# the basics of

# Harmonic Drive Gearing

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Harmonic drives were invented in the late 1950s and have been a major part of the motion control industry since then. In that time, several innovations, improvements and adaptations have been made, allowing harmonic drives to become a primary choice for applications requiring precise positional accuracy and repeatability.

They are now available as fully housed gearheads, actuators complete with motor and encoder, or in custom configurations with special materials, greases or customer-specific designs that allow for easy adaptability.

Since they were invented, one aspect of harmonic drive gearing has remained constant: their principle of operation. Most people in industry are familiar with the term harmonic drive and have either heard about them or seen them in passing, but few understand how they work or why they're capable of high ratios, zero backlash, and high torque-to-weight ratios.

## Harmonic Drive Gearing—Do You Really Know How it Works?

The operating principle of harmonic drive gearing is one of the most misunderstood of all gearing technologies.

The mechanism is comprised of three components: wave generator, flexspline, and circular spline (Fig. 1).

*Wave Generator*. The wave generator is actually an assembly of a bearing and a steel disk called a wave generator plug. The outer surface of the wave generator plug has an elliptical shape that is carefully machined to a precise specification. A specially designed ball bearing is pressed around this bearing plug, causing the bearing to conform to the same elliptical shape as the wave generator plug.

The wave generator is typically used as the input member, usually attached to a servo motor.

*Flexspline*. The flexspline is a thin-walled steel cup with teeth machined into the outer surface near the open end of the cup. The large diameter of the cup allows it be radially compliant, yet remain torsionally stiff.

The cup has a rigid boss at one end to provide a rugged mounting surface. During assembly, the wave generator is inserted inside the flexspline in the same axial location as the flexspline teeth. The flexspline wall near the brim of the cup conforms to the same elliptical shape as the bearing. Effectively, the flexspline now has an elliptical gear pitch diameter on its outer surface.

The flexspline is usually the output member of the mechanism.

*Important*: Although the steel flexspline flexes during normal operation, there is no concern about fatigue failure. The stresses developed are far below the endurance limit of the material. Thus, the flexspline will achieve infinite life when used according to catalog ratings. This is explained better in Figure 2.

*Circular Spline.* The circular spline is a rigid circular steel ring with teeth on the inside diameter. The circular spline is usually attached to the housing and does not rotate.

The teeth of the circular spline mesh with the teeth of the flexspline. The tooth pattern of the flexspline (which is now elliptical—as a result of conforming

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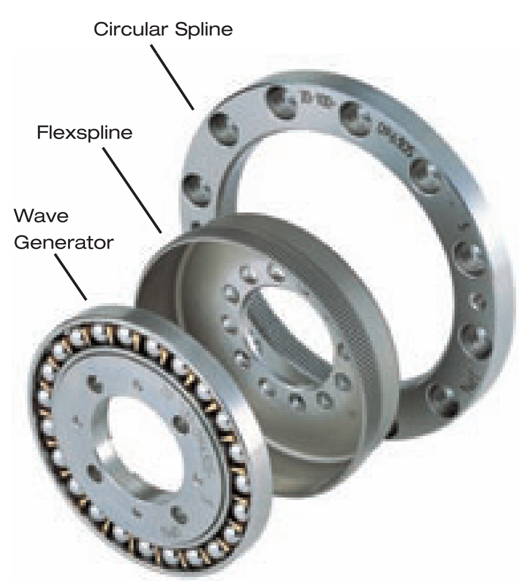


Fig. 1—Components of harmonic drive gearing.

to the wave generator's elliptical shape) engages the tooth profile of the circular spline along the major axis of the ellipse. This engagement is like an ellipse inscribed concentrically within a circle. Mathematically, an inscribed ellipse will contact a circle at two points. However, the gear teeth have a finite height. So there are actually two regions (instead of two points) of tooth engagement.

In fact, up to 30% of the teeth are engaged at all times on the major axis. The pressure angle of the gear teeth transforms the output torque's tangential force into a radial force acting on the wave generator bearing. The teeth of the flexspline and circular spline are engaged near the major axis of the ellipse, and disengaged at the minor axis of the ellipse (Fig. 3).

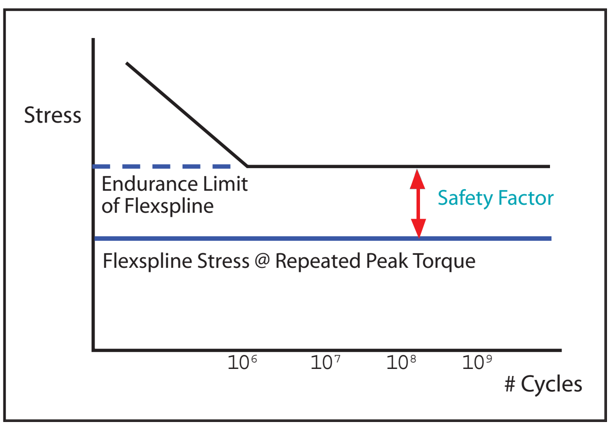


Fig. 2—Harmonic drive gearing is designed for infinite life.

### Here's the Trick...

The flexspline has two fewer teeth than the circular spline. So every time the wave generator rotates one revolution, the flexspline and circular spline shift by two teeth. The gear ratio is calculated by

# Flexspline Teeth / (# Flexspline Teeth – # Circular Spline Teeth)

Since the flexspline has two fewer teeth than the circular spline, the term (# Flexspline Teeth – # Circular Spline Teeth) = –2. For example, if the flexspline has 200 teeth, the circular spline has 202 teeth. The gear ratio will be calculated as 200/(200–202) = –100. The negative sign indicates that the input and output rotate in opposite directions.

### Principle of Operation

As the wave generator is rotated by the primary power source, it imparts a

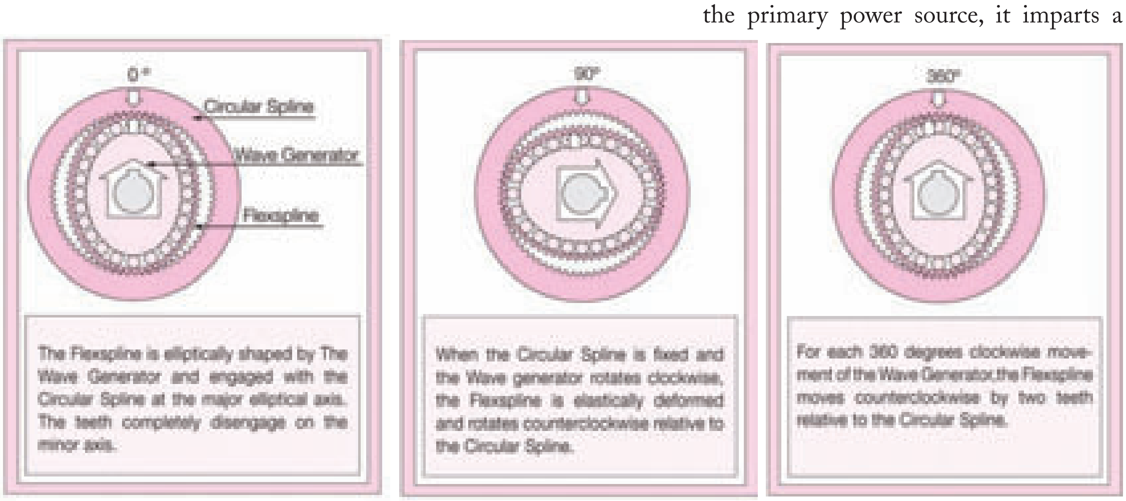


Fig. 3—Tooth engagement of harmonic drive gearing.

continuously moving elliptical form or wave-like motion to the flexspline. This causes the meshing of the external teeth of the flexspline with the internal teeth of the circular spline at their two equidistant points of engagement. This meshing progresses in a continuous rolling fashion. It also allows for a full tooth disengagement at the two points along the minor axis of the wave generator.

Since the flexspline has two fewer teeth than the circular spline and because full tooth disengagement is made possible by the elliptical shape of the wave generator, each complete revolution of the wave generator causes a two-tooth displacement of the flexspline in relation to the circular spline. This displacement is always in the opposite direction of the rotation of the wave generator (Fig. 4).

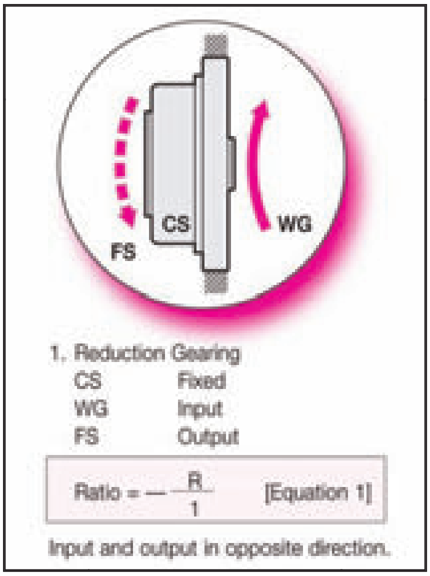


Fig. 4—Normally input and output are in opposite directions.

For example, if the wave generator is rotating in a clockwise direction, the two-tooth per revolution displacement of the flexspline will be in a counterclockwise direction, and vice-versa. In this way, a basic three-element harmonic drive component set is capable of functioning as a speed reducer. Input from a main power source through the wave generator is at a high speed, but the two-tooth per revolution displacement causes the flexspline to rotate at a considerably slower speed than the wave generator.

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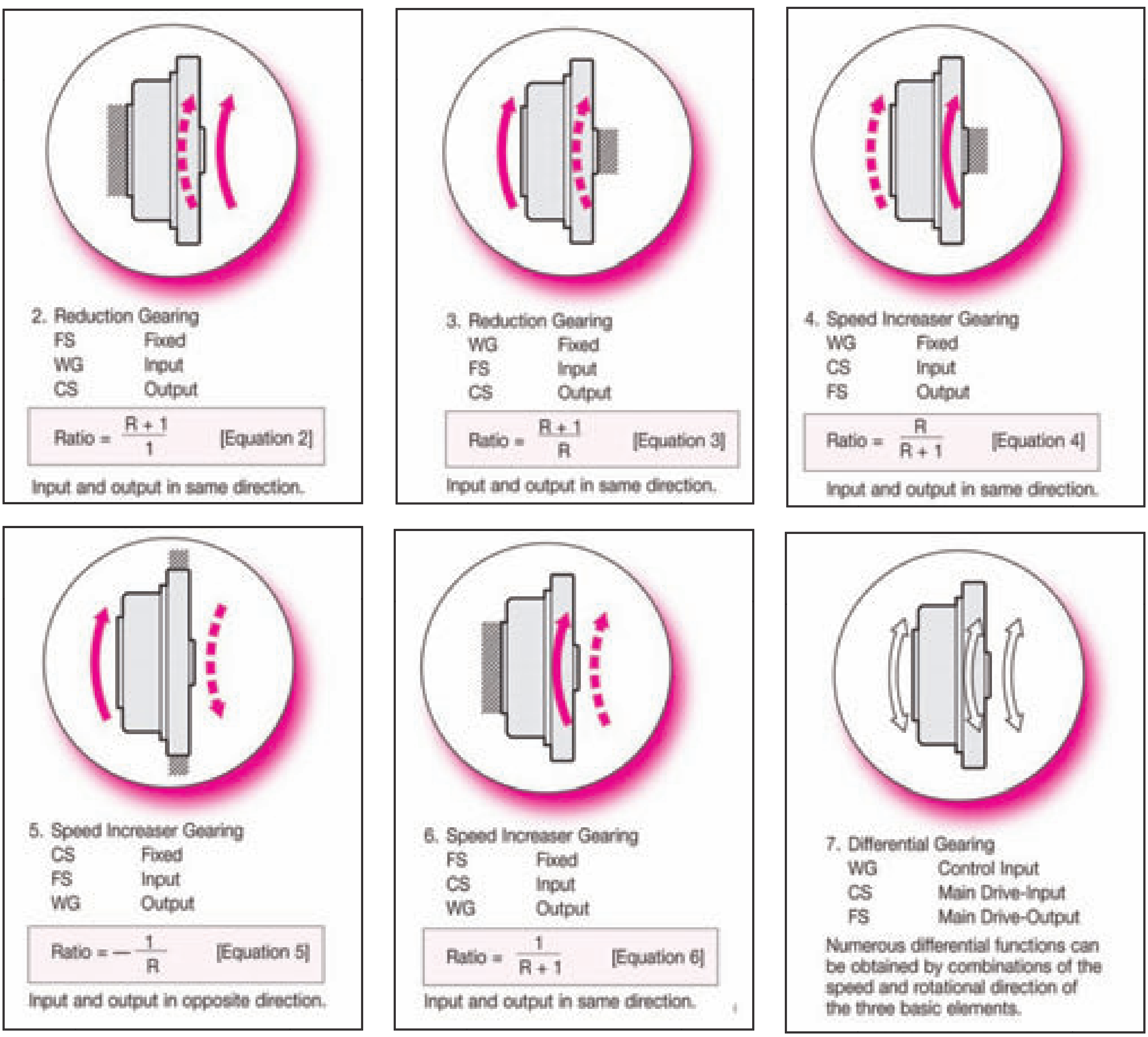


Fig. 5—A variety of configurations are possible.

The reduction ratio which results can be calculated by dividing the number of teeth on the flexspline by two. For example, if a fixed circular spline has 202 teeth and an output flexspline has 200 teeth, the ratio would be 200/(200–202) = –100:1*

*The negative sign indicates that the input and output are turning in opposite directions.

## Other Configurations

In addition to acting as a speed reducer, a wide variety of configurations can be achieved with harmonic drive gearing by changing which element (among the wave generator, circular spline and flexspline) acts as the fixed element, input element and output element (Fig. 5).

## Advantages

The advantages of harmonic drive gearing over other, more conventional gear trains are apparent. A simple three-element construction combined with the unique harmonic drive principle puts extremely high reduction ratio capabilities into a very compact and lightweight package. This remarkable union of simplicity of construction with an operating principle that is unique, also enables backlash to be held to a minimum.

*Zero Backlash.* The unique design and operating principle yield some very convenient benefits. The tooth engagement motion (kinematics) of the harmonic drive gear is very different than that of planetary or spur gearing. The teeth engage in a manner that allows up to 30% of the teeth to be engaged at all times (60 teeth engaged for a 100:1 gear ratio). This contrasts with maybe six teeth for a planetary gear set, and one or two teeth for a spur gear set.

In addition, the unique kinematics allow the teeth of a harmonic drive gear to be engaged on both sides of the tooth flank. Since backlash is defined as the difference between the tooth space and tooth width, this difference is zero for harmonic drive gearing.

*Consistent Performance.* As part of the design, the gear teeth of the flexspline are preloaded against those of the circular spline at the major axis of the ellipse. They are preloaded such that the stresses are well below the material's endurance limit. This has an important benefit.

In conventional gearing, wear results in an increase in backlash over time. In harmonic drive gearing, as the gear teeth wear, the elastic radial deformation acts like a very stiff spring to compensate for space between the teeth that would otherwise cause an increase in backlash. This allows the performance to remain constant over the life of the gear.

*High Positional Accuracy.* The combination of harmonic drive gearing principle and manufacturing technology allows positional accuracy of 30 arc-seconds (0.008°). All three gearing components (wave generator, flexspline and circular spline) are held concentric at all times. In addition, the tooth height, pitch circle and tolerances are controlled to millionths of an inch. These factors, when combined with the 30% tooth engagement, allow for sustained accuracy far better than other gearing technologies.

*High Torque-to-Weight Ratio.* Harmonic drive gearing offers higher torque-to-weight and torque-to-volume ratios than other gearing technologies. The lightweight construction and single-stage gear ratios of up to 160:1 allow the gears to be used in applications requiring minimum weight or volume. Small motors can exploit the large mechanical advantage of a 160:1 gear ratio to create a compact, lightweight and low-cost package.

*Affordable Precision.* Harmonic drive gearing offers many performance advantages as compared to conventional gearing technologies. Yet, its simple and elegant design allows manufacturing costs to be roughly equal to that of other precision motion control technologies. This provides an attractive cost/benefit proposition for most motion control applications. ■

**Anthony Lauletta is manager of marketing communications with Harmonic Drive LLC. On Jan. 1, Harmonic Drive Technologies/Nabtesco of Peabody, MA, and HD Systems of Hauppauge, NY, merged to form a new joint venture, Harmonic Drive LLC. Harmonic Drive remains committed to providing the highest quality harmonic drive gearing and motion control products combined with world class customer service and support. The new company will employ over 90 people and be headquartered in Peabody, MA.**

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