# LIGHTWEIGHT HARMONIC DRIVE GEARS FOR NEXT GENERATION ROBOTS


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***ABSTRACT***

*The Harmonic Drive gear has become established as a "classic" robot gear, featuring zero backlash, high single-stage ratios, compact dimensions and a high torque capacity. Nearly all the world's leading robot manufacturers apply Harmonic Drive gears in one or more of their robot versions. It is the subject of continuous development, which has led to a substantial increase in performance due to new tooth profiles, new component designs and other innovations. In the past few years the torque capacity, operating life and torsional stiffness have been more than doubled by these developments.*

*For new robotic applications lightweight design is becoming particularly important, so the development engineers at Harmonic Drive AG have recently focused on this subject. During the past 3 years a German state-funded research project has investigated the design and development of lightweight Harmonic Drive gears. The basic target has been to save more than 50% in weight, without negatively influencing other gear specifications, such as torque capacity or accuracy.*

*This paper reviews the basic principles of Harmonic Drive technology and then describe the various approaches to reduce weight. These include the use of non-ferrous metals, composite materials and new tribological coatings.*

*The results of this research project are very positive and the basic elements from this research are already being used in both industrial robots and also a number of leading robotic research projects in the field of walking machines.*

*Following a description of these applications and the advantages brought by lightweight gears the paper concludes with a vision of further weight-reducing techniques.*


## BRIEF HISTORY OF THE HARMONIC DRIVE GEAR

The performance capabilities of robots are increasing rapidly. This would not be possible without continuous improvements from the applied technologies and systems. This holds both for industrial and service robots. The gears and actuators used 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 with high reliability.

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 defense 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 saw 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 robotics as the ideal solution in a wide range of different robot types. From the early 1970s, when the majority of industrial robots were still hydraulically driven, to the latest generation of highly accurate and dynamic electrically driven robots, many of the most significant improvements in robot performance have been enabled by the continuous development of the Harmonic Drive gear.

## 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.

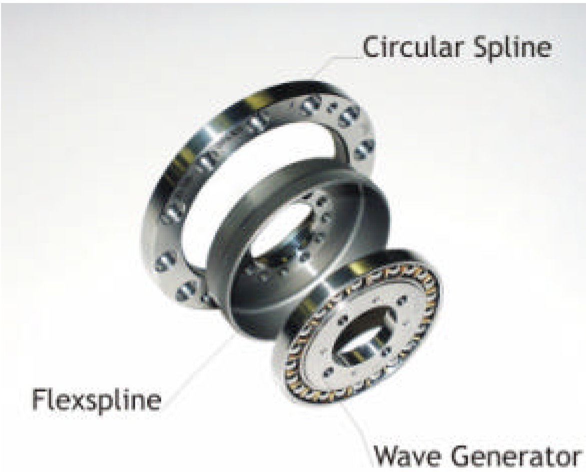


**Fig. 1: Basic gear components**

These three basic components function in the following way:
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 teeth of the FS to engage the CS at two regions at opposite ends of the major axis of the ellipse.
As the WG (input) rotates, the zone of tooth engagement travels with the major axis of the ellipse.
For each 180$^{o}$ clockwise movement of the WG, the FS (output) moves counterclockwise by one tooth relative to the CS (fixed).
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 and its difference between CS and FS.

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.

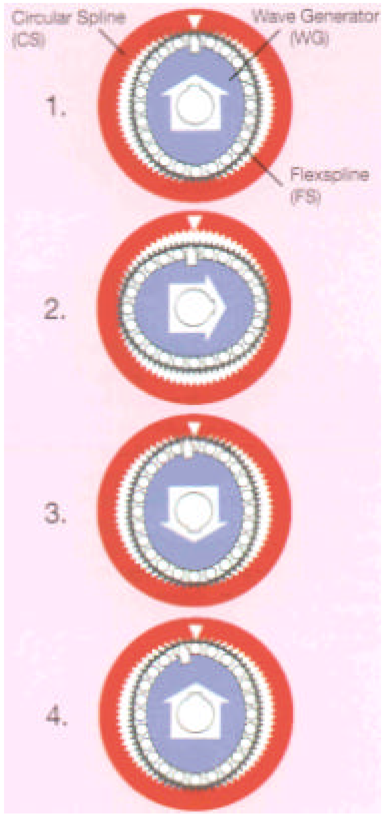


**Fig. 2: Principle of operation**

## 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 1.5 arc minutes for standard series gears with a repeatability of +/- 6 arc seconds. 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.
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 any backlash over its whole lifetime, i e. the characteristics will not change.
Since power is transmitted through multiple tooth engagement (typically about 30% of the teeth are used simultaneously for torque transmission), Harmonic Drive gears offer a very *high torque capacity*, equal to conventional drives twice its size and three times its weight.

The tooth engagement mechanism characteristics ensures that the gear is *stick-slip free*, even for very slow movements.
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.
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 robotic 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 demanding new applications in difficult environments, such as in space.

## 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 and higher torsional stiffness.

There are therefore three key themes driving current product development

- Increased torsional stiffness
- Reduced size
- Reduced weight

### IMPROVEMENT OF THE TOOTH PROFILE

The development of the tooth profile is a key development area. It was recognized early on 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. 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%

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.

### NEW FLEXSPLINE DESIGN

Another key development theme is the reduction in the axial length of the Flexspline cup. As can be seen in Fig. 3, 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. The FEM analysis that supported the introduction of the HFUC-type gear is also the basis for the new „super-flat“ component set, shown also in Fig. 3. 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.

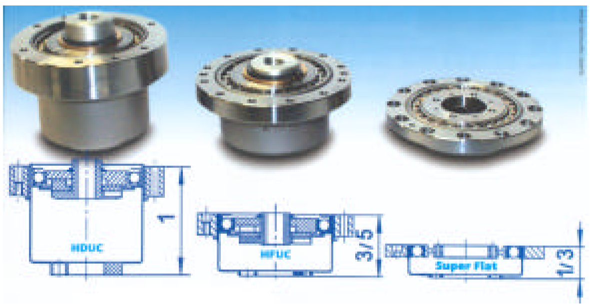


**Fig. 3: Flexspline Length Reduction**

### LIGHTWEIGHT COMPONENT SET DESIGN

In a large number of robot developments, 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.

Since 2001 Harmonic Drive AG has coordinated a German state-funded research project to develop lightweight gears using non-ferrous metals, special tooth profiles and new tribological coatings. This project has a duration of three years and involves a consortium of gear manufacturers, coating equipment suppliers and research institutes.

As can be seen from Fig. 4 there are four basic methods for reducing the weight of the gear and/or the surrounding machine elements in the user machine:

- Modification of the individual gear components, to simplify the integration of the gear and so reduce the weight of the surrounding machine elements.
- Integration of spur- or planetary-gear stages within the Harmonic Drive gear, in order to realize very high reduction ratios in the smallest possible envelope. This allows small, high speed motors to be used, so optimizing the power density of the complete gear-motor assembly.
- Use of special surface treatments to improve the load carrying capacity of individual gear components to so increase torque capacity and power density.
- Application of new materials for the individual gear components, in order to minimize the weight of the gear itself.

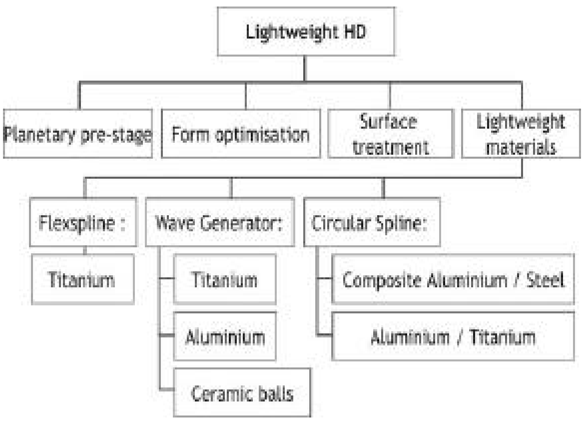


**Fig. 4: Lightweight design strategies**

Fig. 5 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.

Fig. 6 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.

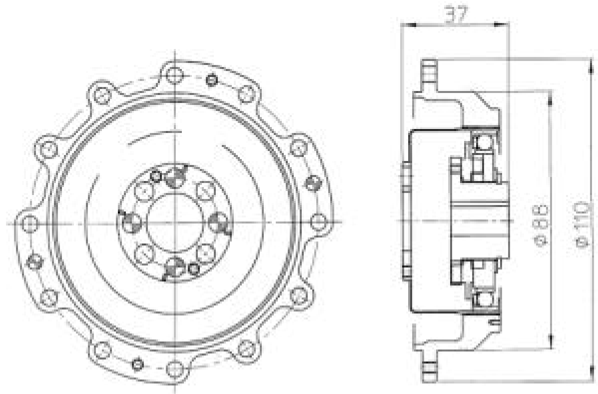


**Fig. 5: Component set with modified circular spline**

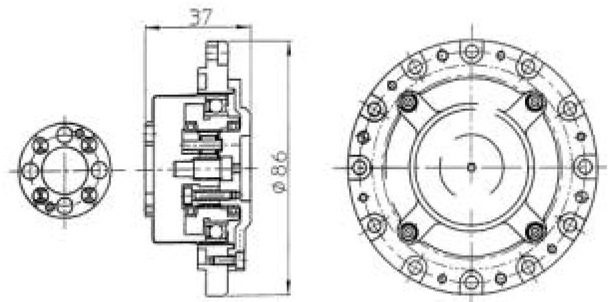


**Fig. 6: Component set with planetary pre-stage**

Fig. 7 shows the most effective technique to reduce weight, that is, to substitute "conventional" gear materials, such as cast iron and steel, with lightweight non-ferrous metals such as aluminium or titanium.

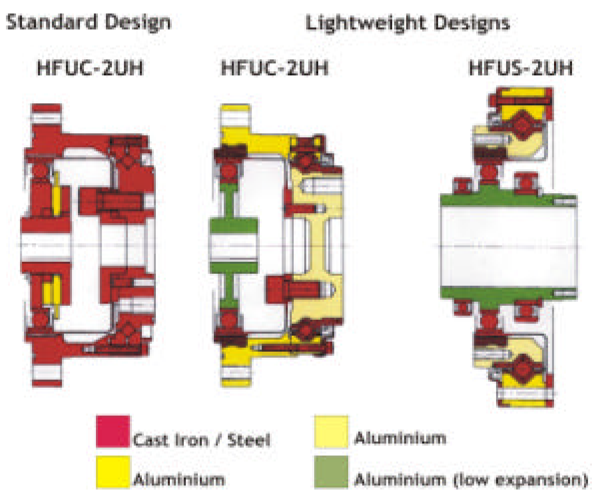


**Fig. 7: Application of lightweight materials**

Both the Circular Spline (housing) and Wave Generator plug of the lightweight unit, comprising gear component set and output bearing, are manufactured primarily from aluminium alloy. Two design techniques are particularly interesting for the circular spline. Fig. 7 shows a composite design, where the Circular Spline teeth are machined into a thin cast iron ring, which has been cast into the aluminium housing. Another approach is to coat the teeth of the Circular Spline using a special principle to achieve the same load carrying capacity as the standard gear teeth. The wave generator ellipse is manufactured from a special aluminium alloy, which has almost the same coefficient of thermal expansion as steel.

As can be seen from table 1, both weight and moment of inertia of the gear component set can be reduced by more than 50 %, leading to an increase in specific torque capacity of 105 %.

| | | Standard gear HFUC-20-160 | Lightweight gear HFUC-20-160-SP | Trend |
|---|---|---|---|---|
| Rated torque | [Nm] | 40 | 40 | = |
| Peak torque | [Nm] | 92 | 92 | = |
| Moment of inertia | [x $10^{-4}$ $kgm^2$] | 0.193 | 0.091 | 53 % |
| Weight | [kg] | 0.26 | 0.127 | 51 % |
| Specific peak torque | [Nm/kg] | 354 | 724 | +105 % |

**Table 1: Comparison of standard and lightweight gears**

## APPLICATIONS

As indicated above, there is already a wide range of different robotic applications for Harmonic Drive gears. The new developments in the field of lightweight gear design are opening up new applications in both industrial and service robots. The following are just a few recent examples showing how lightweight Harmonic Drive gears are already being used in practice.

### SCARA ROBOTS

The primary axes of Scara robots are a traditional application area. Here the required speed is increasing dramatically without any compromise in accuracy. This is also necessitating the use of lightweight gears. Lower gear mass for the elbow-joint reduces the overall mass of the arm, which allows faster cycle times. Reducing the moment of inertia of both shoulder- and elbow-joint gears also allows faster acceleration and therefore reduced cycle times. During the development of a new Scara robot type lightweight gear units were tested for more than 5000 hours in a robot of the type shown in Fig. 8. The robot exhibited consistently high accuracy during the complete endurance test and the robot achieved faster cycle times, whilst the effective motor current was reduced by more than 10 %.

**Fig. 8: SCARA Robot (Source: Bosch Rexroth AG)**

### LIGHTWEIGHT ROBOTS

Lightweight component sets are also used in the 3rd generation of lightweight robots to be developed at the Institute of Mechatronics and Robotics at the German Aerospace Center /DLR). The robot uses 7 Harmonic Drive gears in all axes and can carry a payload of 13 kg, while only weighing 13 kg itself. This relationship is currently the world's best value. Harmonic Drive gears are also used in the unique 4-fingered hand shown in Fig.9. A modified version of this robot is also to be used as a service robot on the International Space Station.

**Fig. 9: Lightweight Robot (Source: DLR)**

WALKING ROBOTS

Another area with expanding Harmonic Drive applications is the field of walking robots. A particularly ambitious research project is the bi-pedal robot "Johnnie", developed by the Institute of Applied Mechanics at the Technical University of Munich. This robot features no less than 17 lightweight Harmonic Drive gears. "Johnnie" has a very high level of autonomy and can mount or avoid numerous obstacles at a walking speed of up to 2 km/hour. Johnnie is 1,8 m tall, yet weighs just 45 kg.

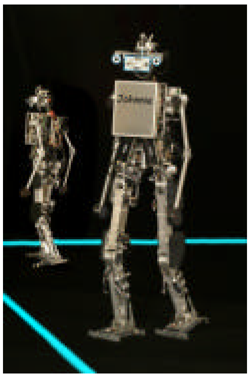

**Fig. 10: Walking Robot (Source: TU Munich)**

## CONCLUSION

Harmonic Drive gears have a long success story in demanding robotic applications. The range of applications is increasing quickly due to continuous product development, which is leading to greatly improved product performance.

One area of particular interest is the development of lightweight gears. The latest research results can reduce weight by more than 50 % without any reduction in torque capacity or accuracy.

This research is continuing with gears manufactured from titanium using special surface treatments currently being tested. It is anticipated that this development can lead to even better performance that that already achieved using composite or aluminium components.

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