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HARMONIC DRIVE GEAR ERROR: CHARACTERIZATION AND COMPENSATION FOR PRECISION POINTING AND TRACKING

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ABSTRACT

Imperfections and geometry effects in harmonic drive gear reducers cause a cyclic gear error, which at a systems level, results in high frequency torque fluctuations. To address this problem, gear error testing was performed on a wide variety of sizes and types of harmonic drives. We found that although all harmonic drives exhibit a significant first harmonic, higher harmonics varied greatly with each unit. From life tests, we found small changes in harmonic content, phase shift, and error magnitude (on the order of .008 degrees peak-to-peak maximum) occurred for drives with many millions of degrees of output travel. Temperature variations also influenced gear error. Over a spread of approximately 56°C (100°F), the error varied in magnitude approximately 20 percent but changed in a repeatable and predictable manner. Concentricity and parallelness tests of harmonic drive parts resulted in showing alignments influence gear error amplitude. Tests on dedoidaled harmonic drives showed little effect on gear error; surprisingly, in one case for a small drive, gear error actually improved. Electronic compensation of gear error in harmonic drives was shown to be substantially effective for units that are first harmonic dominant.

INTRODUCTION

Spacecraft mechanisms of the future are requiring more precise pointing and tracking features while maintaining simplicity, long life, and low weight. One key component that enables space mechanisms to meet these objectives are harmonic drive gear reducers. Shown in Figure 1, harmonic drives are well known for their high gear reduction ratios, low weight, small volume, zero backlash, and high efficiency. For the many beneficial features they possess, there are at least two undesirable characteristics, namely soft torsional stiffness and gear error. Soft torsional windup results in undesirable, low frequency vibration modes in appendages that are susceptible to excitations from gear error or motor ripple torque anomalies. At modal frequencies, the cyclic torque disturbances (or jitter) will resonate payloads and the spacecraft bus. In this article, we discuss gear error in the harmonic drive, what it is sensitive to, and what can be done about it.

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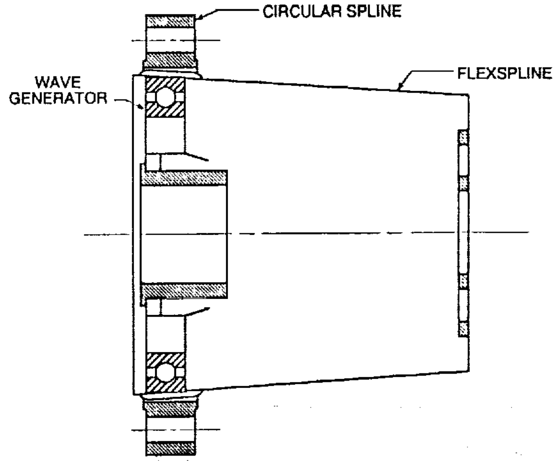

Figure 1 Harmonic Drive Section View

Gear error or positional accuracy is the difference between the theoretical and measured angular position of the input and output of a gear reducer. Typically, we see integer values for a gear ratio. What we actually measure is the integer value plus a small cyclic error imposed upon it. As mentioned previously, this small cyclic error can cause substantial disturbances in appendages.

Sasahara et al. in [1]** documented vibrations in an industrial robot when driven near resonance. Accelerometer data presented showed a beating behavior where the amplitude was influenced by torsional stiffness and circular spline deformation. They concluded that radial tooth errors and tooth meshing composite errors are large contributors to positional accuracy problems. In [2], Ahmadian developed an expression for geometric error in harmonic drives by use of parametric curves to model flexspline deformation. He concluded with a theoretical model that captures the first order effects of gear error behavior due to geometry. A brief, applications oriented discussion on positional error is presented in [3]. Also included is a rough estimating relationship to quantify the error and figures that show the nominal behavior over one revolution of travel.

Harmonic drive gear error could be described in two categories - that caused by internal effects and that caused by external effects. Internal influences are due to geometry, tolerances, tooth shape, and material. The last item has an influence because of machining dimensional stability. External influences on gear error are due to usage and environment such as changes over life, temperature, mounting alignment, incorrect assembly such as dedoidal, over-load effects such as ratcheting, and how error changes with external load.

** Numbers in square brackets refer to references.

MEASUREMENT TECHNIQUES

Figure 2 shows our test setup used for determining positional error. Harmonic drives were mounted in assemblies (actuators) containing a stepper motor and support bearings. Both input and output shaft positions were measured with 19 bit optical encoders. The test was controlled by a PC/AT compatible computer via several interface cards to peripheral devices. Two encoder display readouts were used to visually compare input and output shaft positions. The stepper motor was controlled with an indexer/driver arrangement which allowed the motor to be operated at a selectable power supply voltage and command rate. For life tests, the actuator assembly was enclosed in a vacuum chamber to simulate a spacecraft environment. For thermal tests, the entire encoder/actuator assembly was enclosed in an oven. The majority of measurements were performed at room temperature in a laboratory environment.

Our test procedure involves these basic steps:

1. Zero out input and output encoders at the starting position.
2. Make sure fixture was stable.
3. Step the actuator to a new position by a pre-defined step size.
4. Compare the difference between output and scaled input, this is gear error.
5. Continue steps 3 and 4 for at least one output revolution.

Results were stored on a hard disk, then analyzed and plotted. This setup has proven to be accurate and repeatable for many tests involving harmonic drives.

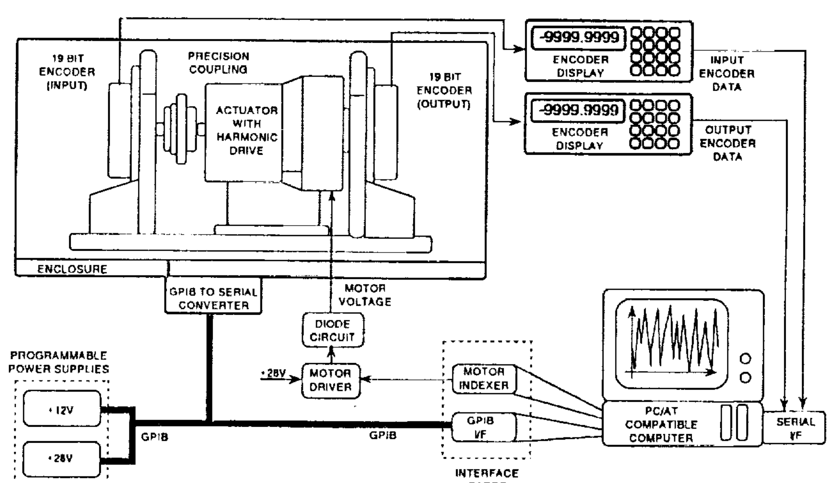

Figure 2 Gear Error Test Station

GEAR ERROR CAUSES

Although a detailed analytical study was not performed with regard to the causes of positional accuracy variations, discussions with harmonic drive manufacturers have indicated some qualitative explanations. For the low cycle beating effect, maximum error is caused by the errors in two parts combining to produce the total error. As the components rotate relative to each other, some errors cancel, which produce the minimum error.

Most of the first through ninth harmonic effects are attributed to:

1. Tooth placement errors on the flexspline.
2. Tooth placement errors on the circular spline.
3. Out-of-roundness of the circular spline.
4. Variation in wall thickness between the flexspline pitch diameter and bore.
5. Flexspline out-of-roundness.
6. Bearing outer race out-of-roundness.
7. Variation in wall thickness between the outer race ball grove and the outside diameter.
8. Lack of concentricity between the flexspline and circular spline in the assembled position.
9. Lack of squareness between the flexspline and circular spline in the assembled position.
10. Fit-up between the flexspline and circular spline teeth in the assembly.

Gear error improves as the harmonic drive size increases. Smaller units become much more sensitive to dimensional tolerances, hence, they are also more likely to contain higher harmonics. A formula given in [3] for the upper bound of positional error is:

$$\epsilon = \frac{8}{d_m} \qquad (1)$$

Where ϵ is the peak-to-peak error in arcminutes and d_m is the pitch diameter in inches. This relationship provides a good estimate for a commercial unit but substantial improvement in performance over this has been demonstrated for flight hardware (typically less than half of the above prediction).

GENERAL CHARACTERISTICS

Harmonic drive positional error is a frustrating phenomenon due to fact that two seemingly identical units may have completely different error signatures. Figures 3 and 4 show such behavior, where for similar units, the second contains harmonics approaching 55 percent of the fundamental. Without a positional accuracy test, one cannot, for example, make simple dimensional checks or get indications of error from other measurements such as friction or stiffness. The general full rotational behavior of gear error is shown in Figure 5. Typically, one sees a characteristic beating amplitude modulated twice per output rotation. There are sometimes exceptions however, as measured in one unit shown in Figure 6. Positional error seems to be independent of gear ratio, but for reference, all units tested in this report had 100:1 reductions. Materials used for the drives in these tests were primarily 304, 17-4, 15-5, or equivalent stainless steels.

"Well-behaved" gear error contains few or no higher harmonics where "poorly-behaved" contains many high frequency components (superimposed upon the fundamental). This qualitative label is given because of the ability to digitize and electronically compensate a given error signature. More discussion on compensation follows in a later section. The harmonic content of a typical gear error plot was analyzed with Fast Fourier Transform software and is shown in Figure 7.

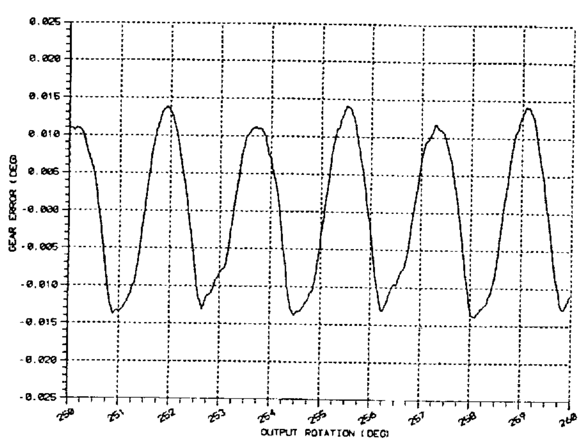

Figure 3 Well-Behaved Gear Error

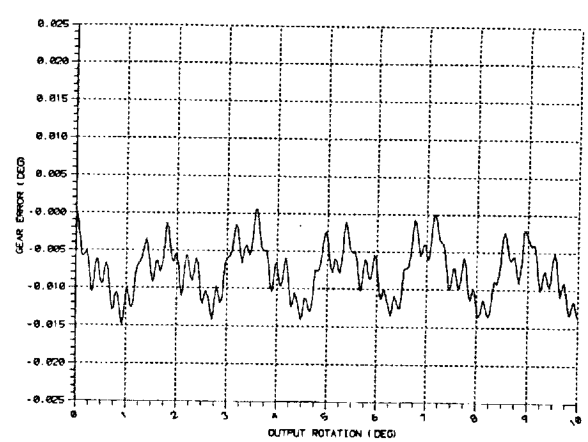

Figure 4 Poorly-Behaved Gear Error

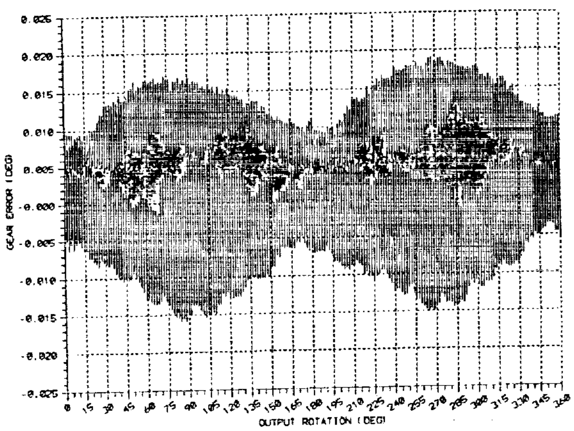

Figure 5 Typical Gear Error Over One Output Revolution

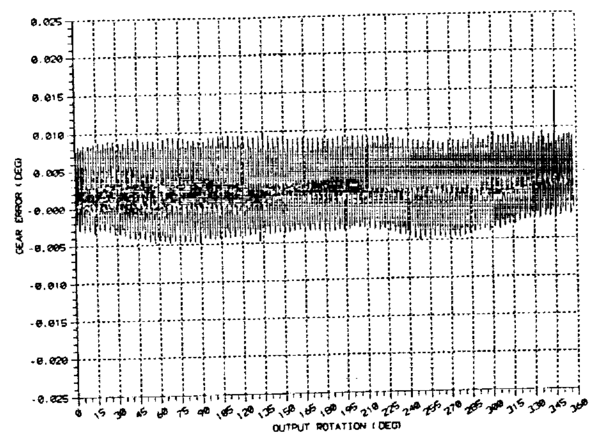

Figure 6 Exceptional Gear Error Over One Output Revolution

Harmonic errors occur in factors of 2 of input rotations. For example in Figure 7, the largest harmonic corresponds to the first harmonic, occurring twice per input rotation. The second harmonic occurs every 4 cycles of input rotation. In many instances we observed a large ninth harmonic, occurring every 18 cycles per input rotation.

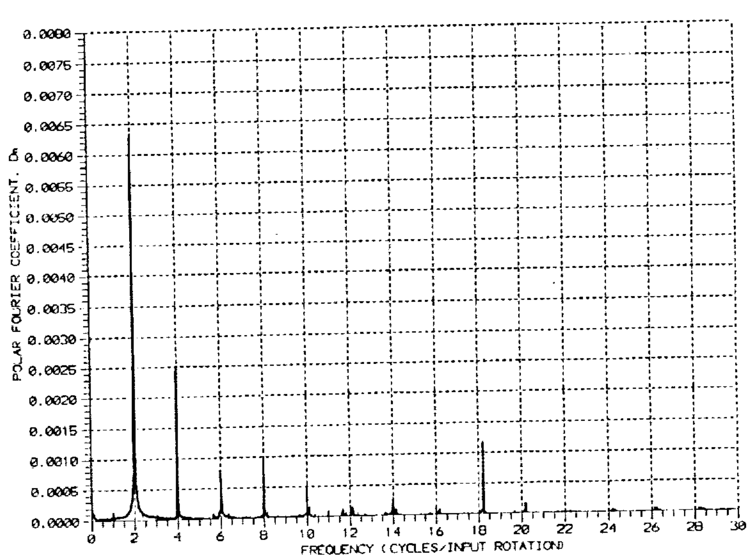

Figure 7 Frequency Plot of Harmonic Drive Gear Error

Recently there have been developments of a new (IH) tooth profile as discussed in [4]. The new tooth, shown in Figure 8, is used with a wave generator plug exhibiting a shape that allows for a higher quantity of teeth to be engaged without "ticking." Ticking is caused when gear teeth tips prematurely collide before engagement. The newer tooth profiles (and perhaps very precise machining) seem to have improved the variation and higher harmonics of gear error for these drives. Figures 9 and 10 show measurements on an IH tooth profile unit. Each IH tooth profile drive tested demonstrates well-behaved gear error. Higher harmonics were present but were observed at very high frequencies. The causes of the high frequency component may be tooth engagement related but are distinctly different from conventional tooth signatures.

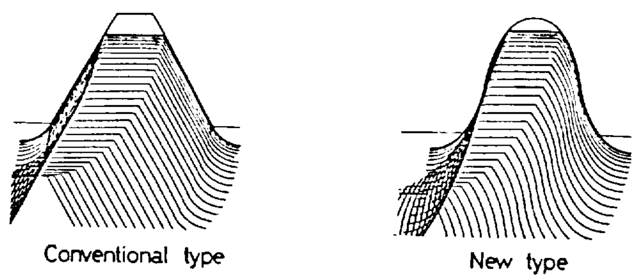

Figure 8 Comparison of Harmonic Drive Tooth Profiles

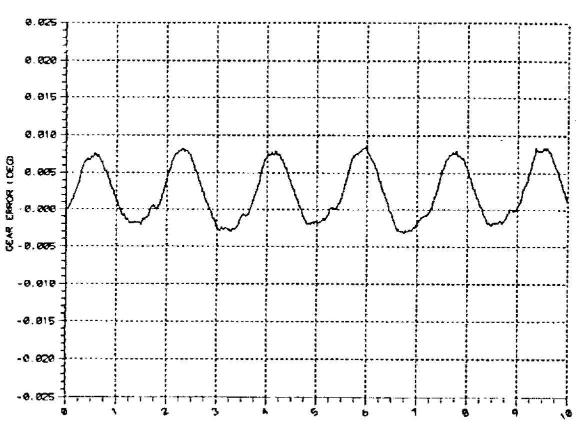

Figure 9 IH Tooth Harmonic Drive Gear Error over One Output Revolution

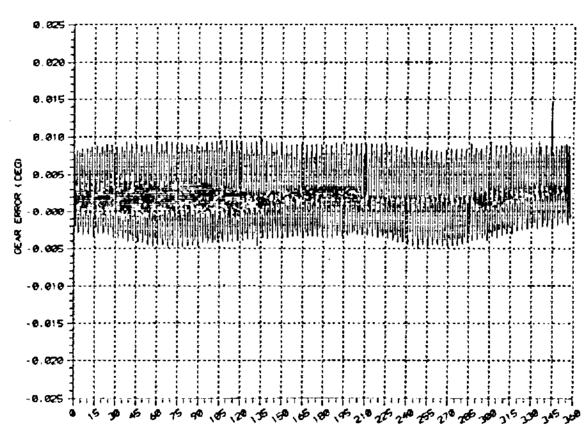

Figure 10 Detailed View of IH Tooth Harmonic Drive Gear Error

BEHAVIOR OVER LIFE

For an electronic compensation scheme to be effective, gear error must be stable in amplitude and phase over life. Several wear tests have shown this to be generally true. Figure 11 shows gear error before and after a life test of many million degrees of output travel.

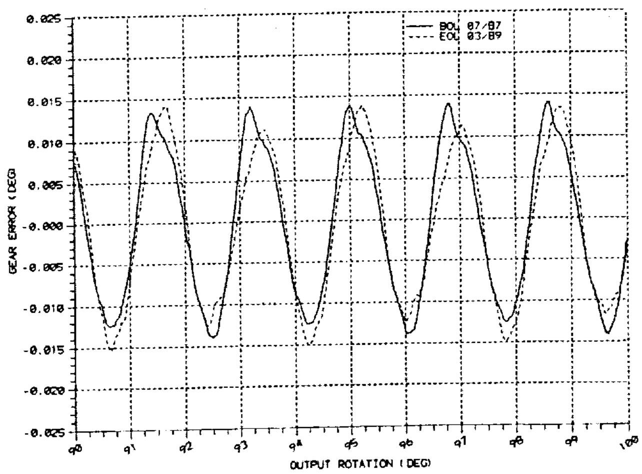

Figure 11 Gear Error Change with Life

Data in Table 1 shows the error measured from life tests. Note that the 8.1 cm (3.2 in) pitch diameter unit used for the life test turned out to have exceptionally small gear error. Very slight changes in the error wave forms did occur with negligible phase shift. Spectral plots shown in Figures 13 and 14 for the 10.2 cm (4.0 in) pitch diameter harmonic drive illustrated how the spectral components changed slightly over life. A slight increase in harmonic content was expected due to generation of wear debris. Wear particles get trapped in the gear teeth and wave generator, thus they affect concentricities and clearances. The counter to this effect is

Table 1 Gear Error Changes from Life Tests

Pitch Diameter	P-P Theoretical Gear Error	P-P Beginning of Life Gear Error	P-P End of Life Gear Error
8.1 cm (3.2 in)	.042 deg	.009 deg	.017 deg
10.2 cm (4.0 in)	.033 deg	.028 deg	.029 deg

removal of material from high and low spots on the gear teeth and interface surfaces. We could, on the other hand, expect this effect to smooth out and reduce the gear error. None-the-less, our only conclusion was that gear error is only slightly affected with life.

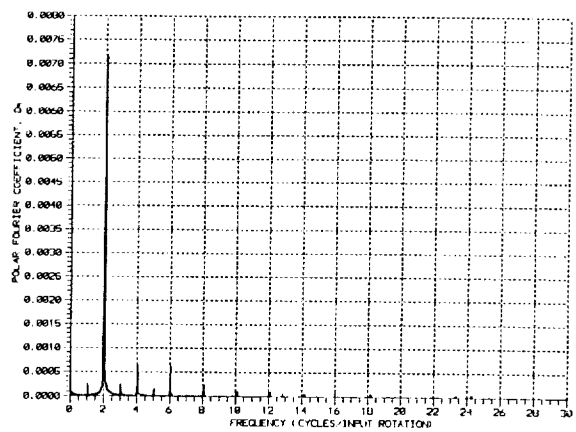

Figure 12 Beginning of Life Gear Error Spectral Content

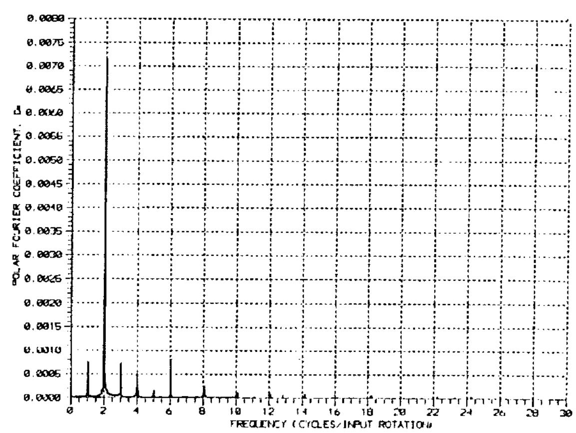

Figure 13 End of Life Gear Error Spectral Content

TEMPERATURE SENSITIVITY

Increasing temperature changes gear error with absolute shifts and small increases of peak-to-peak errors. Harmonic content appears to slightly increase with higher temperatures. Although most of these effects are small, Figures 14, 15, and 16 show the absolute shift and peak-to-peak growth with temperature. Table 2 shows numerically how these variations occurred for this 10.2 cm (4.0 in) pitch diameter test unit. The significance of the absolute error shifts are moot due to the fact that the peak-to-peak oscillations are primarily responsible for dynamic disturbances that concern us. The cause of the error change is unknown, however, similar tests on harmonic drives for stiffness show substantial reductions with increasing temperatures approaching 66°C (150°F).

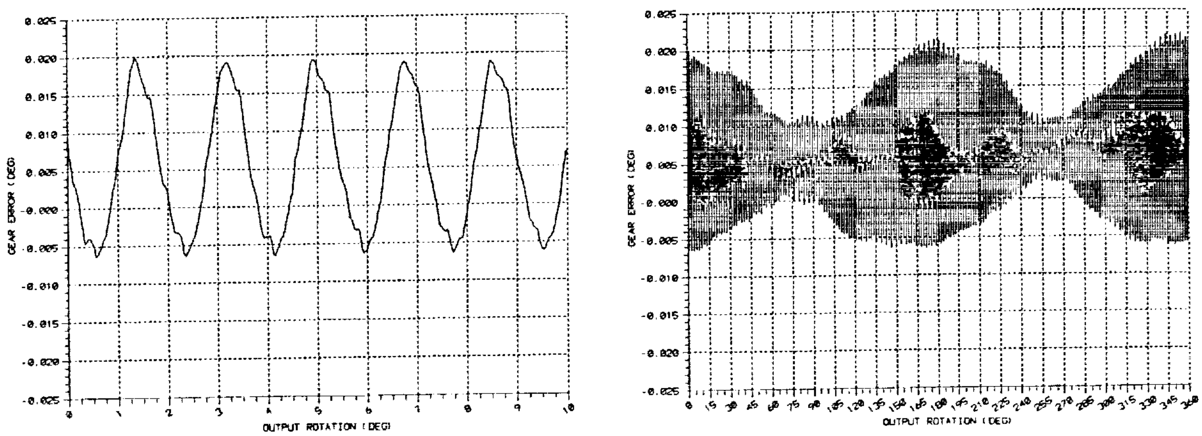

Figure 14 Gear Error Comparison at 52°C (125°F)

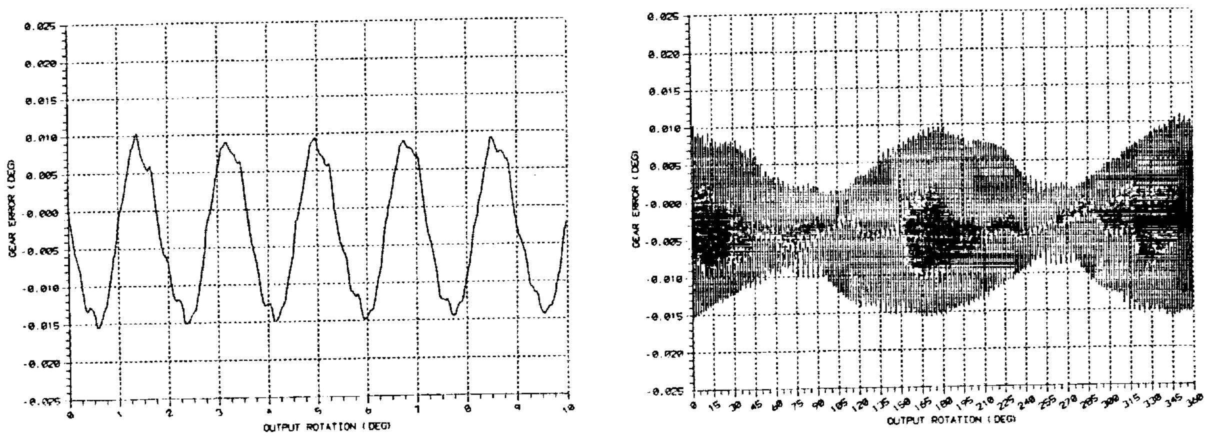

Figure 15 Gear Error Comparison at 24°C (75°F)

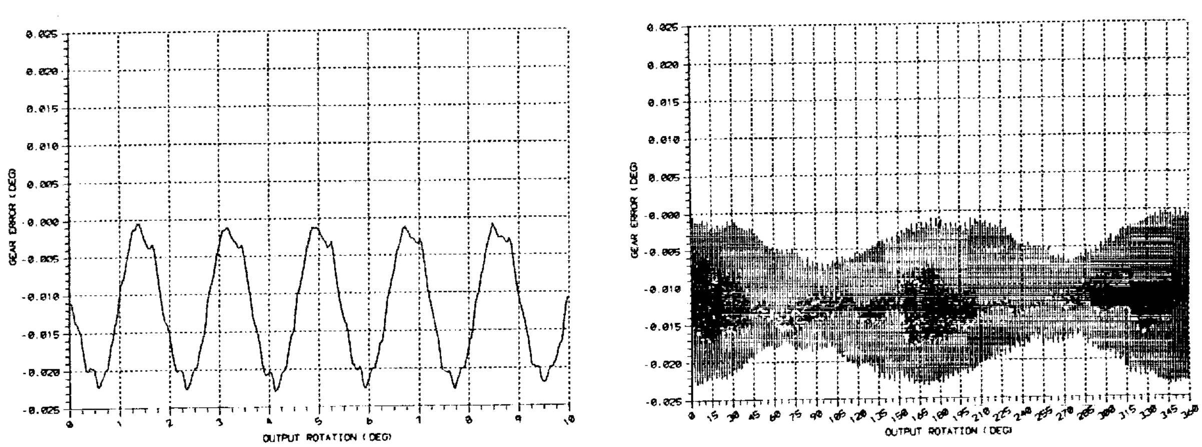

Figure 16 Gear Error Comparison at -1° (30°F)

Table 2 Temperature Effects on Gear Error

Temperature	P-P Theoretical Gear Error	P-P Measured Gear Error	5th Harmonic Polar Fourier Coefficient
52°C (125°F)	.033 deg	.028 deg	.00040
24°C (75°F)	.033 deg	.026 deg	.00035
-1°C (30°F)	.033 deg	.023 deg	.00030

ALIGNMENT SENSITIVITY

Positional error tests were run on a 8.1 cm (3.2 in) pitch diameter unit to determine the importance of concentric and perpendicular mountings. In the first test, several flexspline mounting hubs were intentionally made off-center by a given displacement. Gear error results from this effect are shown in Figure 17. Sensitivity to concentric alignment appears to be relatively small for tolerances that are typical for aerospace assemblies. Commercial products with coarser tolerancing however, could be affected with this runout. The data supports using care in determining concentricity for mounting assemblies.

The second test involved modifying the perpendicularity of the circular spline with respect to the flexspline. Figure 18 shows how gear error increased with mounting angle error. The same conclusion can be drawn as previous, that perpendicularity must be carefully controlled.

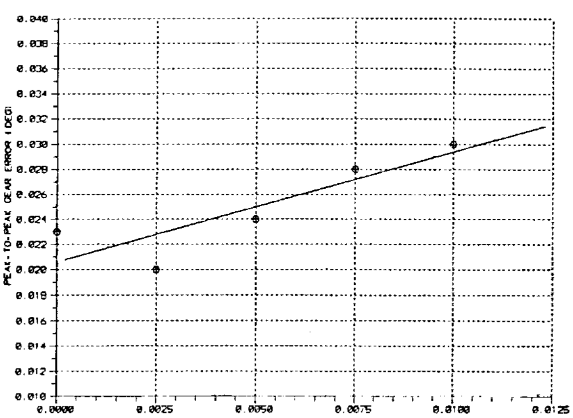

Figure 17 Flexspline and Circular Spline Offset

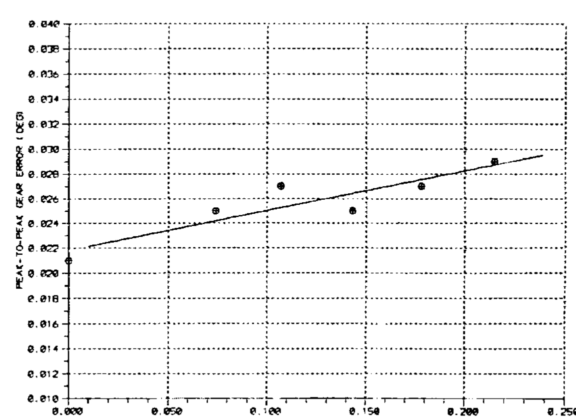

Figure 18 Flexspline and Circular Spline Perpendicularity

EFFECTS OF RATCHET AND DEDOIDAL

Ratcheting is an over-load condition where, due to a high output load, the harmonic drive will slip one or more teeth. Many times this ratcheting will leave the harmonic drive in the dedoidaled condition. Dedoidal is commonly labeled to a harmonic drive where the wave generator and flexspline gears are no longer concentric with the circular spline. Rather than the oval wave generator and flexspline teeth being centered in the circular spline, they are slipped over to one side. This effect is more commonly encountered during incorrect assembly. Symptoms of dedoidal are large variations in starting friction torque and a significantly reduced wear life.

Tests of gear error changes after high loads and ratchet were performed on 3.6 cm (1.4 in) and 8.1 cm (3.2 in) pitch diameter harmonic drives. The smaller units had large gear error prior to testing and did not exhibit the typical modulated two lobed beating pattern as shown for one set of data in Figure 19. Dedoidal conditions did not significantly change the error signatures as seen in Figure 20, but surprisingly, slightly improved the error amplitude. To ratchet our units, the flexspline and circular spline were fixed, and the wave generator was turned until tooth skipping occurred. Each unit was ratcheted at least four times in separate tooth locations with each test resulting in a dedoidaled condition. After ratchet, the gear error again did not seem significantly affected. Figures 21 and 22 show the amplitude and characteristics were comparable, but the dedoidal caused an absolute shift. Tests on the larger units were done in the same manner as the smaller units, but were not torqued to a ratchet condition. Gear error changes were again small. We concluded that gear error is not an effective means to verify the load history of a harmonic drive, nor can it be used to determine dedoidaled conditions.

GEAR ERROR COMPENSATION

Gear error compensation is accomplished by measuring the error of a given harmonic drive and then modifying an input motor voltage appropriately to effect an error cancellation. Figures 23 and 24 show the before and after result of compensation.

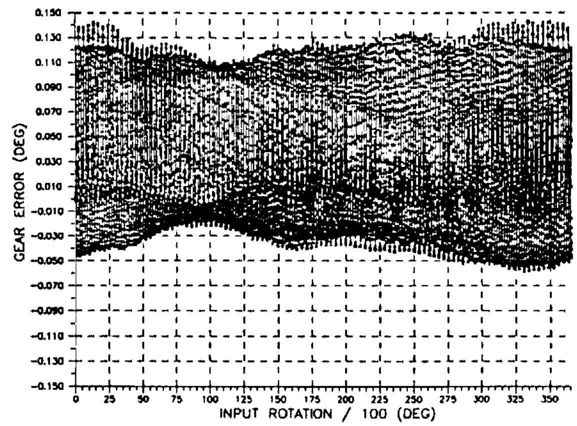

Figure 19 3.6 cm Pitch Diameter Unit, Gear Error Prior to Test

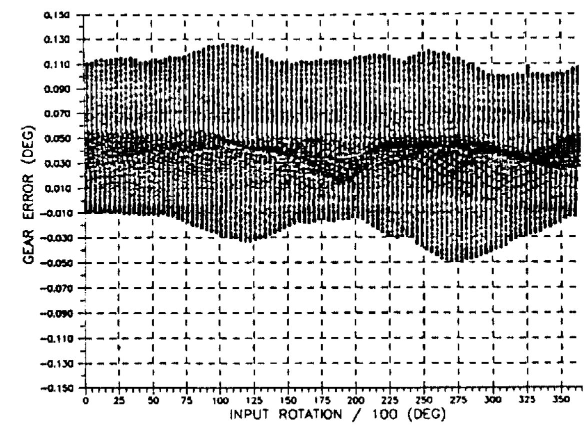

Figure 20 3.6 cm Pitch Diameter Unit Gear Error in Dedoidal Condition

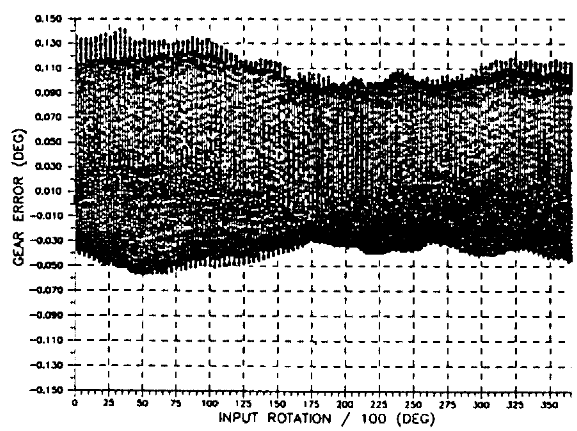

Figure 21 3.6 cm Pitch Diameter Unit Gear Error After Ratchet

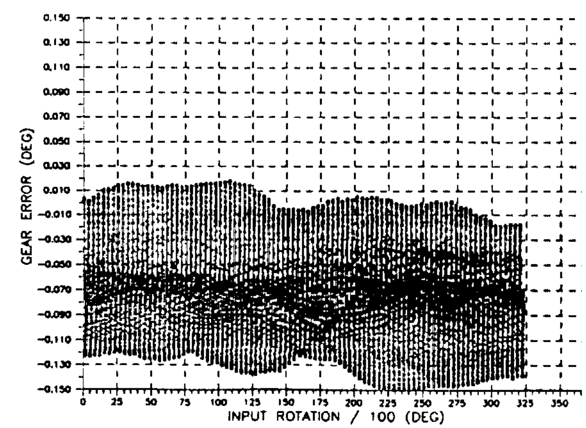

Figure 22 3.6 cm Pitch Diameter Unit, Gear Error After Ratchet in Dedoidal Condition

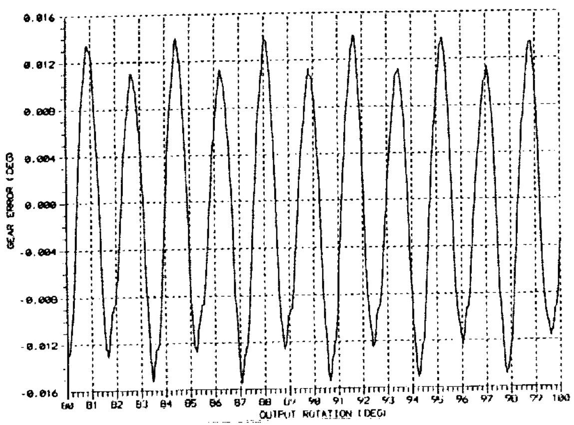

Figure 23 Uncompensated Gear Error

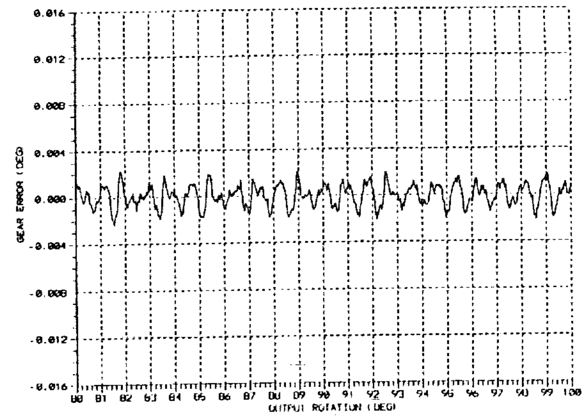

Figure 24 Compensated Gear Error

To implement this scheme, a sine wave excited stepper motor was driven in a variable frequency fashion. This means for one sine wave that would cause 15 degrees of motor output rotation for example, the voltage waveform was artificially shortened or lengthened to effect an output position compensation. Figures 25, 26 and 27 show graphically the compensation effect. Compensation is implemented with a look-up table (and linear interpolation algorithm) that contains sufficient entries to cancel as many higher harmonic terms as desired. For our 15° stepper system with 100:1 gear ratio, we chose one compensation voltage point for every 15 degrees of motor shaft rotation, or 24 entries per revolution. Thus, our compensation table contained 2400 entries.

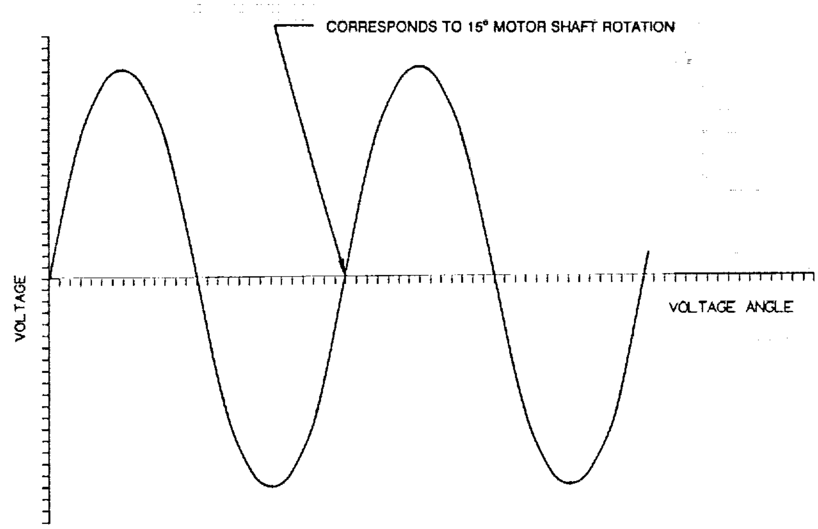

Figure 25 Nominal Motor Input Voltage

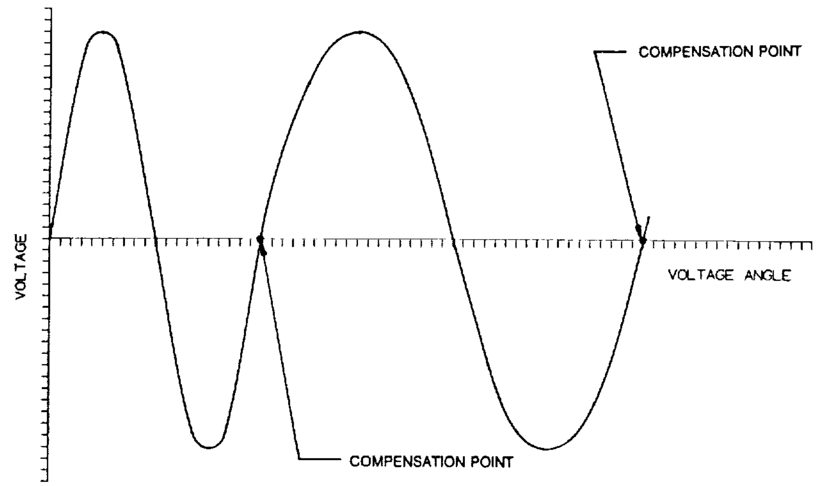

Figure 26 Compensated Motor Input Voltage

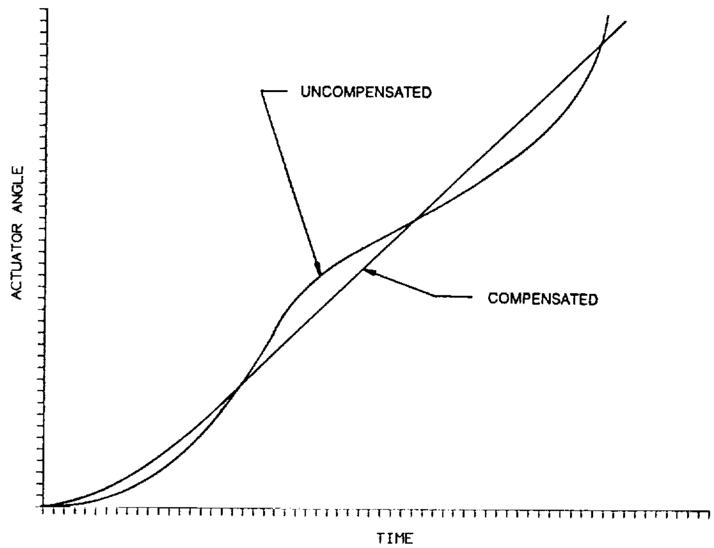

Figure 27 Actuator Output Displacement with Time

The need for "well-behaved" gear error that is first harmonic dominant is now evident. Canceling the higher harmonics is required above the Nyquist frequency. The alternative is a much larger compensation or look-up table. The Nyquist frequency of our system was 12 cycles per revolution of the input shaft, which meant we could cancel up to the sixth harmonic. Some harmonic drives contained a strong ninth harmonic that, with our chosen frequency, could "alias" to below the Nyquist frequency. Higher harmonics such as this were therefore filtered out from the compensation table.

This compensation scheme has worked well provided the harmonic content of gear error does not become too large. The total positional error, which translates into a torque ripple when gimballing a payload, can be typically reduced as much as 80 percent over a non-compensated system. The idea has been implemented on flight hardware to increase pointing/tracking accuracy and reduce on-orbit vibrational disturbances.

SUMMARY

Harmonic drive gear error was studied for the effects of unit size, tooth form, life, temperature, alignment and overload conditions. We verified that gear error decreases with larger size and always demonstrates a significant first harmonic. Life tests showed the error to be fairly stable in amplitude and phase for many million degrees of output travel. Our tests showed gear error increased slightly with temperature and misalignments between components. Overload conditions resulted in little change to gear error signatures, including tests run in the dedoidaled condition. Finally, a compensation scheme was presented that takes measured error anomalies for the gear reducers and electronically corrects for them via the motor driver.

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