Introduction

Strain wave gear was invented by W. Musser in 1955 [1]. Its application is in aerospace since then. The strain wave gear is a type of mechanical gearing system that has unique characteristics comparing with cycloidal drives or planetary gears. It has the advantages of zero backlash, high precision, and high gear ratio from 30:1 to 320:1 in a compact packaging. Recent years, its main application is for robotic arm joint. Since the availability of robotic arm increases substantially due to its important role in automation, so the high-performance strain wave gear is also in need. The goal of this paper is to introduce the basic concepts of strain wave gear to students majored in Mechanical Engineering, Mechanical Engineering Technology, and Mechatronics.

Gear ratio

There are two types of strain wave gear commercially available [2]. One has three components as shown in Figure 1 (a). The wave generator (WG) is a ball bearing with an elliptical cam insert. Its circumference is an ellipse, which is an offset curve from the cam. The flex spline (FS) is a cup shape thin shell. The flex spline is deformable along the radial direction, but has high torsional stiffness. The flexspline has spur gear teeth at the open end and rigid flange at the close end. The circular spline (CS) is a rigid ring gear.

The flexspline will fit tightly round the wave generator, the open end of flexspline will deform with the wave generator when wave generator rotating. The teeth mesh at the major axis of the ellipse between flexspline and circular spline. The three components system has two degree of freedom as a planetary gear train. The kinematic diagram is shown in Figure 1 (b). The rotational speed between the components is in Equation (1).

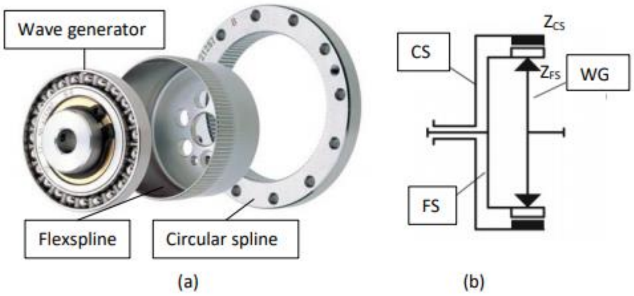


Figure 1. Cup style strain wave gear

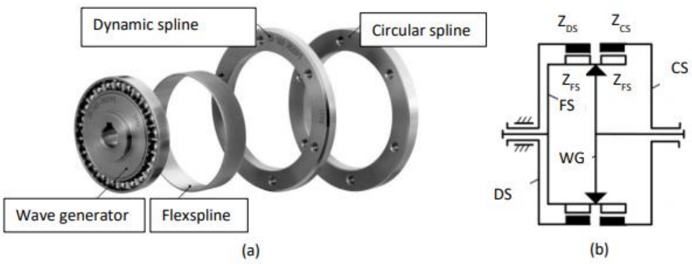


Figure 2. Pancake style strain wave gear

$$\frac{\omega_{CS}-\omega_{WG}}{\omega_{FS}-\omega_{WG}}=\frac{z_{FS}}{z_{CS}} \tag{1}$$

In the equation, z is tooth number, ω is angular velocity. For example, if the flexspline has tooth number z_{FS} = 160, circular spline has tooth number z_{CS} = 162. The circular spline is connected to the fixed link of a robotic arm, angular velocity ω_{CS} = 0. The wave generator is driven by servo motor as input. The flexspline rigid end flange is connected to the robotic arm moving link. The gear ratio can be calculated from Equation (1).

$$i=\frac{\omega_{input}}{\omega_{output}}=\frac{\omega_{WG}}{\omega_{FS}}=\frac{z_{FS}}{-z_{CS}+z_{FS}}=\frac{160}{-162+160}=-80 \tag{2}$$

The speed of the servo motor will be reduced 80 times to the moving link. Meanwhile, the output torque will increase 80 times, due to conservation of energy. The negative sign means the wave generator and flexspline will rotate in opposite direction.

To reduce the lengthwise dimension of the strain wave gear, the second type of strain wave adds a fourth component called dynamic spline (DS) as shown in Figure 2 (a). The flexspline is a flexible spur gear without the rigid end flange. The kinematic diagram is shown in Figure 2 (b). The rotational speed between components are shown in Equation (3) and (4).

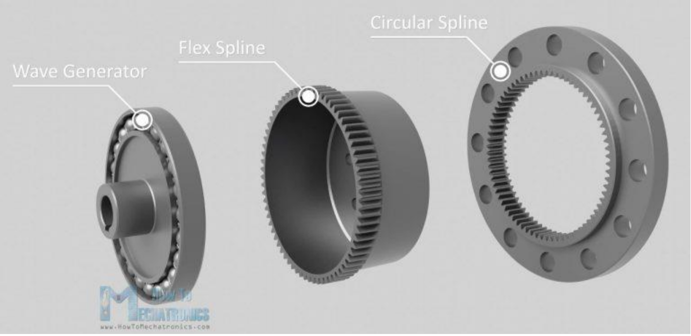
$$\frac{\omega_{DS}-\omega_{WG}}{\omega_{FS}-\omega_{WG}}=\frac{z_{FS}}{z_{DS}} \tag{3}$$

$$\frac{\omega_{CS}-\omega_{WG}}{\omega_{FS}-\omega_{WG}}=\frac{z_{FS}}{z_{CS}} \tag{4}$$

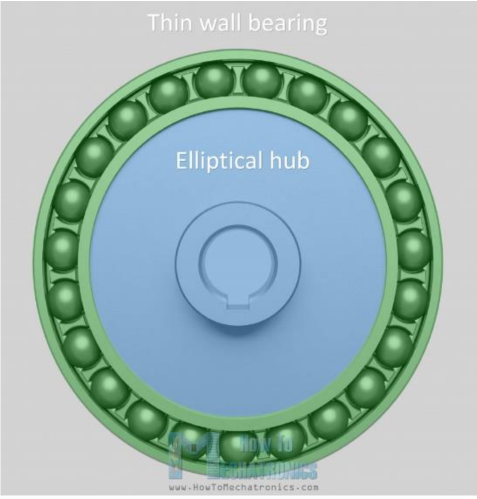
A strain wave gear is a two degree of freedom mechanism. If different component is used as input, such as back drive load condition, Equation (1), (3), (4) are still applicable.

How It Works

All right, so let’s take a look how it works now. A harmonic drive has three key components, a wave generator, a flex spline and a circular spline.



The wave generator has an elliptical shape and consists of an elliptical hub and a special thin walled bearing which follows the elliptical shape of the hub. This is the input of the gear set and it's connected to the motor shaft.

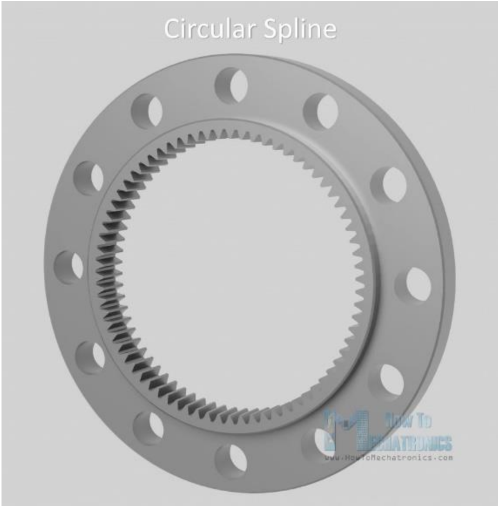


As the wave generator rotates it generates a wave motion.

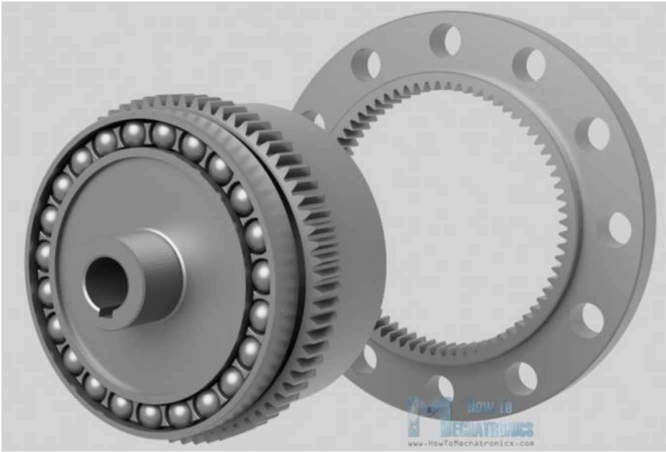
The Flex spline has a form of a cylindrical cup and it's made out of flexible but torsionally stiff alloy steel material. The sides of the cup are very thin but the bottom is thick and rigid.

This allows the open end of the cup to be flexible, but the closed end to be quite rigid and therefore we can use it as an output and connect the output flange to it. The flex spline has external teeth on the open end of the cup.

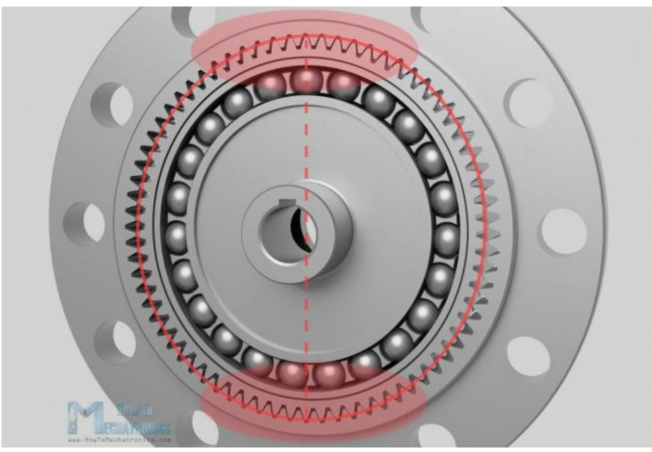
On the other hand, the Circular spline is a rigid ring with teeth on the inside. The circular spline has two more teeth that the flex spline, which is actually the key design of the strain wave gear system.



So, when we insert the wave generator into the Flex spline, the flex spline takes the shape of the wave generator.

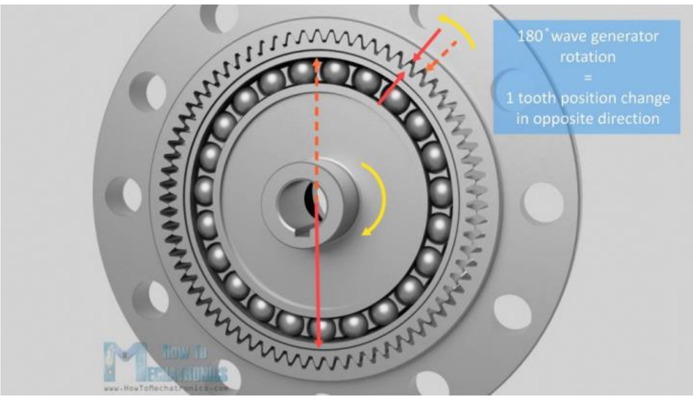


As the wave generator rotates, it radially deforms the open end of the flex spline. The wave generator and the flex spline are then placed inside the circular spline, meshing the teeth together.

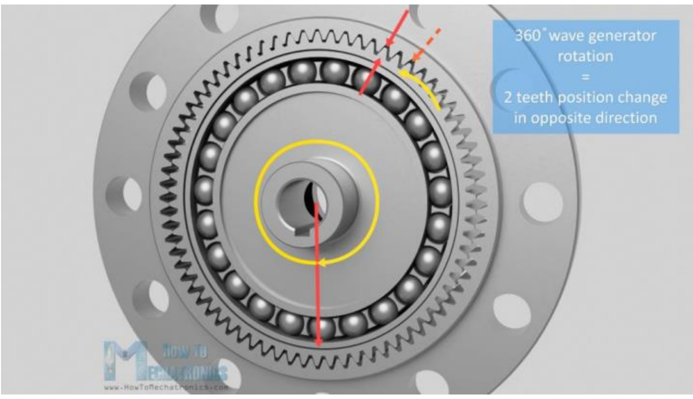


Because of the elliptical shape of the flex spline, the teeth mesh only in two regions on the opposite sides of the flex spline, and that's across the major axis of the Wave Generator ellipse.

Now, as the wave generator rotates, the Flex spline teeth that are meshed with those of the circular spline will slowly change position. Because of the tooth count difference between the Flex spline and the Circular spline, for each 180 degrees rotation of the wave generator, the teeth meshing will cause the flex spline will rotate a small amount backward relative to the wave generator. In other words, with each 180 degrees rotation of the wave generator, the flex spline teeth mesh with the circular spline will advance by only one tooth.

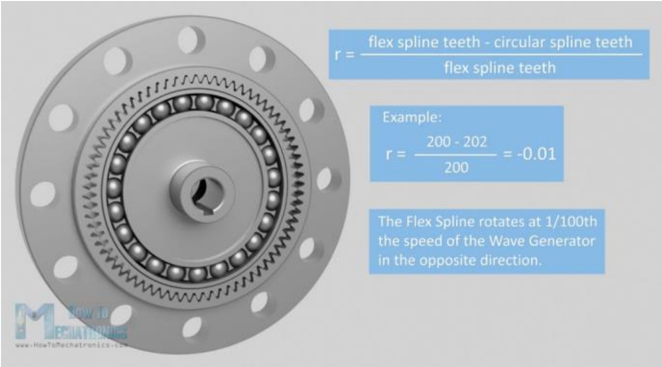


So, for a full rotation of 360 degrees of the wave generator, the flex spline will change position or advance by two teeth.



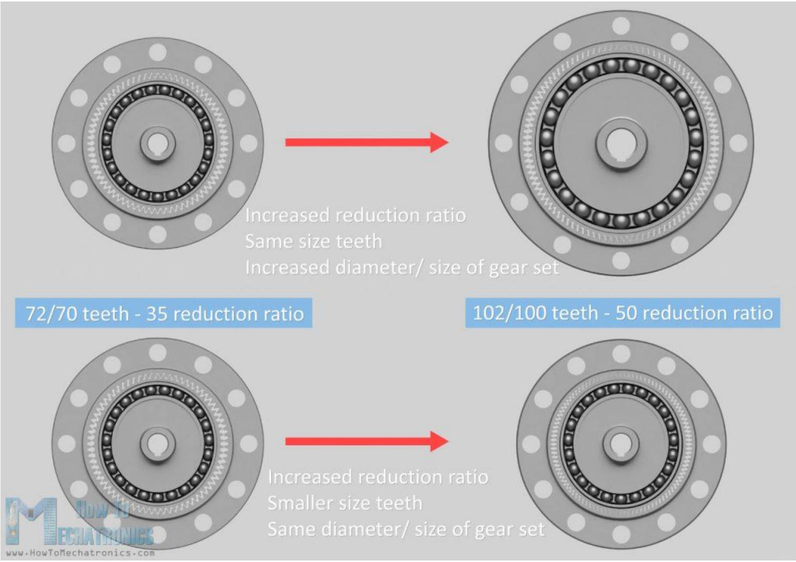
For example, if the flex spline has 200 teeth, the wave generator has to do 100 revolutions in order the flex spline to advance 200 teeth, or that's just a single rotation for the flex spline. That's a ratio of 100:1. In such a case the circular spline will have 202 teeth, as the circular spline number of teeth is always greater that the flex spline teeth by two.

We can easily calculate the reduction ratio with the following formula. The ratio is equal to the flex spline teeth – circular spline teeth, divided by the flex spline teeth.



So, with the example of 200 teeth on the flex spline and 202 teeth on the circular spline, the reduction ratio is -0.01. That's 1/100 the speed of the wave generator and the minus sigh indicates that the output is in the opposite direction.

We can get different reduction ratios by changing the number or teeth.



We can achieve that by either changing the mechanism diameter while having the same size teeth, or by changing the teeth size preserving the size and weight of the gear set.

Reference

[1] Walton, Musser C. "Strain wave gearing." U.S. Patent No. 2,906,143. 29 Sep. 1959.

[2] http://www.harmonicdrive.net/

[3] https://howtomechatronics.com/how-it-works/what-is-strain-wave-gear-harmonic-drive-a-perfect-gear-set-for-robotics-applications/