESTL has measured the torsional stiffness of the gearbox which agrees with results quoted by Harmonic Drive, however the hysteresis measured of 0.03° at loads of +/- 255 Nm is higher than expected.

The test programme involves moving through set move profiles with load applied, both in air and in vacuum. To this end the test facility has been improved to include positional feedback from an encoder mounted on the input shaft. Controlled motion profiles are available through the programming of a proprietary servo-amplifier control board.

Following the earlier success of Lubeco spray-bonded MoS_2 during the efficiency measurements, it was decided to lubricate the whole of the gearbox with MS16 for this test programme. Very soon into the in-air testing with an applied load of only 60 Nm, the testing was stopped because of rough running. On stripdown it has been found that the MoS_2 has been almost completely removed from the working zones.

Pin-on-disc tests have shown the durability of Lubeco MS16 to be improved nearly 50 times by running in dry nitrogen (simulating vacuum conditions) versus running in air. ESTL is currently evaluating three other types of spray-bonded MoS_2 lubricant, with a view to choosing the best lubricant for completion of the test schedule.

6. CONCLUSIONS

1) For the grease-lubricated Harmonic Drive, efficiencies of about 85% were recorded at ambient temperature in vacuum, for output torques greater than 150Nm. A marked reduction to 70% was witnessed at -40 degrees C, whilst efficiencies of 90% or greater were measured at 82 degrees C. Efficiency levels increased with increasing speed levels. With back-driving the effects were the same, but with an overall reduction in efficiency of a few percentage points.

2) Results for the MoS_2 dry-lubricated Harmonic Drive show the efficiency to vary between 80 and 90% for output torques above 150Nm. Little variation is evident due to temperature, speed or being back driven.

3) For the grease lubricated Cycloid gearbox, efficiency levels tend towards 80% over output torque levels of 100Nm. Little variation is evident due to temperature effects. Back driven efficiencies of around 70% are at least 10% lower, reducing further to 60% at -40 degrees C.

4) Dry-lubricated Cycloid gearboxes have efficiency levels between 70 and 80% regardless of conditions or direction of driving.

5) General efficiency comparisons imply that the Harmonic Drive performs marginally better than the Cycloid gearbox, however it does appear to be more susceptible to temperature effects.

6) Wear and deformation damage has been sustained by the Harmonic Drive at the highest stress contact point between flexspline and circular spline after only a short test duration. Similar wear patterns occur when grease or dry-lubricated. The Cycloid gearbox has not suffered any similar wear damage, only light burnishing.

7) The dry-lubricated Harmonic Drive provides the best overall performance of the combinations tested as assessed by efficiency measurements. However, current testing at ESTL is aimed at proving the durability of such a combination.

8) A full-scale life test of any design incorporating a novel gearbox is of vital importance to prove the long-term durability with space-lubricants in the space environment.

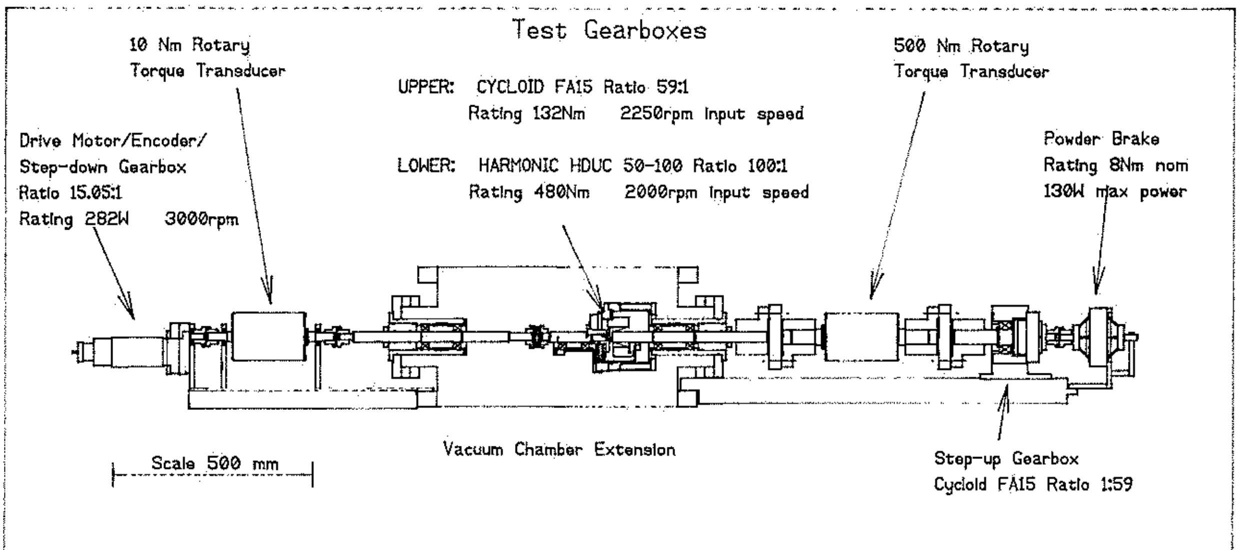
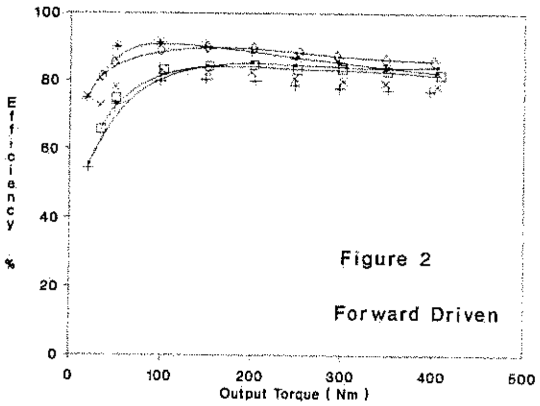


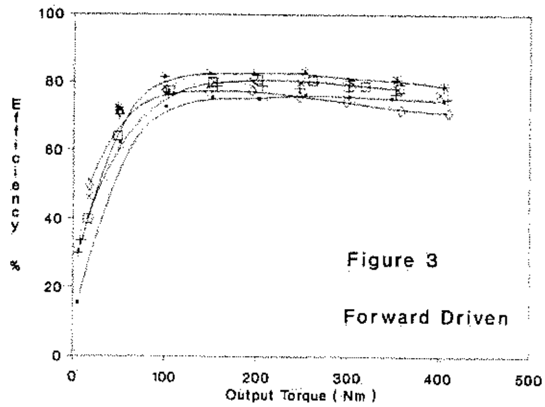
Figure 1: SCHEMATIC DIAGRAM OF THE ESTL TEST FACILITY

Key to Graphs, Figures 2-5 & 10-13.

Input Speed / Temp

50rpm/-40degC	50rpm/21degC	50rpm/82degC
200rpm/-40degC	200rpm/21degC	200rpm/82degC



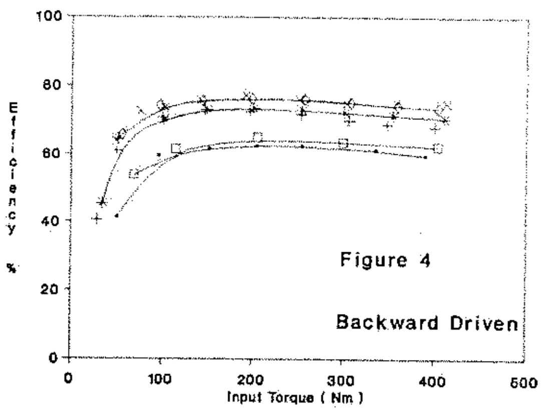


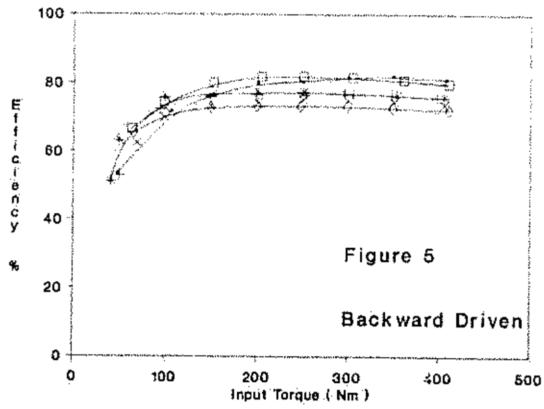
CYCLOID GEARBOX TYPE FA15-59

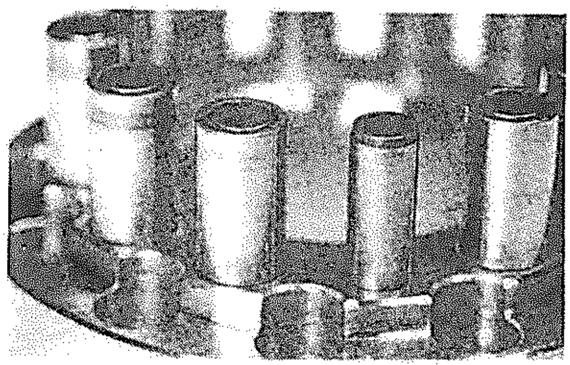
BRAYCOTE 601 Lubricated

CYCLOID GEARBOX TYPE FA15-59

MoS2 DRY Lubricated







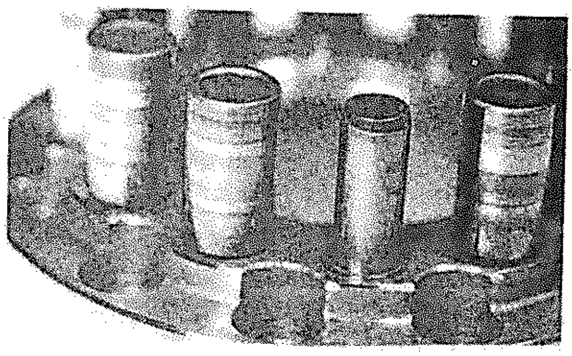
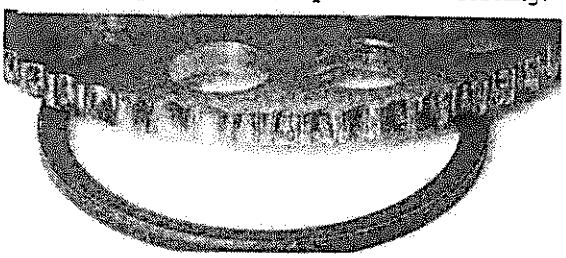
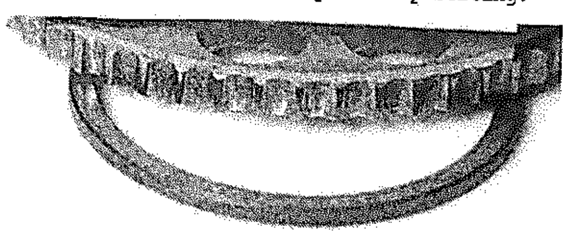
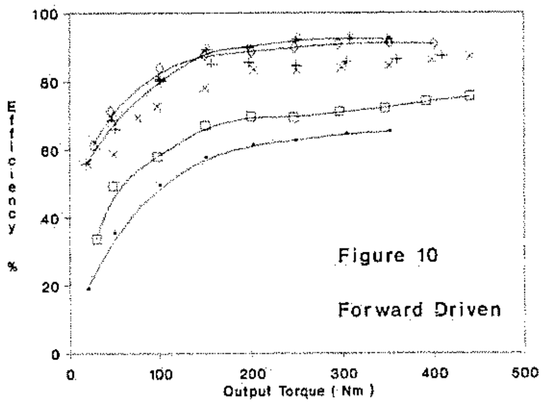


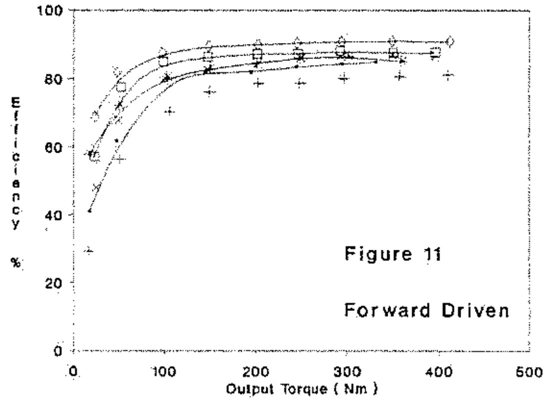
Figure 6: Output Hub post Grease Lubricated Tests.
Figure 8: Cycloidal Plate post Grease Testing.

Figure 7: Output Hub post MoS_2 Lubricated Tests.
Figure 9: Cycloidal Plate post MoS_2 Testing.



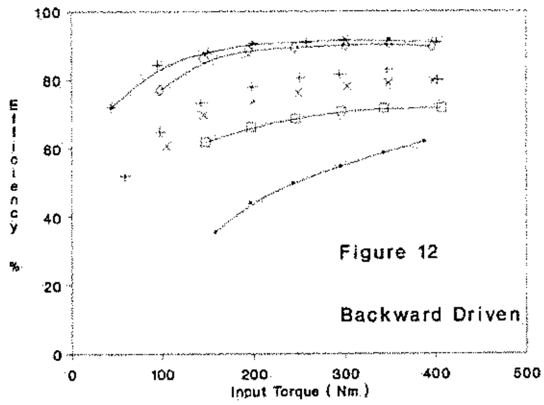


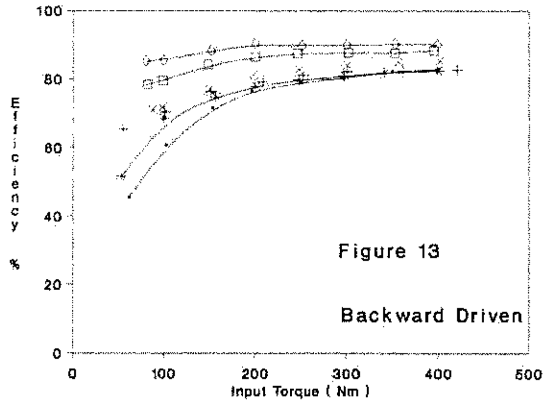


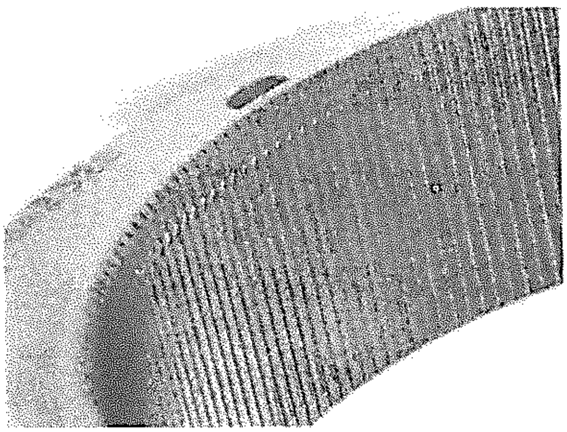


HARMONIC DRIVE TYPE HDUC50-100
BRAYCOTE 601 Lubricated

HARMONIC DRIVE TYPE HDUC50-100
MoS2 DRY Lubricated







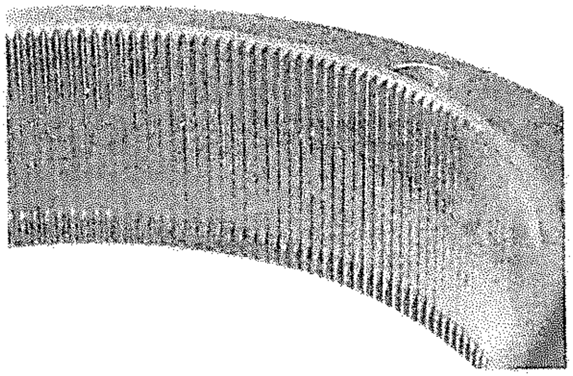


Figure 14: Circular Spline post Grease Testing.
Figure 16: Flexspline post Grease Testing.

Figure 15: Circular Spline post MoS_2 Testing.
Figure 17: Wave Generator post MoS_2 Testing.