THE PERFORMANCE AND LIFE OF FLUID-LUBRICATED HARMONIC DRIVE® GEARS

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ABSTRACT

It is known that the performance and life of fluid-lubricated Harmonic Drive® gears are dependent on a number of parameters. These include speed of rotation, output load, temperature, and type and amount of lubricant. In this paper we present and compare data on the performance and life of Harmonic Drive® gears lubricated with PFPE and MAC fluid lubricants. These data include in-situ measurements of efficiency, torsional stiffness and, uniquely, axial force at the Flexspline/Wave-Generator interface made possible by a new test-rig. The latter measurement allows the friction at the WG/FS interface to be monitored which in turn provides an indication of the condition and effectiveness of the lubricant at this interface. The evolution of such parameters during the course of life tests has provided new insights into the behaviour of Harmonic Drive® gears and, in particular, the fall-off in performance that defines useful life.

1. HARMONIC DRIVE GEARBOX

Harmonic Drive® gears are characterised by compactness, high reduction ratios, zero backlash and high positioning accuracy. Additionally they offer high power density (torque-to-weight ratio) and torsional stiffness and these, in particular, make them attractive for use in space applications [1, 2]. The first reported use of Harmonic Drive® gears in space was in 1971 during the Apollo 15 mission (in actuators driving the lunar rover wheels) and since then they have found increasing use in space applications, most commonly in compact drive actuators for SADMs and APMs.

In the present study testing was carried out on Harmonic Drive® HFUC-20-160 component set fitted with hybrid-ceramic Wave Generator bearings (silicon nitride balls, Cronidur® X30 steel races). The gearboxes were supplied fully lubricated and integrated within a test-box by Harmonic Drive AG, Limburg, Germany. Each gearbox comprises: a hybrid Wave Generator (WG) - a thin-section radial bearing fitted onto an elliptical plug manufactured from 17-4PH, cond. H1150; a Circular Spline (CS) - a rigid gear with internal teeth manufactured from 17-4PH steel, cond. H1150; and a Flexspline (FS) – manufactured from 15-5PH, cond. H1075 and comprising a non-rigid, thin-walled cylindrical cup with external teeth on a slightly smaller diameter than the Circular Spline. The gear ratio is 160:1. The rated torque of the units is 40Nm.

It is noted that the components parts of these gears are all sourced within Europe and that this is the first time this configuration has been subjected to thermal-vacuum testing.

2. LUBRICATION

Two Harmonic Drive® gears were lubricated prior to assembly and installed into the test-box at HDAG. One gearbox was lubricated with PFPE oil and grease and the other with identical volumetric quantities of a MAC oil and grease. The types and quantities of lubricants applied are indicated in Table 1.

*Table 1 Lubrication details**

	PFPE-lubricated gearbox	**MAC-lubricated gearbox**
WG bearing	Fomblin Z25 oil	Nye 2001a oil
Quantity (% of free volume)	5 (equivalent to ~100µl)	5 (equivalent to ~100µl)
WG bearing cage (phenolic)	Fomblin Z25 oil	Nye 2001a oil
Process	Vacuum impregnation	Vacuum impregnation
WG (outer diameter)	Braycote Micronic 601EF	Maplub SH100b
Quantity (mg/µl)	40/21.6	23.8/21.6
FS bore	Braycote Micronic 601EF	Maplub SH100b
Quantity (mg/µl)	200/108	119/108
FS teeth	Braycote Micronic 601EF	Maplub SH100b
Quantity (mg/µl)	100/54.1	59/54.1
CS teeth	Braycote Micronic 601EF	Maplub SH100b
Quantity (mg/µl)	500/270	297/270

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'*' the lubricant amounts shown above were target figures. In practice these amounts were achieved typically to within 5%.

3. TEST RIG

The test set-up is as shown schematically in Fig. 1. The test gearbox is located in a test housing mounted to a heat exchanger providing both location and heat transfer. Both the input and output shafts are located on a pair of dry-lubricated angular contact bearings. Input drive is by means of a stepper motor which supplies torque measured by an in-line rotary torque transducer. Optical encoders provide angular measurements mounted to both input and output shafts. Torque loading (output load) is applied by means of a motor gear-head whose speed is controlled in relation to the input motor via a proportional controller. The load on the output shaft is measured by means of an in-line torque transducer.

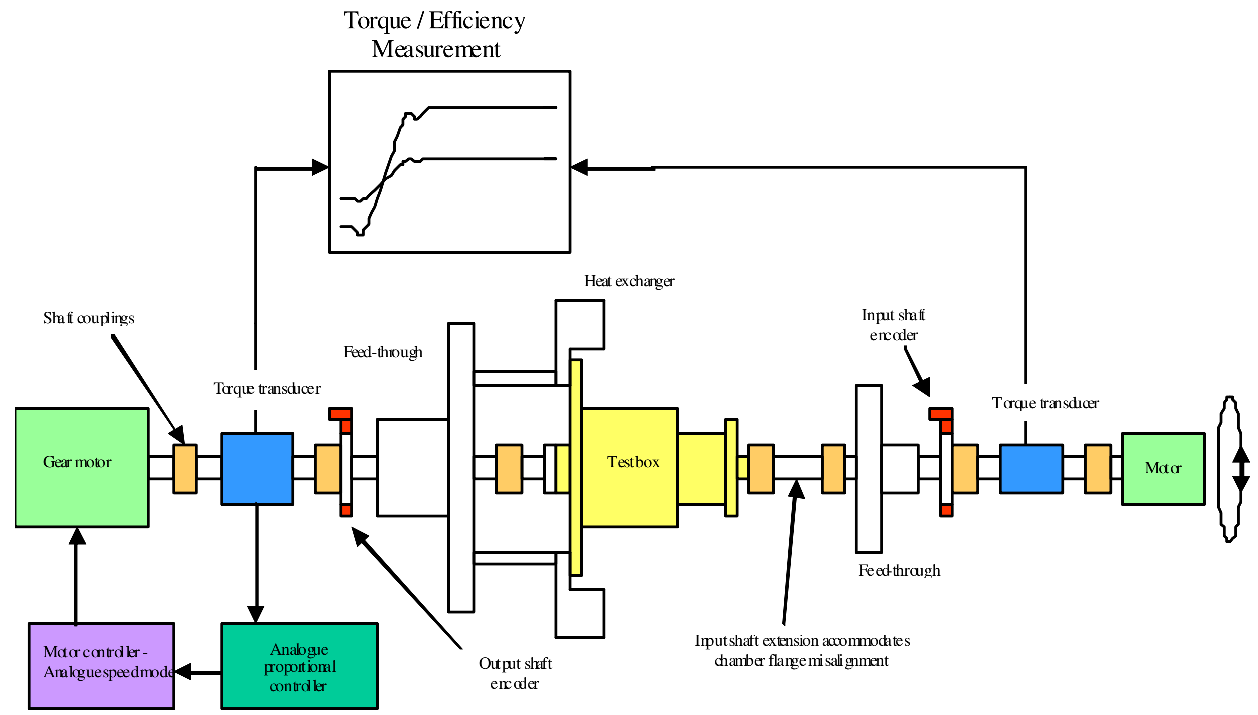


Figure 1. Schematic diagram of test rig

Measurement of stiffness/hysteresis is achieved by locking the input shaft, applying torque to the output shaft (using the motor gear-head) and measuring angular displacement with the output-shaft optical encoder. Together with efficiency, the measurement of stiffness provides probably the most important information with regards to the health condition of the gear. As a common feature of Harmonic Drive® gears is the zero backlash, the onset of degradation, which is typically caused by a failure of the lubrication, can be identified by a change in the gear stiffness close to the zero crossing. A monitoring of this characteristic is therefore very helpful to determine the condition of the gear.

Besides the measurement of stiffness, the Transmission Accuracy (TA) is also assessed. The TA is defined as the maximum error which occurs between the ideal and real output position. It is measured over one output revolution. Since for many mechanisms the accuracy of the entire actuator is determined by the gear's precision, a knowledge of this characteristic is considered essential to the end user. The axial load developed on the Wave - Generator - which is dependent on the output torque and friction at the WG/ FS interface - is measured by three equispaced piezoelectric load cells arranged within the test-box housing. The relationship between axial force and friction coefficient is given in Eq. (1) below:

$$F_{ax} = 2\,(T/D)\,\mu\,\tan 20° \qquad (1)$$

where,

F_{ax} is the axial force (N)
D is a gearbox size factor
T is the output torque (Nm)
μ is the coefficient of friction at the FS/WG interface

For a HFUC-20-160 gearbox equation (1) reduces to:

$$\mu = 0.07 \frac{F_{ax}}{T} \quad (2)$$

Evaluation of the gradient of a plot of axial load vs. output load allows a calculation of the friction coefficient at the WG/FS interface and thus the detection of tribological changes at that interface.

In practice the axial load was measured as the output torque was increased from 10Nm to 25Nm and the mean gradient used to calculate μ from Eq.(2). All F_{ax} measurements were made with the gearbox operating at an input speed of 100 rpm.

In summary the facility allows the measurement of the following parameters:

- no-load driving torque
- hysteresis and torsional stiffness
- no-load back-driving torque
- efficiency
- transmission accuracy
- axial load on Wave Generator

4. TEST CONDITIONS

Each gearbox was subjected to efficiency tests followed by an endurance (life) test in high vacuum at a temperature of +90ºC with an input speed of 50rpm and output load of 4Nm. Gearbox efficiency was monitored continuously. Initially the planned duration was 50,000 output revs. (8 million input revs.) but in practice the tests were run beyond this point, the tests eventually being stopped when the efficiency had dropped to ~40%. In addition interim tests (at +90ºC) were performed at 100, 500, 1000, 5000, 11000 output revs. and thereafter every 7000 output revolutions. Each interim test comprised three individual test measurements, as follows:

- Axial load on Wave Generator
- Torsional stiffness
- Transmission accuracy

Cold soaks at -25°C were executed every 1000 output revolutions for the first 11,000 output revolutions followed by cold soaks every 3,500 output revolutions thereafter. Each cold cycle consisted of 1 output revolution at 50rpm with an output load of 4Nm, in order to assess the efficiency of the gearbox during cold soaks.

5. TEST RESULTS

5.1 PFPE-lubricated gearbox (designated HFUC5)

The evolution of efficiency (at +90°C and -25°C) during the endurance test is illustrated in Fig. 2. At +90°C the efficiency remained at a high level (between 80 and 90%) over the first 5 million input revs. Thereafter it decreased (somewhat erratically) to levels of between 50 and 70% until falling off again after completion of ~11 million input revs to 40%, the test being stopped after ~12 million input revs.

As expected the efficiency at -25°C was appreciably less than that at +90°C due to increased viscous losses. However, throughout the endurance test there appeared to be, in broad terms, a convergence of the cold-soak and hot-soak efficiency values, such that after 7.3 million input revs. (the last point at which the cold-soak efficiency was measured) the two values are rather similar (45% and 55% respectively). Thus, at this point in the endurance test, the gearbox efficiency had become fairly insensitive to temperature indicating in turn that the lubricant had lost much of its viscous properties. This may be because the lubricant at this point no longer comprised clean, pure grease but, rather, a mixture of oil-depleted grease (i.e. PTFE-rich due to oil evaporation), wear debris and degraded oil products.

Fig.3 plots the gearbox performance during the endurance test in terms of efficiency (at 90°C), torsional stiffness K1 (over an output torque range 0-7Nm) and friction coefficient (at the FS/WG interface). The plots show that there is a correlation between efficiency, stiffness and friction in that, in general, decreases in efficiency correspond to increases in stiffness and friction. In previous TV tests on grease-lubricated Harmonic Drive® gears, we have attributed fall-off in performance (efficiency) at least in part to depletion of lubrication at the FS/WG interface [3, 4, 5].

A post-test strip examination of the gearbox revealed the CS and FS gear teeth to be in good condition, the teeth surfaces having a smooth, burnished appearance (Fig.4a). The WG bearing races and balls were also in a good condition and, apart from some micro-pitting of the raceways, showed little evidence of wear (Fig.4b). Examination of the FS/WG interface indicated that there had occurred some metal transfer (confirmed by EDAX analysis) from the FS bore to the OD of the WG bearing (Fig.4c) which, again, points to the lubrication having become ineffective at this interface.

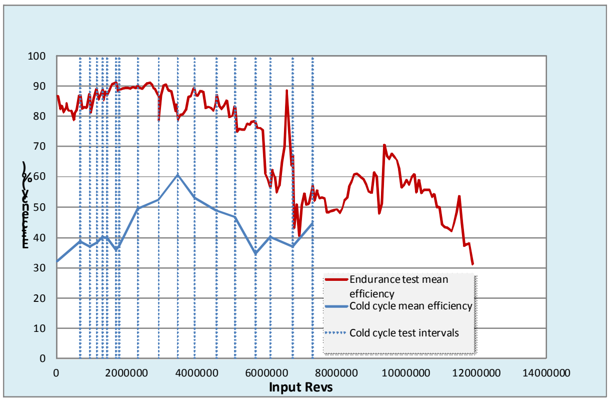


Figure 2. Evolution of efficiency of PFPE-lubricated gearbox (HFUC5) during endurance test.

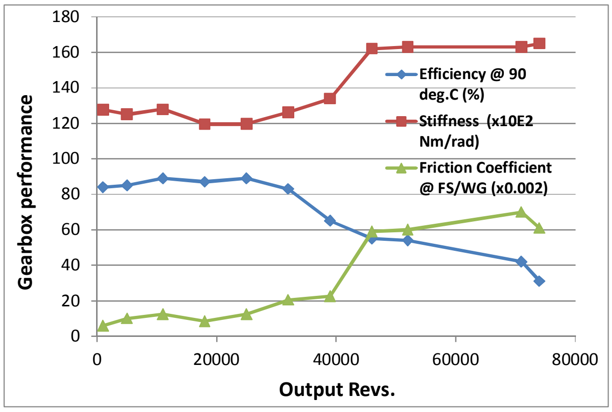
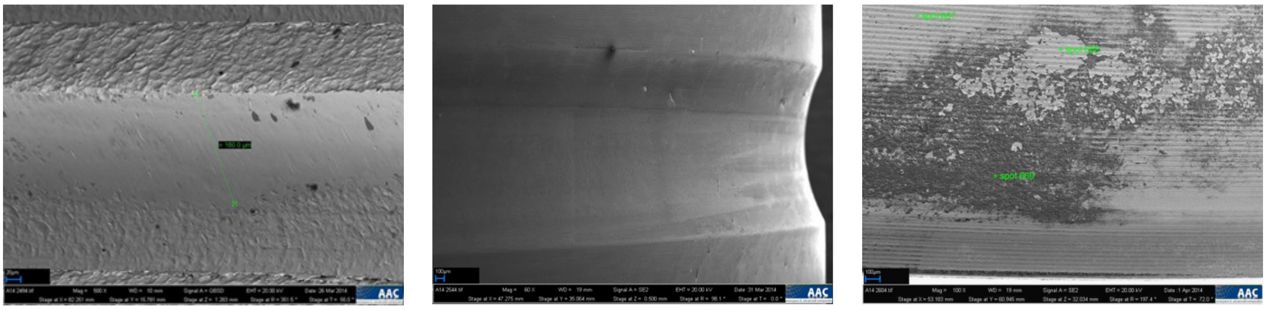


Figure 3. The evolution of efficiency, stiffness and FS/WG friction (at +90°C) during the endurance testing of a PFPE-lubricated HFUC-20-160 Harmonic Drive® component set.



a) Flexspline tooth *b) WG bearing inner race* *c) WG bearing OD (dark areas indicate metal transfer from FS)*

Figure 4. SEM micrographs of surface condition of gearbox (HFUC5) parts

5.2 MAC-lubricated gearbox (designated HFUC7)

Fig. 5 plots the change in efficiency during the course of the endurance test on the MAC-lubricated gearbox. Although upon commencement of testing the efficiency at 90°C was relatively low it quickly increased to a high value (typically 80%) and maintained this performance over ~12 million input revs. This high-efficiency period is notably longer than that achieved with PFPE lubrication (~5.5 million input revs. – see Fig.2). Thereafter the efficiency dropped off to low values.
During the cold soaks the efficiency started at around 20% and thereafter decreased monotonically throughout the life test reaching a value of ~10% at test completion. As would be expected given the higher pour point of the MAC grease the cold soak efficiency values are appreciably lower than those achieved with Braycote 601EF lubrication.

If we compare the evolution of efficiency, FS/WG-interface friction and torsional stiffness (Fig. 6) we again (as with PFPE lubrication) observe an increase in friction which, as before, points to lubrication degradation and/or loss at the FS/WG interface. This time, however, the drop in friction precedes a decrease in efficiency. There is however no corresponding change in stiffness, which maintained a near-constant value throughout the endurance test period.

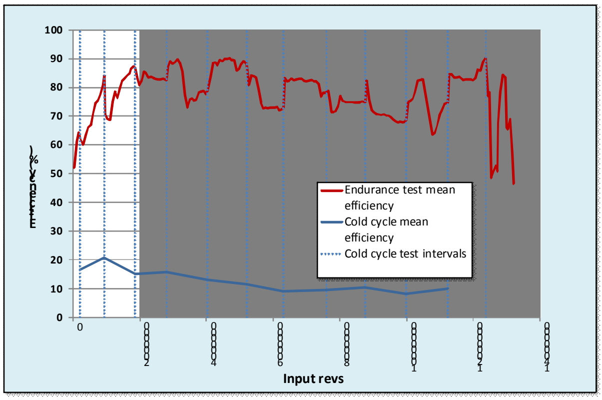


Figure 5. Evolution of efficiency of MAC-lubricated gearbox (HFUC7) during endurance test.

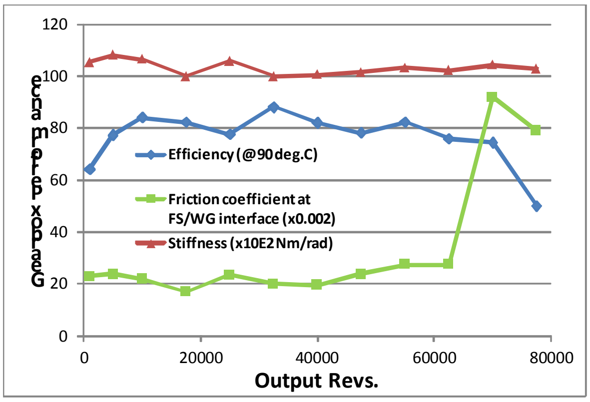


Figure 6. The evolution of efficiency, stiffness and FS/WG friction (at +90°C) during the endurance testing of a MAC-lubricated HFUC-20-160 Harmonic Drive® component set

Examination of the component parts showed evidence of wear (galling) on the FS bore (Fig. 7). The grease appeared black throughout (virgin SH100b grease is cream-coloured) indicating tribo-degradation and /or inclusion of wear particles.

Figure 7. Showing wear on bore of flexspline

6. COMPARISON WITH PREVIOUS LIFE-TEST DATA (PFPE LUBRICATION ONLY)

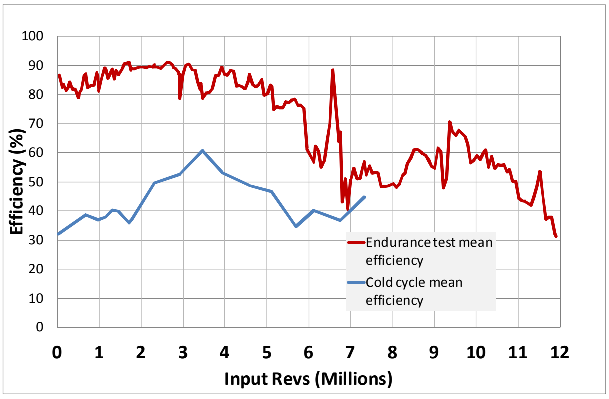
Fig.8 presents a comparison of the life of the HFUC5 Harmonic Drive® gear tested in the present study with three previous life-tests made on three HFUC-20-160 gearboxes similarly lubricated with Braycote 601EF grease (and Z25 oil in the WG bearing). Note that the previous tests (on gearboxes designated HFUC1, HFUC2 and HFUC4) were carried out on gearboxes fitted with all-steel WG bearings. In addition the third of these, HFUC4, was run-in over ~1 million revs in vacuum and then cleaned and re-lubricated prior to the life test. In each case the gearboxes were operated at 50 rpm input speed, 4 Nm output load and a temperature of +90°C (HFUC4 was also subjected to cold cycles).

In comparison to HFUC1 and HFUC2, the gearbox of the present study (HFUC5, fitted with a hybrid ceramic WG bearing) has produced a longer life. This is despite the fact that the stiffness, and hence internal preloading, of HFUC5 exceeded that of HFUC1 and HFUC 2 (the K1 stiffness values measured at 20°C prior to life testing being as follows: HFUC1: 10095 Nm/rad; HFUC2 11709Nm/rad ; HFUC5: 15946 Nm/rad). These observations imply that the hybrid-ceramic WG bearing offers an advantage i.e. a longer low-torque life that contributes to the prolonged life of the Harmonic Drive® gear. This is consistent with the findings of in-vacuo tests carried out by ESTL on Cronidur® X30 bearings fitted with either 440C or Si_3N_4 balls and lubricated with Z25 oil [6]. These tests (peak stress = 850 MPa) resulted in the onset of oil degradation in Z25-lubricated bearings fitted with 440C balls after 40 million revs. at 200rpm. No degradation was observed (in the test period, namely 43 million revs.) in identical tests in which the bearings where fitted with Si_3N_4 balls.

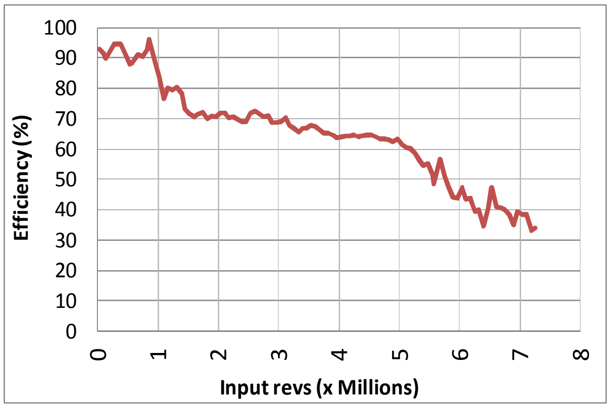
A factor that needs to be taken into account is that for a given preload (set by the fit of the component parts at room temperature) the internal preload at the test temperature (+90°C) will be less in the gearbox fitted with a hybrid ceramic bearing due to the difference in thermal expansivities of silicon nitride and bearing steel. As a result lower loads will lead to lower contact stresses and, in turn, longer lubricant life as it has been shown that the rate of tribo-degradation of PFPEs decreases with decreasing stress [7]. It is noted that that the stiffness of HFUC5 at +90°C (14241 Nm/rad) is indeed decreased below that at 20°C (15946 Nm/rad) but that the 90°C value still exceeds that of HFUC1 and HFUC2. The notion that a hybrid-ceramic WG bearing is beneficial to the life of fluid-lubricated HD gears thus remains credible. This improvement might be a result of the smoother surface of silicon nitride balls compared to that of 440C balls (R_a values being respectively 0.008 µm and 0.031 µm for the grade of balls employed). Given that the lubrication mode within the WG bearings is expected to be in the mixed regime at the life test

speed of 50 rpm [1] a smoother ball surface would lead to less asperity-asperity interactions between balls and raceways and a consequent increase in life.
It should be noted that for gearbox operations below room temperature the use of a hybrid-ceramic WG bearing will result in increased internal stresses and presumably reduced lubricant life. More test work is therefore required before it can be concluded that this design of Wave Generator brings benefits below room temperature.

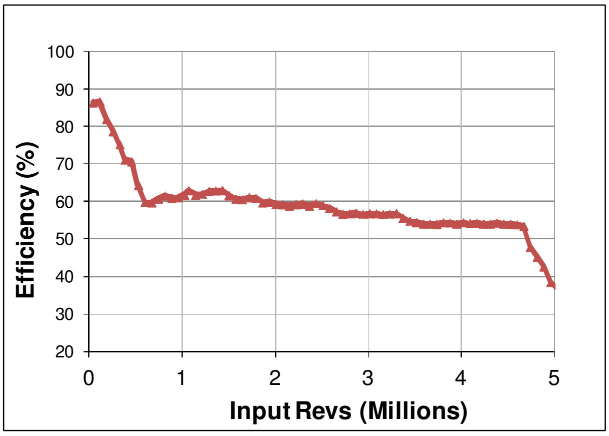
The present test campaign (HFUC5 and 7) also differed to that of HFUC 1 & 2 in that the gearboxes were installed in a customised test box, this having been designed and manufactured by HDAG. Use of this test box removed the need for manual alignment of the input and output halves of the test housings used for HFUC1 and 2 (and indeed HFUC4). Although the alignment specifications were met for HFUC1 and 2 it is noted that the degree of alignment was not as good as that achieved for HFUC5. Whilst the HFUC5 performance was superior to that of HFUC1 and 2, its life (as defined by the number of output revs. achieved at the point when the efficiency has fallen to 40%) was shorter than that achieved with HFUC4 (Fig.8). In the HFUC4 test campaign the gearbox was run-in, cleaned and re-lubricated prior to commencement of the endurance test. Taking all the above observations into account it would seem that, for optimum life, PFPE-lubricated Harmonic Drive® gears should be a) well aligned b) fitted with hybrid ceramic WG bearings and c) run-in, cleaned and re-lubricated.



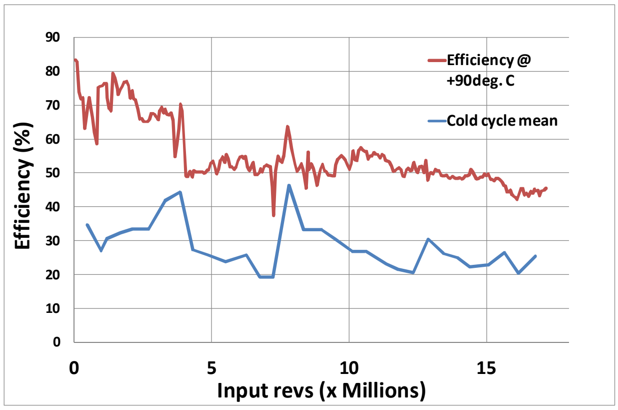
a) Present study (HFUC5)



b) Previous study (HFUC1) [Ref. 3]



c) Previous study (HFUC2) [[Ref.4]



d) Previous study (HFUC4) [Ref.5]

Figure 8. Comparison with previous life-tests on PFPE-lubricated Harmonic Drive® gears

7. CONCLUSIONS

The study, based on in-vacuo life testing of Harmonic Drive® gears at +90°C, showed that:

- For optimum life, PFPE-lubricated Harmonic Drive® gears should be; a) well aligned b) fitted with hybrid ceramic WG bearings and c) run-in, cleaned and re-lubricated. However, more testing on units fitted with hybrid-ceramic bearings is needed before it can be concluded that this design of Wave Generator brings benefits below room temperature.

- The stiffness of Harmonic Drive® gears was measured for the first time during thermal vacuum endurance testing. No evidence for degradation (i.e. reduction in value) of this characteristic, neither for the PFPE – based lubricant nor for the MAC – based lubricant, was found.

- The implementation of load cells within the test box allowed the periodic measurement of axial force acting on the WG bearing. The progressive increase in axial force (and friction coefficient) is interpreted as being due to increasing friction at the FS/WG interface which, in turn, implies a progressive depletion/loss/degradation of lubricant in this area. The fall-off in lubricant performance at this interface is accompanied by metal transfer from the FS bore to the WG OD.

- Operating durations between 12 Million (PFPE – lubricated) and 13 Million (MAC – lubricated) input revolutions were achieved. However, the MAC-lubricated (2001a oil within WG bearing; Maplub SH100b grease elsewhere) Harmonic Drive® gearbox exhibited high efficiency (~80%) at 90°C for appreciably longer than the PFPE-lubricated unit. However, as expected from pour-point considerations, the MAC-lubricated gearbox yielded a significantly lower efficiency at -25°C (compared to PFPE lubrication).

8. REFERENCES

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