DEVELOPMENT OF THE HARMONIC DRIVE GEAR FOR SPACE APPLICATIONS

Keiji Ueura* & Dr. Rolf Slatter**

*Harmonic Drive Systems Inc.
Minamiohi 6-25-3, Shinagawa-ku, Tokyo 140, Japan
Telephone: (81) 3-5471-7800/ Fax: (81) 3-5471-7811
E-mail: ueura@hds.co.jp

**Harmonic Drive Antriebstechnik GmbH
Hoenbergstrasse 14, 65555 Limburg, Germany
Telephone: (49) 6431-5008-21 / Fax: (49) 6431-5008-18
E-mail: slatter@harmonicdrive.de

ABSTRACT

It is now more than 25 years since the first harmonic drive gears were used in space during the Apollo 15 mission. This unique gear principle has since repeatedly proven its performance and reliability in a wide range of space applications. The harmonic drive is a backlash-free precision gear and is unusual in using an elastically deformable component to achieve a high reduction ratio in just a single gear stage with only 3 basic gear components. The harmonic drive gear is the subject of continuous development in both Japan and Germany and in this paper the latest advances, with particular emphasis on improved performance characteristics, reduced size and reduced weight, will be presented.

1. A BRIEF HISTORY OF THE HARMONIC DRIVE GEAR

The performance requirements of space vehicles are increasing steadily. This would not be possible without continuous improvements from the applied gear and actuator technology. Precision gears and actuators must fulfil a complex set of requirements – they must provide high positioning accuracy and repeatability, high torque capacity and high torsional stiffness, a compact and light design at a competitive price.

These requirements have led to significant further development of the harmonic drive gear. This gear type, also known as „strain wave gearing“ is a standard transmission component in a wide range of application areas, from industrial robots and machine tools to printing machines, medical equipment and machines for semi-conductor manufacturing.

Invented in 1959 by Walt Musser in the United States, the harmonic drive gear was first applied in aircraft and defence applications. The reliability, low weight and compact design were unique advantages that soon established this new gear principle in these fields. In the 1970s and 1980s the range of applications extended into industrial robotics and machine tools, where the harmonic drive has become *de facto* the standard for precise positioning drives. The 1990s have seen a rapid increase in applications as requirements for increased accuracy and improved dynamic performance have necessitated the use of high quality gears and actuators, in fields as diverse as surgical robotics, measuring machines and silicon wafer processing equipment.

From its origins in aerospace the harmonic drive gear has now established itself in this field as the ideal solution in a wide range of different uses. The first major space application was in 1971 as the mechanical tranmission element within the individual wheel drives of the Lunar Roving Vehicle on the Apollo 15 mission This application tbrought this unique gear principle into the public eye for the first time. Soon afterwards harmonic drive gears were applied as part of the telescope drive actuator for the imaging photopolarimeter that flew on NASA‘s Pioneer 10 planetary probe, launched in March 1972. In 1984 this actuator was still working perfectly as Pioneer left the Solar System. At that time the hermetic sealing possible with the harmonic drive gear was an important additional attribute, given the high vapour pressure and migrating tendencies of the silicone-based lubricants then used.

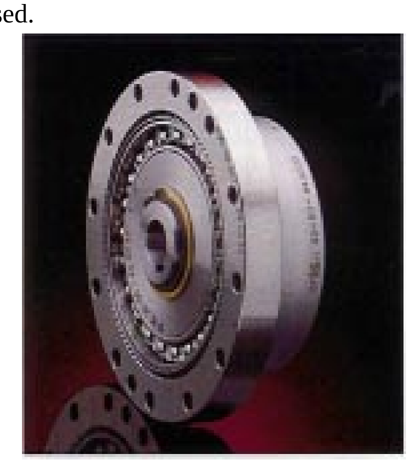

Figure 1. Harmonic drive component set

In the meantime this gear has become the preferred solution for compact, powerful positioning drives with references including the Hubble space telescope and the Mars Pathfinder mission.

2. PRINCIPLE OF OPERATION

The harmonic drive gear is unique in transmitting high torque through an elastically deformable component. The gear has just three concentric elements:

- The *Circular Spline* (CS) is a solid cylindrical ring with internal gear teeth.
- The *Flexspline* (FS) is a non-rigid, thin cylindrical cup with external teeth at the open end of the cup. The closed end of the cup is provided with a flange connection to following machine elements.
- The *Wave Generator* (WG) comprises a thin-raced ball bearing fitted onto an elliptical plug, serving as a high efficiency torque converter.

Figure 2. Basic gear components

These three basic components function in the following way:

1. The Flexspline is slightly smaller in diameter than the circular spline and usually has two fewer teeth than the CS. The elliptical shape of the Wave Generator causes the the teeth of the FS to engage the CS at two regions at opposite ends of the major axis of the ellipse.
2. As the WG (input) rotates, the zone of tooth engagement travels with the major axis of the ellipse.
3. For each 180^{o} clockwise movement of the WG, the FS (output) moves counterclockwise by one tooth relative to the CS (fixed).
4. Each complete clockwise rotation of the WG results in the FS moving counterlockwise by two teeth from its previous position relative to the CS.

The reduction ratio is therefore not a function of the relative sizes of the toothed components, as is the case for spur gears or planetary gears, but simply of the number of teeth.

where i = reduction ratio (input speed/output speed)

$$i = \frac{n_{fs}}{n_{cs} - n_{fs}}$$

n_{cs} = number of CS teeth
n_{fs} = number of FS teeth

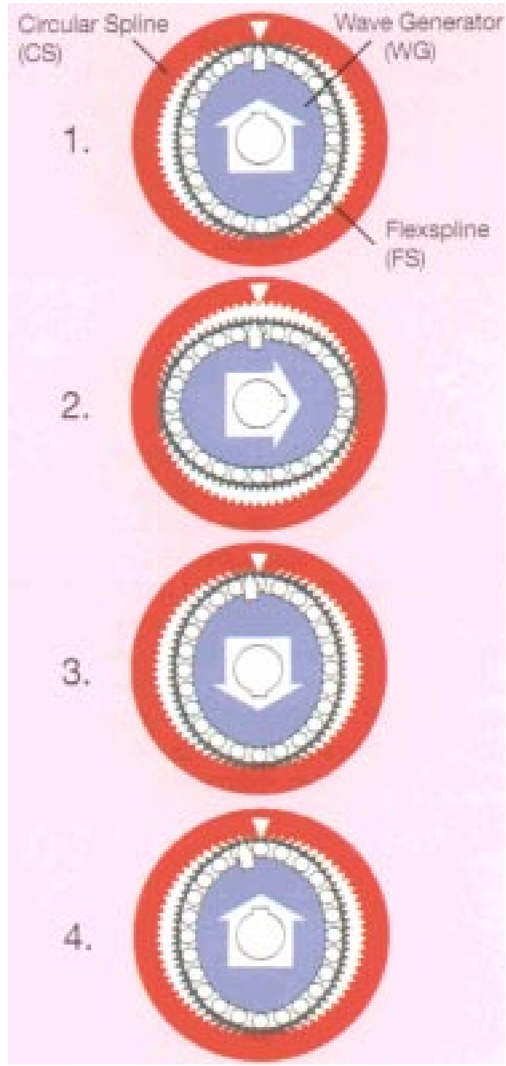

Figure 3. Principle of operation

Using this principle of operation, reduction ratios of 30:1 to 320:1 can be achieved with just three basic components. Gears are available with outer diameters from 20 to 330 mm with a peak torque capacity from 0.5 to more than 9000 Nm respectively.

3. KEY FEATURES

Compared to conventional gearing the harmonic drive gear offers the user a number of significant advantages.

The key feature is the exceptionally *high positioning accuracy and repeatability*. This is the result of the high transmission accuracy, which is better than 30 arc seconds for standard series gears. For selected gears a transmission accuracy of better than 20 arc seconds is possible. Due to the small number of basic components and the multiple tooth engagement, the transmission accuracy is not so dependent on the accuracy of many gear components or on individual tooth pitch errors.

Due to the very low hysteresis losses a repeatability of +/- 5 arc seconds is achieved for standard series gears. For selected gears a repeatability better than +/- 3 arc seconds is possible. These values are assisted by the fact that the harmonic drive gear can operate with *zero backlash*. Due to natural radial pre-loading in the region of tooth engagement, the gear operates without backlash.

Since power is transmitted through multiple tooth engagement, harmonic drive gears offer a very *high torque capacity*, equal to conventional drives twice its size and three times its weight

Harmonic drive gears exhibit very *high torsional stiffness* with an almost linear stiffness characteristic. The *hysteresis* losses are also extremely low, which reflects the very low internal friction within the gear assembly. For conventional gears backlash can usually only be removed by means of external pre-loading, which then results in increased hysteresis losses and increased lost motion.

Compared to other high ratio gears the *efficiency* of the harmonic drive gear is very high. An efficiency of over 80% is typical for a gear with ratio 100:1 at rated torque and rated input speed.

As indicated above, the high efficiency and low hysteresis losses show that there is very *low friction* within the gear. The teeth come into contact with an almost pure radial motion, and have essentially zero sliding velocity, even at high input speeds. Tooth friction losses and wear are thus negligible. As a result, there is no increase in backlash during the operating life of the gear, as long as the manufacturer's guidelines for assembly and lubrication are fulfilled.

The high efficiency as a speed reducer also means that the gear is *reversible*. In an emergency situation it is possible to back-drive the gear.

For space applications the *compact, lightweight design* are particularly important, as well as the *design flexibility* offered by this principle. As will be seen later, all the basic gear components can be readily modified to reduce weight, and can be manufactured in materials suitable for space applications.

4. DEVELOPMENT THEMES

The harmonic drive gear is the subject of continuous development, due to new market requirements from each of the major application areas. Common requirements are the desire for higher power density, higher torsional stiffness and lower ratios.

There are therefore four key themes driving current product development

- Reduced size
- Reduced weight
- Increased torsional stiffness
- Ratios below 50:1

4.1 Improvement of the tooth profile

The development of the tooth profile is a key development area. It was recognized early that many properties of the harmonic drive gear can be improved by means of an optimisation of the tooth profile. Complex calculations, computer simulations of the tooth engagement locus and exhaustive tests provided the basis for an improved tooth profile, the IH profile, which was patented in 1989 and has been steadily further developed since.

As shown in Figure 4, the area of tooth engagement is considerably larger for the IH profile. For the conventional involute tooth profile ca. 15% of teeth are in simultaneous contact, while for the IH profile this proportion increases to ca. 30%

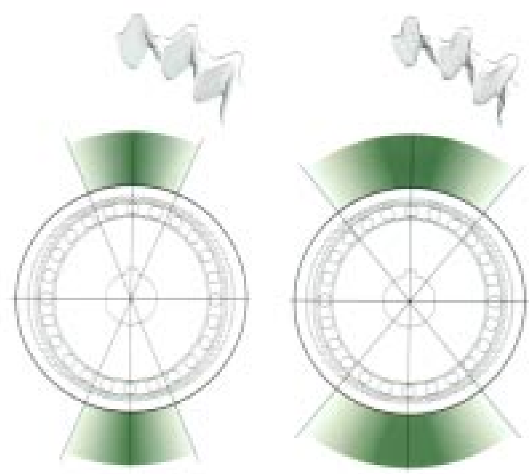

Figure 4. Comparison of involute and IH tooth profiles

This development brings three significant advantages:

1. The torsional stiffness of the gear is primarily dependent on the number of teeth in contact. The increase in the area of tooth engagement leads to a doubling of the torsional stiffness of the gear.
2. The operating life of the gear is determined by the wave generator bearing. The increased area of tooth engagement leads to a more even loading of the bearing, which in turn leads to a doubling of the operating life.
3. The larger tooth root radius of the IH profile reduces the critical stress in the flexspline and so leads to a significant increase in torque capacity within the same gear envelope.

4.2 Low ratio harmonic drive

Until recently the ratio 50:1 was the lower limit for harmonic drive gears. For low reduction ratios the number of FS and CS teeth is smaller than for higher ratios (see equation for reduction ratio above). The teeth are larger and therefore require a larger deflection of the flexspline (across the minor axis of the ellipse) to bring the teeth out of engagement. The higher stress associated with this deflection has previously limited the lowest ratio that can be practically realized to 50:1. Extensive FEM analysis of the flexspline cup and optimization of the tooth profile has now made the ratio 30:1 possible. This opens up new applications where the user requires the benefits of the harmonic drive gear with a lower reduction ratio.

4.3 New flexspline design

Another key development theme is the reduction in the axial length of the flexspline cup. As can be seen in Figure 5, the axial length of the HDUC-type gear could be reduced by 40% with the introduction of the short flexspline HFUC-type gear. This reduction in axial length has also enabled a 20% reduction in weight for the same torque capacity.

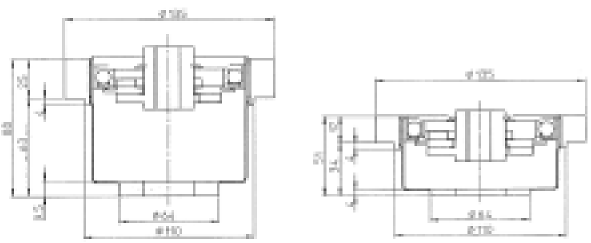

Figure 5. Short flexspline design

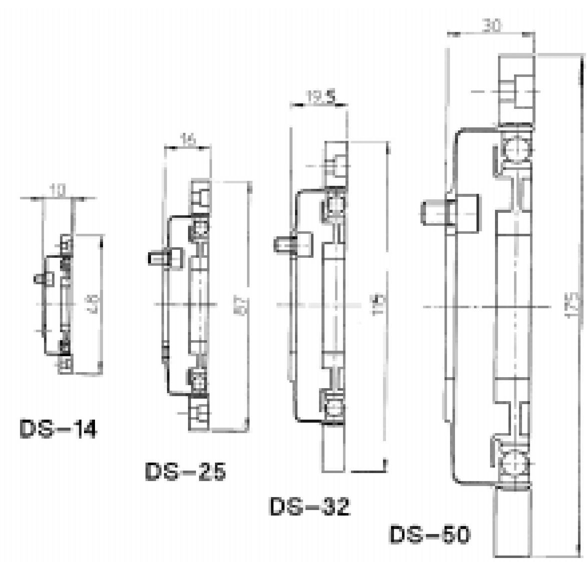

Figure 6. „Super-Flat“ component set design

The FEM analysis that supported the introduction of the HFUC-type gear is also the basis for the new „super-flat“ component set, shown in Figure 6. The axial length of the flexspline cup could be reduced once again and is just over 50% of the length of the HFUC-type gear. The increased conical deformation of the cup means that the torque capacity is reduced slightly compared to the standard gear.

4.4 Lightweight component set design

Particularly in the field of robotics, whether for terrestrial or space applications, the market requirement is for higher power density. The development of lightweight gears is therefore a further key development area. There are three basic methods for reducing the weight of the gear and/or the surrounding machine elements in the user machine:

1. Modification of the individual gear components, to simplify the integration of the gear and so reduce the weight of the surrounding machine elements
2. Integration of spur- or planetary-gear stages within the harmonic drive gear, in order to realise very high reduction ratios in the smallest possible envelope. This allows small, high speed motors to be used, so optimising the power density of the complete gear-motor assembly.
3. Application of new materials for the individual gear components, in order to minimise the weight of the gear itself.

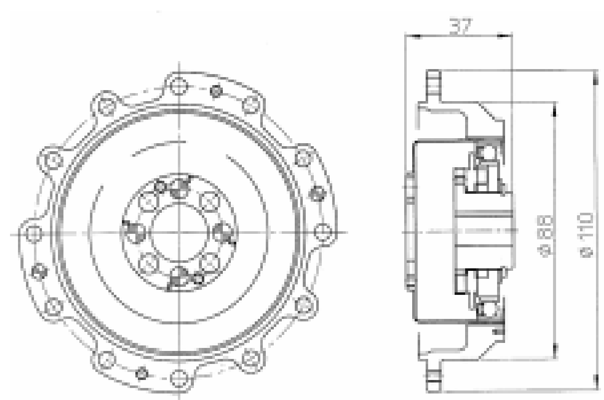

Figure 7. Component set with modified circular spline

Figure 7 shows a special design, where the Circular Spline has been strongly modified to simplify the integration of the gear into the joints of a telerobotic manipulator.

Figuer 8 shows a further design example, where a planetary-gear stage has been integrated within the elliptical wave generator plug. This design makes use of the space available within the flexspline to achieve a total reduction ratio of 800:1 in a very small envelope. Here, too, the circular spline has been modified to simplify integration within the joint of a portable service robot.

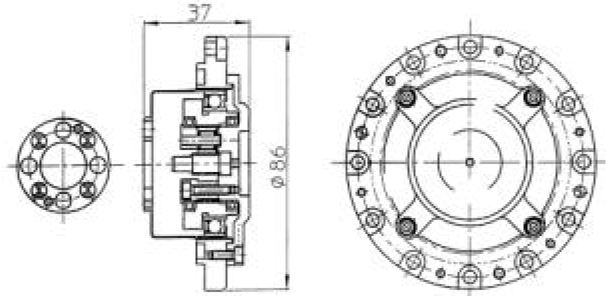

Figure 8. Component set with planetary pre-stage

Figure 9 shows the latest development in this area. Both the Circular Spline and Wave Generator plug of the lightweight component set are manufactured from aluminium alloy. The teeth of the circular spline are coated using a patented principle to achieve the same load carrying capacity as the standard gear teeth. As can be seen from Table 1, the weight of the gear can be reduced by 60% leading to an increase in specific torque capacity of 266%.

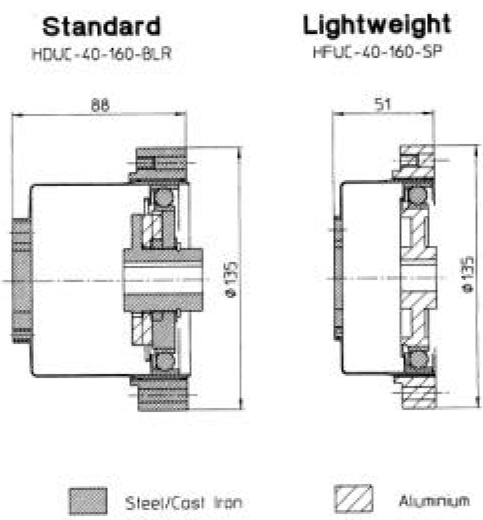

Figure 9. Application of lightweight materials

		Standard gear HDUC-40-160-BLR	Lightweight gear HFUC-40-160-SP	Trend
Rated torque	[Nm]	294	294	=
Peak torque	[Nm]	559	559	=
Moment of inertia	[x 10^{-4} kgm^2]	3.98	1.60	-60%
Weight	[kg]	2.10	0.79	-60%
Specific peak torque	[Nm/kg]	266	708	+266%

Table 1. Comparison of standard and lightweight gears

5. SPECIAL CONSIDERATIONS FOR SPACE APPLICATIONS

There are three main areas where the design of standard industrial gears must be modified to suit the requirements of space applications:

- Material Selection
- Mechanical Design
- Lubrication

5.1 Material selection

For space applications harmonic drive component sets are typically manufactured from stainless steel. This material has the benefit of better corrosion resistance, higher rigidity, higher hardness and lower coefficient of thermal expansion compared to the conventional gear materials listed in Table 2.

Stainless steel gears have been the subject of extensive testing. Fatigue testing shows that similar performance to standard materials can be achieved, in terms of torque capacity. Furthermore, durability tests have also indicated similar performance to standard materials.

	Standard Gear	Space Specification Gear
Circular Spline	FCD 80 Ductile Iron	SUS 630 Stainless Steel
Flexspline	SNCM 439 Alloy Steel	SUS 304L or 15-5PH Stainless Steel
Wave Bearing	SUJ 2 Bearing Steel	SUS 440C Stainless Steel
Wave Plug	S 45 C Carbon Steel	SUS 630 or SUS 304L Stainless Steel
Bearing Retainer	Nylon 66 with glass-fibre reinforcement	Phenolic Resin

Table 2. Comparison of gear materials

5.2 Mechanical design

As indicated above, FEM analysis enables an optimisation of each individual gear component in order to reduce weight. The weight of the Circular Spline can be reduced by reducing its thickness by removing material from both sides. It is also possible to reduce the width of the CS teeth. The weight of the Flexspline can be lowered by reducing the thickness of the flange at the closed end of the cup. It is also possible to reduce the weight of the Wave Generator by removing the oldham coupling, that is usually integrated within the plug, and optimising the cross-sectional profile.

5.3 Lubrication

A variety of different lubricants have been used successfully with harmonic drive gears in space. Different lubricants can be used for the wave generator bearing and the gear teeth.

For the wave generator bearing, perfluorinated oil e.g. Fomblin Z25 or Brayco 815Z, is typically used. The phenolic resin bearing retainer is impregnated with oil in a vacuum environment. The gear teeth are typically lubricated with grease e.g. Braycote 601. Gold-plating has been used to support the grease lubrication of gear teeth. Similarly, silver ion plating of the inner and outer bearing races and also of the wave generator balls has been undertaken.

Initial experiments at ESTL with sputtered and spray-bonded MoS_2 were not successful, but tests are continuing at both Japanese and German research facilities to reserach appropriate dry lubricants for harmonic drive gears.

6. APPLICATIONS

As indicated above, there is now a wide range of different applications for harmonic drive gears in space. The following are just a few recent examples that show the versatility of this unique gear operating principle.

6.1 Lander Applications

An important recent application was on the Mars Pathfinder mission. The lander consists of a base plate and three petals. In order to orient the lander each petal was deployed by means of a petal actuator mounted at the hinge connecting the petal to the base petal. Each of the three actuators is a high-torque mechanism comprising a brushless DC gearmotor, spur gear, clutch and harmonic drive gear with ratio 160:1. The complete actuator weighs just 5.7 kg yet was performance tested to an output torque of more than 1200 Nm.

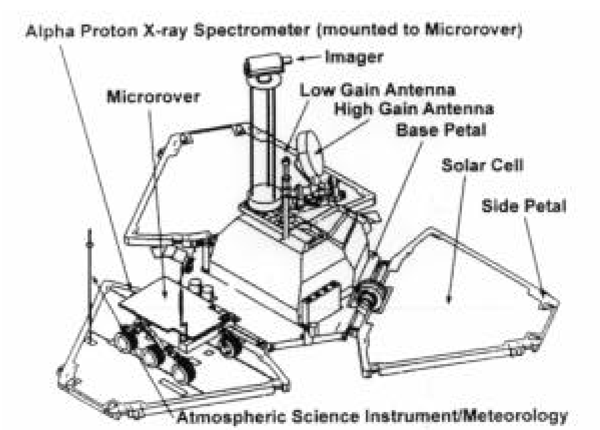

Figure 10. Pathfinder Lander
(Diagram courtesy of JPL/NASA)

6.2 Rover Applications

The Lunar Roving Vehicle wheel drive was the application that first brought the harmonic drive principle into the public eye. Planetary rovers continue to be important application area.

An important current project is the Nomad four-wheeled robot, designed to traverse planetary analogous terrain. This vehicle features individual propulsion drive units that reside inside the wheel. This configuration has the advantages of sealed drive units, identical drive components, simplicity and improved motion control. Each drive unit contains a brushless DC motor and harmonic drive gear.

Figure 11. Nomad Planetary Rover
(Photograph courtesy of NASA Ames Research Centre)

6.3 Satellite Applications

Harmonic drive gears have a wide range of applications in positioning drive mechanisms for solar arrays, antennae, mirrors, instruments, video cameras, as well as in one-shot applications such as latch actuators.

A typical application is in an electro-mechanical actuator used in the SS/L401S satellite, originally developed as a low-cost platform for the Globalstar worldwide digital telephone system with an initial production run of 64 spacecraft.

Figure 12. Actuator for Globalstar Satellite
(Photograph courtesy of Space Systems Loral)

7. CONCLUSION

In the 25 years since harmonic drive gears were first used in space this unique gear principle has established itself as a precise and extremely reliable solution. The new developments described in this paper offer a variety of performance benefits that will open up even more application possibilities.