Development of Strain Wave Gearing* for Space Flight Application

Harmonic Drive Systems, Inc.
HD Division / Research & Development

*Strain wave gearing is also known as “Harmonic Drive®”

“Harmonic Drive®” is a registered trademark that can be used only on products which are manufactured and sold by Harmonic Drive Systems, Inc.
## Harmonic Drive Systems Inc.

### Business Location
- Head Office: 6-25-3 Minami-Oi, Shinagawa-ku, Tokyo JAPAN
- Hotaka Plant: 1856-1 Hotakamaki, Azumino-shi, Nagano JAPAN
- Sales Office: 6 Business Offices in Japan

### Founded
- October 1970

### Business Domain
- Manufacturing and sales of precision speed reducers

### Capital
- ¥666.8 million

### Net Sales
- ¥13,937 million (FY2005 ended March 31, 2006)

### Employees
- 207 (as of March 31, 2006)

### Domestic Subsidiaries
- HD Logistics, Inc.
- Harmonic Precision Inc.
- Harmonic AD, Inc.

### Overseas Subsidiaries and Affiliates
- Harmonic Drive L. L. C. (Peabody, Massachusetts U.S.A.)
- Harmonic Drive AG (Limburg a.d. Lahn GERMANY)
Key Word: Total Motion Control

- Sensor System
- Harmonic Drive®
- Mechatronics
  - Rotary Actuator
  - Linear Actuator
  - Direct Drive Motor
  - Beam Servo Scanner
- AccuDrive®
Basic gear component of Harmonic Drive®

- Circular Spline
- Flexspline
- Wave Generator
  - Wave Generator Plug
  - Wave Generator bearing
  - Retainer
  - Oldham Coupling
- Retainer
The flexspline is deflected by the wave generator into an elliptical shape causing the flexspline teeth to engage with those of the circular spline at the major axis of the wave generator ellipse, with the teeth completely disengaged across the minor axis of the ellipse.

When the wave generator is rotated clockwise with the circular spline fixed, the flexspline is subjected to elastic deformation and its tooth engagement position moves by turns relative to the circular spline.

When the wave generator rotates 180 degrees clockwise, the flexspline moves counterclockwise by one tooth relative to the circular spline.

When the wave generator rotates one revolution clockwise (360 degrees), the flexspline moves counterclockwise by two teeth relative to the circular spline because the flexspline has two fewer teeth than the circular spline. In general terms, this movement is treated as output power.
Type of Harmonic Drive®

Cup Type
(Cup Style)

Silk Hat Type
(Hollow Shaft Style)

Ring Type
(Pancake Style)
Circumstance of Development Start

- The NASDA authorized parts for space application which make the base technology of space development decreases rapidly by authorization declining etc. (〜2000)
- Task team for space application was organized, and the future parts for space application program was studied. (2001)
- In order to deal with in the long run and systematically, technical committee of parts for space application was established in NASDA. (2002)
- In the committee, HD was authorized as an important part, and the development support was decided. (2003)

Development of Harmonic Drive® for Space Flight Application

- Concept:
  - To develop strain wave gearing as a internationally competitive part for space flight application
Specification (Type, Size, Gear Ratio)

- **Application**: PDM, APM
  - Request: long life, high positioning accuracy, hollow shaft design

  **Long Use Type**
  - Type: SHF, Size: 20, Gear ratio: 1/160
  - (SHF-20-160-2A-GR-SP)

- **Application**: one shot mechanism
  - Request: Light weight, Compact

  **Light Weight Type**
  - Type: CSD, Size: 20, Gear ratio: 1/160
  - (CSD-20-160-2A-GR-SP)
Type of Harmonic Drive®

Cup Type
(Cup Style)

Silk Hat Type
(Hollow Shaft Style)

Ring Type
(Pancake Style)

CS                          CSF                        CSD
SH                          SHF                        SHD
FR                           FR

Light weight type

Long use type
## Requirement

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Long Use Type</th>
<th>Light Weight Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Life</strong></td>
<td>Output Revolution: $1 \times 10^6$ rev</td>
<td>100 Cycles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 cycle: Within 360°</td>
</tr>
<tr>
<td><strong>Lubrication</strong></td>
<td>MAC Grease</td>
<td></td>
</tr>
<tr>
<td><strong>Transmission</strong></td>
<td>Less than 30 arc-sec</td>
<td>Less than 60 arc-sec</td>
</tr>
<tr>
<td>Accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Spring Rate</strong></td>
<td>K1 $1.38 \times 10^4$ Nm/ rad (minimum)</td>
<td>K1 $1.10 \times 10^4$ Nm/ rad (min.)</td>
</tr>
<tr>
<td></td>
<td>(Load Torque: 7.0 Nm )</td>
<td>(Load Torque: 7.0 Nm )</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>Operating: -10° ~ +80°</td>
<td>Operating: -30° ~ +80°</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>Un-operating: -40° ~ +80°</td>
<td>Un-operating: -60° ~ +95°</td>
</tr>
<tr>
<td><strong>Vacuum Pressure</strong></td>
<td>Less than $10^{-4}$ Pa</td>
<td></td>
</tr>
<tr>
<td><strong>Vibration</strong></td>
<td>Sign Wave Vibration $X$, $Y$ and $Z$ axis $10 \sim 100$ Hz 25G</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Random Vibration $X$, $Y$, and $Z$ axis $5 \sim 20$ kHz 21G RMS 180 sec.</td>
<td></td>
</tr>
</tbody>
</table>
Development Flow

1. **Basic test and trial production**
   - Effect of grease quantity
   - Effect of input speed
   - Evaluation of processability

2. **Engineering model test**
   - Vibration test
   - Thermal vacuum test
   - Life test

3. **Qualification Model Test**
   - Vibration test
   - Thermal vacuum test
   - Life test
Result of Basic Test and Trial Production

- **Condition of Engineering Model test**
  - Grease quantity

<table>
<thead>
<tr>
<th>Parts of grease application</th>
<th>Grease quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave Generator bearing</td>
<td>0.1g</td>
</tr>
<tr>
<td>Inside of Flexspline</td>
<td>0.4g</td>
</tr>
<tr>
<td>Teeth Flexspline</td>
<td>0.3g</td>
</tr>
<tr>
<td>Circular Spline</td>
<td>0.3g</td>
</tr>
</tbody>
</table>

- **Input speed**
  - 500 r/min

- **Evaluation of processability**
  - Oil impregnation process
    - It was established.
  - Domestic phenolic material for retainer
    - It was evaluated that domestic material is equivalent to imported material.
Effect of Input Speed

- **Surface of the Flexspline inside after endurance test**

  Wear is concentrate to the opening end side of Flexspline.

  **High Speed**
  
  **Input speed**
  
  **Low Speed**
  
  Wear is generated on the average.

- Inside surface of Flexspline

  Loaded torque: $92$Nm, Total input revolution: $1 \times 10^6$ rev.

  Contact area with Wave Generator bearing

  Diaphragm ↔ Flexspline opening end
## Engineering Model Test

### Test flow

<table>
<thead>
<tr>
<th>Test</th>
<th>Place</th>
<th>Test condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial performance test</td>
<td>HDS Hotaka Factory</td>
<td>Starting Torque, Efficiency, Spring Rate, Transmission Accuracy Under atmospheric pressure</td>
</tr>
<tr>
<td>Vibration test</td>
<td>JAXA TSC</td>
<td>Sign Wave: X, Y, Z axis 5〜100Hz, 0.6〜25G, 2oct/min Random: X, Y, Z axis 5〜2,000Hz 21G RMS 180 sec.</td>
</tr>
<tr>
<td>Thermal vacuum test</td>
<td>JAXA TSC</td>
<td>-10 ℃ to +95 ℃ 1H hold 4cycle, Vacuum pressure: 1 × 10^-4Pa (Max.) Measurement of Efficiency &amp; starting torque on each cycle</td>
</tr>
<tr>
<td>Life test</td>
<td>JAXA TSC</td>
<td>Load Torque: 40 Nm, 20Nm one direction, continuous Input speed: 500 rpm Vacuum pressure: 1 × 10^-4Pa (Max.)</td>
</tr>
</tbody>
</table>
**EM Test (Life Test)**

### Test Condition

<table>
<thead>
<tr>
<th></th>
<th>No.1</th>
<th>No.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmonic Drive®</td>
<td>Long Use Type (SHF-20-160-2A-GR-SP)</td>
<td></td>
</tr>
<tr>
<td>Lubrication</td>
<td>MAC grease</td>
<td></td>
</tr>
<tr>
<td>Input speed</td>
<td>500 r/min CW continuous</td>
<td></td>
</tr>
<tr>
<td>Loaded torque</td>
<td>40Nm continuous</td>
<td>20Nm continuous</td>
</tr>
<tr>
<td>Temperature</td>
<td>Room temperature</td>
<td></td>
</tr>
<tr>
<td>Vacuum Pressure</td>
<td>Less than $1 \times 10^{-4}$ Pa</td>
<td></td>
</tr>
<tr>
<td>Verification</td>
<td>Efficiency, Increase of Lost Motion</td>
<td></td>
</tr>
<tr>
<td>Requested life</td>
<td>$1 \times 10^6$ rev. (output total revolution)</td>
<td></td>
</tr>
</tbody>
</table>
**EM Test (Life Test)**

- **Efficiency under life test (No.1)**
  - Lubricant: MAC grease, Loaded torque: 40 Nm, Input speed: 500 r/min

![Graph](image)

- Test was stopped because of efficiency drop. (Test jig input bearing was damaged.)
- Lost Motion was measured at these points.

Efficiency: 5346 rev. (output total revolution)
EM Test (Life Test)

- Efficiency under life test (No.2)
  Lubricant: MAC grease, Loaded torque: 20 Nm, Input speed: 500 r/min

Test jig input bearing was replaced.
Lost motion was measured at these point.

13513 rev. (output total revolution)
Test was stopped because of efficiency drop.
EM Test (Life Test)

- Flexspline after life test (No.2)

Flexspline inner surface

Flexspline tooth
EM Test (Life Test)

Wave Generator after test (No.2)

Wave Generator after life test

Wave Generator bearing balls

Outer surface of Wave Generator bearing outer race
## Results of Life Test

<table>
<thead>
<tr>
<th>No.</th>
<th>Test condition</th>
<th>Output total revolution</th>
<th>Results</th>
</tr>
</thead>
</table>
| No.1 | Output torque: 40Nm  
      Input speed: 500 r/min | (5346 rev.)  
This test was stopped because of efficiency drop, but it found the cause was damage of jig bearing by investigation after test. | • The cause of efficiency drop was loss torque of input jig bearing.  
• Harmonic Drive can still on operate though wear can be seen on the inside of Flexspline. |
| No.2 | Output torque: 20Nm  
      Input speed: 500 r/min | 13513 rev. | • The test was stopped because the efficiency drop rapidly.  
• Remarkable wear can be seen on the Circular Spline teeth, Flexspline teeth and inside and outside of Wave Generator bearing outer race. |
EM Test (Life Test)

- **Expected life**

  ![Graph showing expected life vs. output torque (continuous) [Nm].](image)

  - **Life requirement**
  - **Expected life**
  - **EM test result**

  W/G total revolution [rev]

  Output torque (continuous) [Nm]
Conclusion

- There is no damage of Harmonic Drive under vibration test and thermal vacuum test.
- Lubrication under vacuum environment is a much tougher condition more than under atmosphere.
- To satisfy the life requirement, operating torque should be lowered.
- Process from wear start to the end of life should be investigate in future development.
FNE MECHANICS & TOTAL MOTION CONTROL