MachineDesign

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Basics of Design

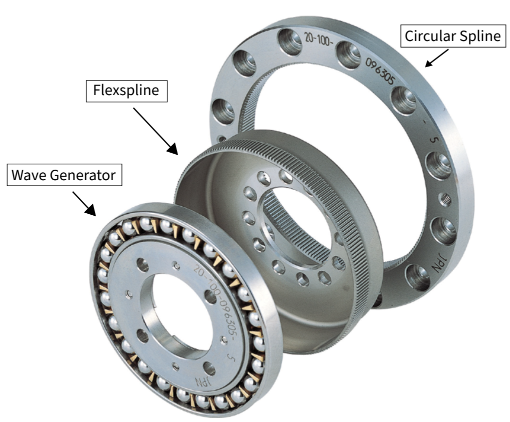
STRAIN WAVE GEARING

Strain wave gears like those engineered by Harmonic Drive LLC deliver precision motion in many industries including robotics, aerospace, machine tools, test and measurement, and semiconductor manufacturing equipment.

Made up of only three basic components, strain wave gears provide a high speed-reduction ratio, mechanical advantage, and precision positioning in an extremely compact, lightweight package. Read on for more details about the design of strain wave gears, how they perform, and how they compare with other gear reduction technologies.

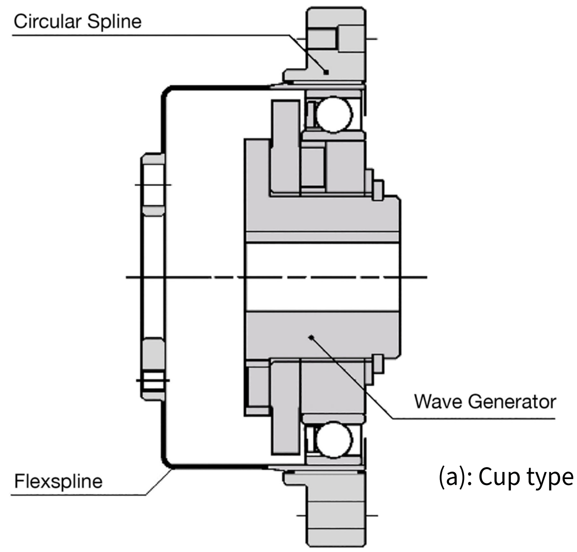
Strain Wave Components

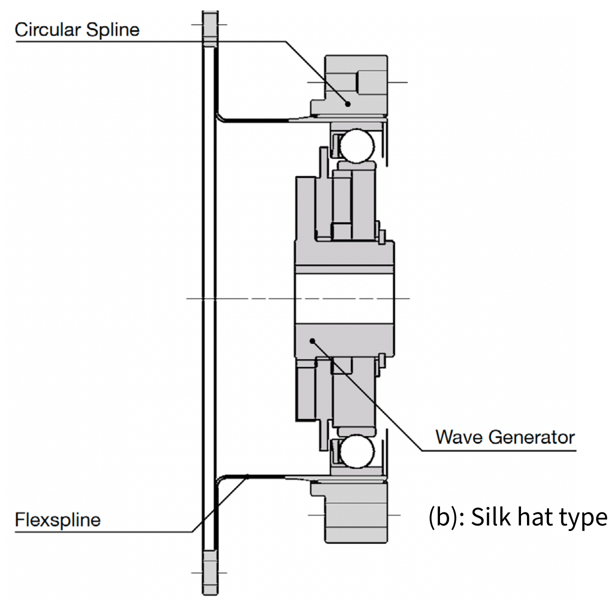
Strain wave gears consist of a wave generator, a flexspline, and a circular spline. The wave generator is a thin race ball bearing deflected into an ellipse-like shape by being pressed over a contoured cam. The cam connects to the input drive, usually a servomotor, and provides the primary motion to the gears by creating a wave in the flexspline.



Strain wave gear components
Strain wave gears are made up of a wave generator connected to the input motor, a flexspline with external teeth connected to the output, and a fixed, rigid circular spline with internal teeth.

The flexspline is a flexing element commonly in the form of a thin-walled cylinder. One end of the cylinder is deflected into an elliptical shape by the wave generator. At the same time, the other end is held circular by the torsionally stiff diaphragm connected to the output member. The flexible open end of the flexspline has external gear teeth. The number of teeth is generally twice the required gear ratio. For instance, a strain wave gear that achieves a 100:1 ratio would have a flexspline with 200 teeth. Importantly, the gear ratio does not alter the size of a given component set.

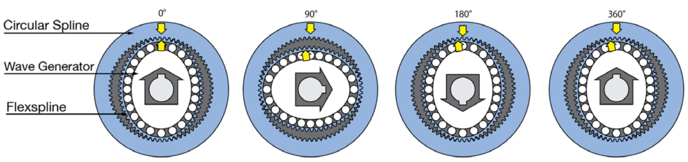




Flexspline configurations
Flexsplines can have (a) a cup shape with a flexible, toothed rim and a torsionally rigid base connected to the output or (b) a silk-hat shape where the output flange flares outward, creating a hollow bore and additional attachment points.

Flexsplines come in two configurations: the conventional cup type and the silk-hat type. While the cup type is a cylinder with one open end, the rigid diaphragm of the silk-hat type flares outwards instead of inwards.

The third element in a strain wave gear is a circular ring gear with internal teeth. The number of internal teeth is always two greater than the external teeth on the flexspline. The circular spline is usually fixed and rigidly held by a housing. This lets the flexspline rotate and efficiently transmit motion to the output.



Strain wave operation
Because the tooth count on the circular spline is two greater than that of the flexspline, the flexspline progresses by two teeth each time it makes a complete revolution.

Operating Principle

When the wave generator is inserted into the flexspline, the flexspline is deformed such that two segments of its teeth engage with the teeth of the circular spline. Approximately 18% of the flexspline teeth on each side of the wave generator's major axis engage the teeth of the circular spline. This level of engagement creates a preloaded, torsionally rigid, and backlash-free connection.

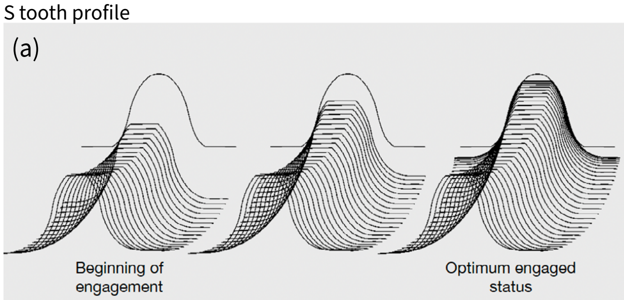
As the wave generator rotates one complete revolution, the flexspline progresses by two teeth of the circular spline. This creates a ratio equal to half the number of circular spline teeth when the flexspline is the output member.

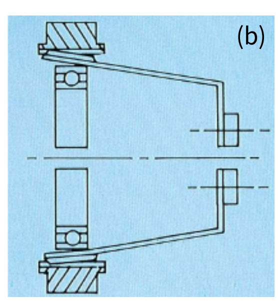
Unlike spur gears, which require some design clearance between the teeth to allow for the rolling motion of the tooth, the flexspline tooth progresses around the inside of the circular spline in a step-like trajectory, much like the motion of a walking beam. This trajectory ensures zero true backlash between the teeth in contact.

In addition, the engaged teeth of the flexspline are of identical pitch to the circular spline, leading to a purely radial motion component at the time of tooth mating. The multiple teeth fully engaged at the major axis of the wave generator act as a pivot at top dead center. This cusp-like tooth path and the flexing of the cup create maximum motion and tooth sliding velocity at the minor axis, where the teeth are not engaged, and minimize tooth sliding velocity at the point of engagement. This phenomenon reduces tooth wear and improves durability.

Because multiple teeth are in preloaded contact at both sides of the wave generator major axis, high torque can be achieved in a very compact, lightweight package. The preload comes from the flight angle or cone angle, occurring in the wall of the flexspline cup when it is deflected into an ellipse-like shape at the open end by the wave generator. This preload provides the zero-backlash associated with strain wave gearing and is present for the effective life of the gear, providing accurate, controlled dynamic response and minimizing residual vibration.

S tooth profile





Optimized gear meshing for zero backlash and high torque.

(a)Teeth on the flexspline and circular spline experience purely radial forces when meshing. (b) The wave generator deflects the flexspline, creating a cone angle and associated preload. Together, these geometries eliminate backlash and minimize tooth wear.

Life and Performance

Strain wave gears are known for their ability to deliver precision motion and excellent dynamic response and reliability, even at high torques. When designing any component for high reliability, engineers choose configurations that minimize and predict wear and utilize the infinite stress life of materials. Strain wave gears are no different.

One example of wear minimization is the previously mentioned unique tooth relationship between flexspline and circular spline. Minimizing the tooth sliding velocity at the point of engagement means strain wave gear teeth are less subject to wear than those of other gear designs. The failure probability of Harmonic Drive® gears due to tooth wear is extremely low and exceeds other rating limitations.

Strain wave gears are also designed to make use of the infinite stress life of their component materials. The specified output torque limits are far below the endurance limit of the flexspline material. Strain wave gears that are correctly mounted and operated within published maximum repeated torque limits do not experience fatigue failures of the flexspline, irrespective of the number of input revolutions.

Therefore, the basic catalog life ratings for strain wave gear component sets are based on the life of the wave generator bearing. Studies have shown that the ball bearings of the wave generator have the same mode of wear as any normally applied ball bearing.

Bearing-life calculation combines output torque, input speed, and load duration for any given application. The load capacity and resultant life of the wave generator bearing agree with that of conventional round ball bearings, where, for a given load, the life of the bearing may be predicted from the general cubic relationship of life to load:

$$B_{10} = (C/P)^3$$

Where C is the load rating and P is the equivalent dynamic bearing load, which can be further defined as the level of ball-to-race compressive stress and the number of times this stress is applied, the latter being a function of rotational speed.

L_{10} (B_{10}) life is defined as the output torque of the gear running at an input speed of 2,000 rpm for 10,000 hours. This output torque is the rated load capacity of the gear.

Strain wave gears are available in many sizes to suit a wealth of applications. Size, determined by the pitch circle of the gear teeth, can range from as small as 0.3 inches up to 10 inches in diameter. These gears achieve ratios from 30:1 to 320:1 in a single stage and support torques up to and greater than 26,000 inch-pounds. Strain wave gears can withstand shock loads of up to five times the rated torque, an important consideration when output interference or crashes are possible.

Selecting Strain Wave Gearing

Strain wave gears are used in rotary motion control applications in which spur gears, cycloidal gears, and planetary gears are also potential design choices. Like strain wave gears, cycloidal gears have low to zero backlash and are available in high gear ratios. These ratios are often achieved by adding extra lobes and pins or by the addition of a primary planetary reduction input into the cycloidal section, adding size and weight to an already large and heavy design. For these reasons, cycloidal gears are often more suited to base axis or azimuth drives.

Spur and planetary gears have inherent backlash because of the clearance needed for the motion of the tooth. While precision planetary gears are available with backlash down to about 1 arc-minute, the backlash often increases over time because of wear on the teeth. Additionally, planetary gears are usually limited to 10:1 for a single stage system. Adding a second stage increases size and weight.

In contrast, strain wave gearing is very adaptable where designs demand it. Special shapes and configurations of circular splines and wave generators are available in addition to the two standard flexspline designs described above. Strain wave gears specifically made for spaceflight applications are one example. The ability to create ultra-lightweight, stainless steel strain wave gears has given this technology a substantial space flight heritage.

Conclusion

When a design calls for a combination of high torque capability, high reduction ratios, and zero backlash in a lightweight, compact design with superior dynamic response, designers turn to strain wave gear systems over other types of gear systems. Strain wave gear systems have design and installation options that ensure each application achieves its desired performance over a long, predictable lifetime.

If you are implementing strain wave gearing, component manufacturers like Harmonic Drive LLC have application experts ready to help.