

The Road Leads Straight to Hypoflex®

Content:

- State of the Art ... Page 2
- Theoretical Bases ... Page 3
- Hypoflex® Process ... Page 4
- Advantages of the Hypoflex® Process ... Page 5
- Sample Gear ... Page 6
- What are Cycloids? ... Page 7

Straight bevel gears are used in ever greater numbers in power engineering. Apart from their use in vehicle differentials, examples of other applications are power tools and a wide range of agricultural machinery and equipment.



In comparison to spiral bevel gears, straight bevel gears have a lower load capacity and run less silently. The reason why they are used so extensively lies in their lower axial forces in comparison to spiral bevel gears, whose quantity and direction do not vary with the direction of rotation, requiring less design effort for the bearings. This is coupled with the additional advantage of unrestricted axial mounting in the gear-box, bringing substantial design benefits.

This article describes the application of modern dry cutting technology to straight bevel gears, using calculation and optimization software which matches state-of-the-art technology.

State of the Art

Straight bevel gears are manufactured by means of primary forming, forming, or cutting processes. Examples of primary forming are casting and sintering. Casting is used on a large scale to manufacture straight bevel gears from non-metallic and non-ferrous materials for gear systems which are undemanding in terms of accuracy and power density. Sintered bevel gears are used in relatively large quantities in hand-held power tools like, for example, angle grinders. In comparison to other processes, it is difficult to avoid inadequate homogeneity, due to uneven densification. Dies are also very expensive to produce and gear modifications are costly if dies have to be modified [KLI08].

Both forging and wobble pressing have proven to be useful as alternatives for mass producing differential bevel gears. Requirements in terms of tooth pitch tolerances and gear topography are lower than for running gears. The gear quality achieved with wobble pressing is roughly IT8 [RUE09]. Nonetheless, cutting processes remain the first choice for greater accuracy or greater flexibility and in producing small batch sizes.

As far as soft machining is concerned, cutting processes like generate planing, hobbing and broaching may be noted. Hard machining of straight bevel gears occurs to only a very limited extent, by means of lapping or grinding. Grinding is also used for a few applications in the aircraft sector.

Planing by the Heidenreich-Harbeck process is still used to a limited extent in one-off and spare part production.

The Revacyle® broaching process is used especially for the production of differential bevel gears. The tool is a circular broaching tool with a large number of differently profiled form cutter blades at the circumference. A first circular segment consists of roughing blades, with a slight outward offset to one another, followed by segments with finishing blades, leading to a gap in which the workpiece is turned by one pitch (Fig. 1). One tooth gap is produced for each revolution of the tool.

The finishing blade has a concave arc profile, which is reproduced in the workpiece, while the center point of the tool is displaced in a straight line, creating a straight tooth root. The tooth profile, which changes along the face width, and the lengthwise crowning are generated by the form of the individual cutter blades and by a tangential motion of the broaching tool.

Revacyle® is characterized by its very high productivity, but the only means of influencing the tooth form is the tool. In consequence, this process is suited only for mass production.

A more general-purpose process is hobbing. Here, three different systems are in use, varying only slightly in the tools employed. These are Coniflex®, Konvoid and Sferoid – Coniflex® being the method used most.

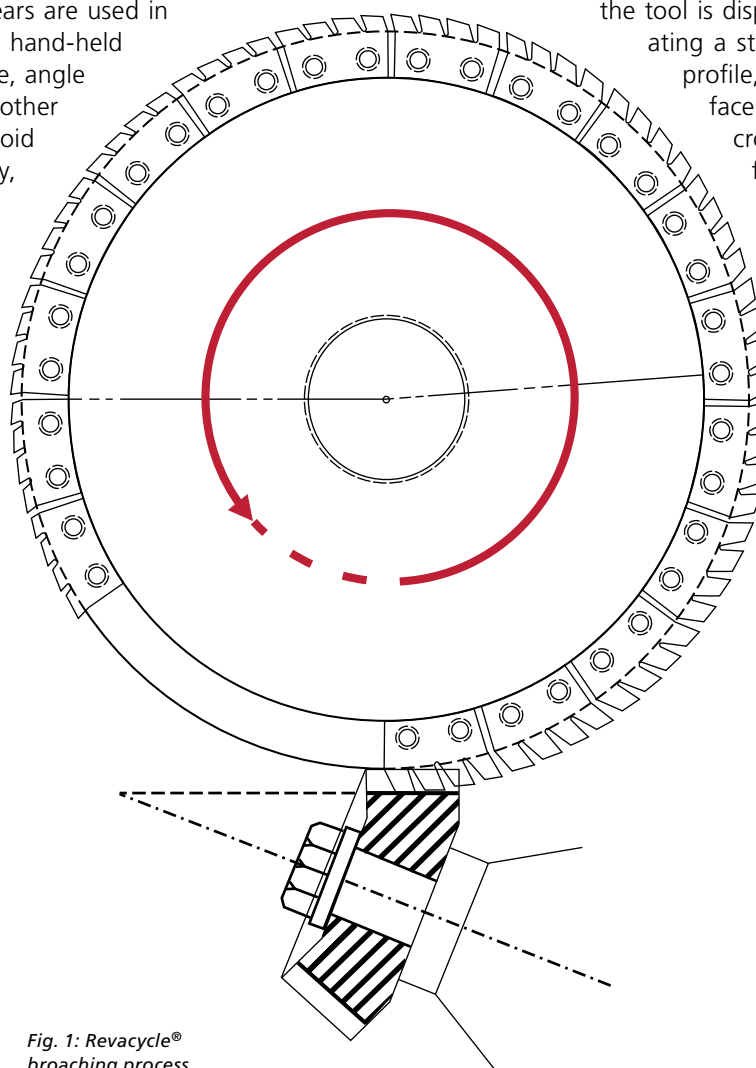


Fig. 1: Revacyle® broaching process

The tool consists of two circular intermeshing side milling cutters, which represent a crown gear tooth. The axes of the two side milling cutters – one for the left flanks, one for the right – are placed at a specific angle to one another, so the cutters alternately intermesh with each other, causing their main cutting edges to form a trapezoid profile. Since the cutting edges are not exactly in the plane of rotation of the respective cutters, but are located on a slight internal taper (see Fig. 2), the teeth receive a fixed lengthwise crowning and a tooth root that is not straight but elliptical, with its lowest point in the middle of the tooth. The tooth's lengthwise curve deviates from the linear depending on the tool and its settings.

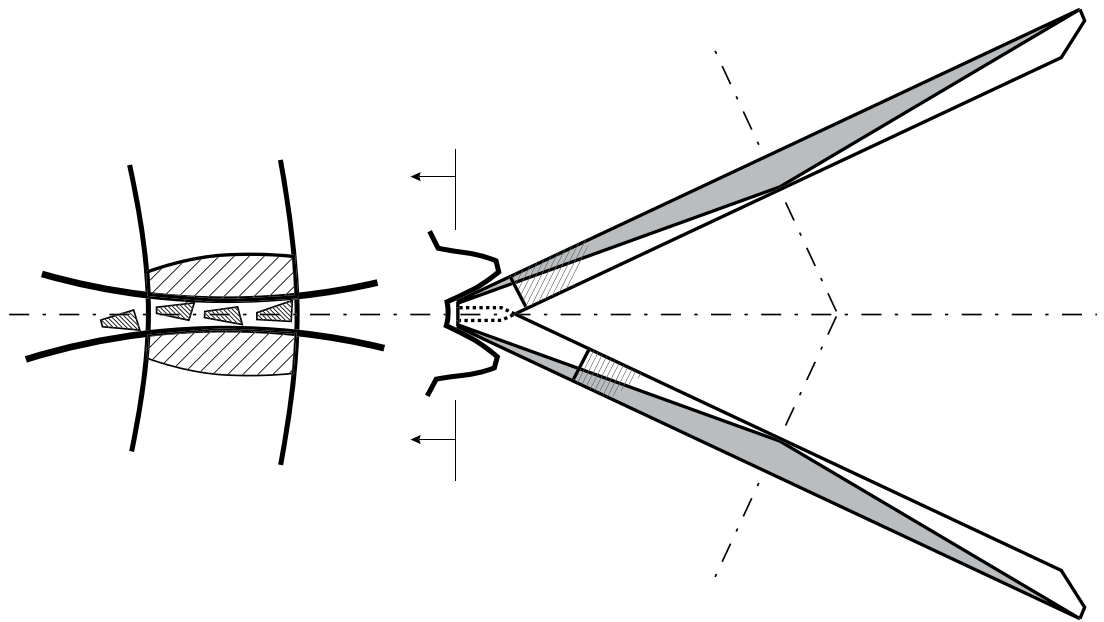


Fig. 2: Hobbing with intermeshing side milling cutters

The lengthwise crowning of the tooth is governed by the angle at which the two side milling cutters are inclined to each other and by the diameter of the tool. A change in this angle entails a change in the flank angle of the cutting edges, since the pressure angle of the tooth is otherwise altered.

The generating motion generates the tooth height profile. The two tools are swivelled round the apex while the workpiece turns on its axis. By means of different machine settings, it is possible to manufacture different bevel gears with a single tool.

Hobbing and broaching processes have been established for many years. The technology of these cutting processes dates back to the nineteen-sixties. They are wet cutting processes performed at relatively low cutting speeds. In terms of productivity and flexibility, they can no longer be compared to the dry cutting processes used today.

As opposed to spiral bevel gears, no software tools as known there are used. No modern program exist for dimensioning the gear or for the calculation and optimization of its contact behavior. Computer-aided topography measurement based on 3D nominal data is also lacking.

Theoretical Bases

Single-indexing and continuous-indexing processes are common for spiral bevel gears, employing face cutter heads as tools. Single-indexing processes machine single tooth gaps successively. The cutters are arranged in a circle and generate an arc-shaped lengthwise tooth form.

If an outer circle is rolled off on another circle, an epicycloid is created. The circle that is rolled off is usually referred to as the rolling circle, with the radius E_b , and the fixed circle as the base circle, with the radius E_g . If the generating point of the epicycloid lies within the rolling circle, the resulting curve is known as a shortened epicycloid; otherwise, it is called an extended epicycloid (Fig. 3).

Continuous indexing processes employ a face cutter head, whose individual cutting edges are arranged in groups consisting of inner and outer blades. Each group machines one gap.

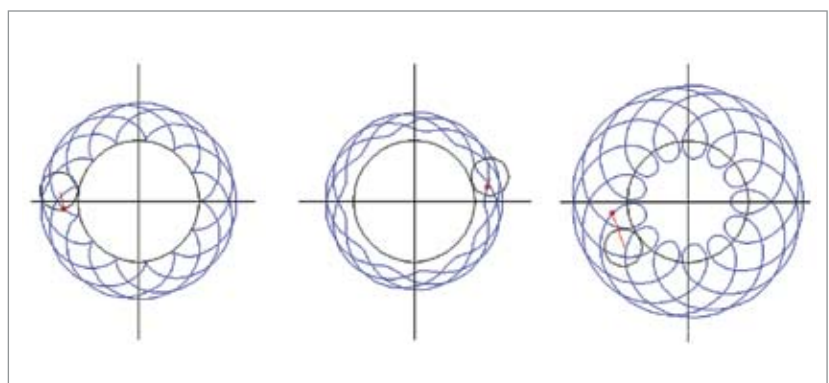


Fig. 3: Epicycloid, shortened and extended epicycloids

The number of groups is referred to as the number of cutter head starts or simply as the number of starts z_0 . In relation to the workpiece, a group of blades moves along an extended epicycloid. In continuous cutting processes for spiral bevel gears, the lengthwise tooth form on the crown gear are therefore sections of extended epicycloids.

When spiral bevel gears are cut in a continuous process, the ratio of the number of starts to the number of crown gear teeth is equivalent to the ratio of the rolling circle radius to the base circle radius:

$$\frac{z_0}{z_p} = \frac{E_b}{E_y}$$

A hypocycloid is produced when the rolling circle rolls on the inside of the base circle (Fig. 4). This is equivalent to reversing the direction of rotation of the cutter head compared to that for cutting an epicycloid.

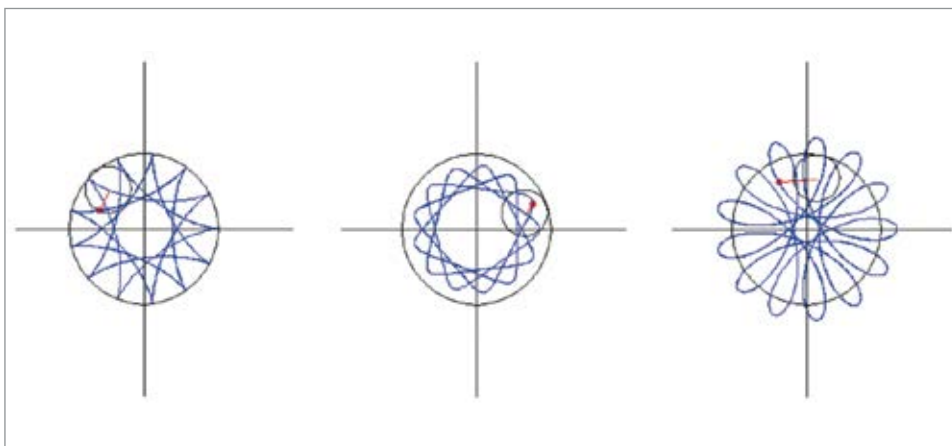


Fig. 4: Hypocycloid, shortened and extended hypocycloids

How is it possible to generate a straight line, and hence a straight tooth, on this basis? In the special case in which the radius of the rolling circle is exactly half the radius of the base circle, all the points generated by a point on the rolling circle will lie on a straight line. In this case, shortened and extended hypocycloids become ellipses.

Hypoflex® Process

The kinematics of the Hypoflex® process rely on the relationship mentioned above [ENG02], i.e. the fact that, in the theoretically exact case, the number of starts corresponds to half the number of crown gear teeth.

The number of crown gear teeth is not usually a whole even number, and only in rare cases the requirement can be fulfilled exactly. Generally, the whole number nearest to half the number of crown gear teeth is chosen as the number of starts. Tooth lengthwise curves (extended or shortened hypocycloids) are then generated with a radius of curvature of several meters, corresponding to a deviation of 2 to 3 µm from the straight line for usual face widths. This is a much smaller deviation than in hobbing or broaching by the methods described above.

The continuous indexing Hypoflex® process is performed both as a completing and as a semi-completing dry cutting operation. In the completing process, a stick blade cutter head, possessing two blades per blade group – one inner and one outer blade – is used to machine the left and right flanks simultaneously, in a single machine setting. In semi-completing, only one cutter head is used, cutting the left flank in one machine setting and the right flank in another. A special feature of the latter process is that only one blade per group is employed. The blade has two cutting edges, and it is called TwinBlade by Klingelberg®. The disadvantage of a longer processing time in semi-completing as opposed to completing must be compared with the greater flexibility and easier realisation of high numbers of starts when only one blade per group is used.

Hypoflex® gears have a tooth height varying over the face width, whose dedendum and addendum angles can be chosen within a meaningful range. This makes it possible to retain the same type of blank when making a change from straight bevel gears previously produced in a different process.

Due to the difference between the root and pitch angles, a helix angle of 0° in the pitch plane can be realized only by cutting with different cutter radii for the inner and outer blade. The size of the difference is partly dependent on the dedendum angle and the pressure angle. The size of the group angle between two successive cutters of the same type in the continuous process is:

$$\omega_{Gr} = \frac{360^\circ}{z_0}$$

As the expert will recognize, a gap width deviating strongly from the desired value would occur when milling with the completing process with a blade sequence angle between the inner and outer blades which equalled half the group angle. It is thus necessary to adapt the blade sequence angle. This means that the blades move closer together in comparison to an operation with bevel gears with a constant tooth height made in a continuous process. The size of the blade sequence angle is dependent on the number of starts, the dedendum angle, the pressure angle, and the rolling circle or base circle radius. This criterion must be taken into account when designing the gear and when selecting a real cutter head.

The usual crownings are generated using various methods of modification. As in other bevel gear cutting processes, lengthwise crowning is produced by tilting the cutter head with adapted pressure angles. If a hollow cone modification is combined with the lengthwise crowning, a contact pattern located in the profile height direction occurs. Another method to generate a profile crowning is to use spherical profile blades. Further contact modifications (contact pattern and ease-off) can be achieved by applying the same method used for spiral bevel gears.

All potential methods of dimensioning the gear and calculating load-free contact behavior and load contact, including stresses, that are state-of-the-art technology for spiral bevel gears [KIM08] are also used for Hypoflex®. For the first time, it is also possible, to measure the gear against 3D nominal data, using a computer-based calculation of the possible required machine setting corrections. This enables the user to produce straight bevel gears by the Hypoflex® method in a closed-loop operation, with in-process testing of all quality-relevant attributes.

Using this process, straight bevel gears can be produced on existing Oerlikon bevel gear cutting machines, the only requirement being to update the machine software. The same applies for the cutter head adjusting device and the dimensioning and correction software. For the cutting operation itself, it is possible to use existing ARCON® cutter heads with appropriate stick blades and numbers of starts.

Advantages of the Hypoflex® Process

The Hypoflex® process can be used to manufacture straight bevel gears in a cutting operation. It is a continuous-indexing cutting process, employing a face cutter head with stick blades as the tool. Apart from its pioneering use of the latest dry cutting technology in the straight bevel gear sector, it has the further advantage of great flexibility. It achieves high productivity by using cemented carbide tools with correspondingly high cutting speeds.

The Hypoflex® cutting process can be realized on the same CNC bevel gear machines as are used to manufacture spiral bevel gears. The only necessity is to update the machine software. The straight bevel gears are dimensioned using the KIMoS 5 program already known in the spiral bevel gear production, which calculates not only the machine settings, tool data, contact pattern, and ease-off optimization, but also the nominal test data and load contact analysis. All required data are stored in the KIMoS database, in the familiar neutral data format.

Apart from an advance in productivity, the Hypoflex® process enables the user to set up modern closed-loop production with all quality-relevant testing conducted in-process. This is achieved by including all the same means for manufacturing, testing and correcting tools and for calculating machine correction settings via the KOMET 3D-topography-based software package that are employed with spiral bevel gears.

Sample Gear

Fig. 5 shows a bevel gear with the data listed in Table 1, designed for the axle drive of an off-road vehicle and cut using the Hypoflex® process.

Some contact analysis results are given in Fig. 6. The ease-off and contact pattern are in line with specifications collated from customers' data.

The gear was cut in a semi-completing process on an Oerlikon C 29 bevel gear cutting machine, using a 14-start ARCON® cutter head with cemented carbide stick blades. TiAlN-coated 3-face blades were employed. The pinion was produced in 4.25 minutes and the wheel in 4.5 minutes. The pitch measurement according to DIN 3965 [DIN 3965] achieved quality 3 for the pinion and quality 2 for the wheel. Topography measurements of the tooth flanks also revealed only minor deviations from the desired surface, in the order of a few micrometres.

This represents a great leap forward in terms of both productivity and quality, as compared to the processes used to date.



Fig. 5: Bevel gear cut in the Hypoflex® process

Gear data

	Pinion	Wheel
Number of teeth	13	24
Pressure angle	Grad	22,5
Outer pitch diameter	mm	174,17
Outer transverse module	mm	7,2571
Mean normal module	mm	5,9543
Face width	mm	35,56
Outer whole depth	mm	14,74

Table 1

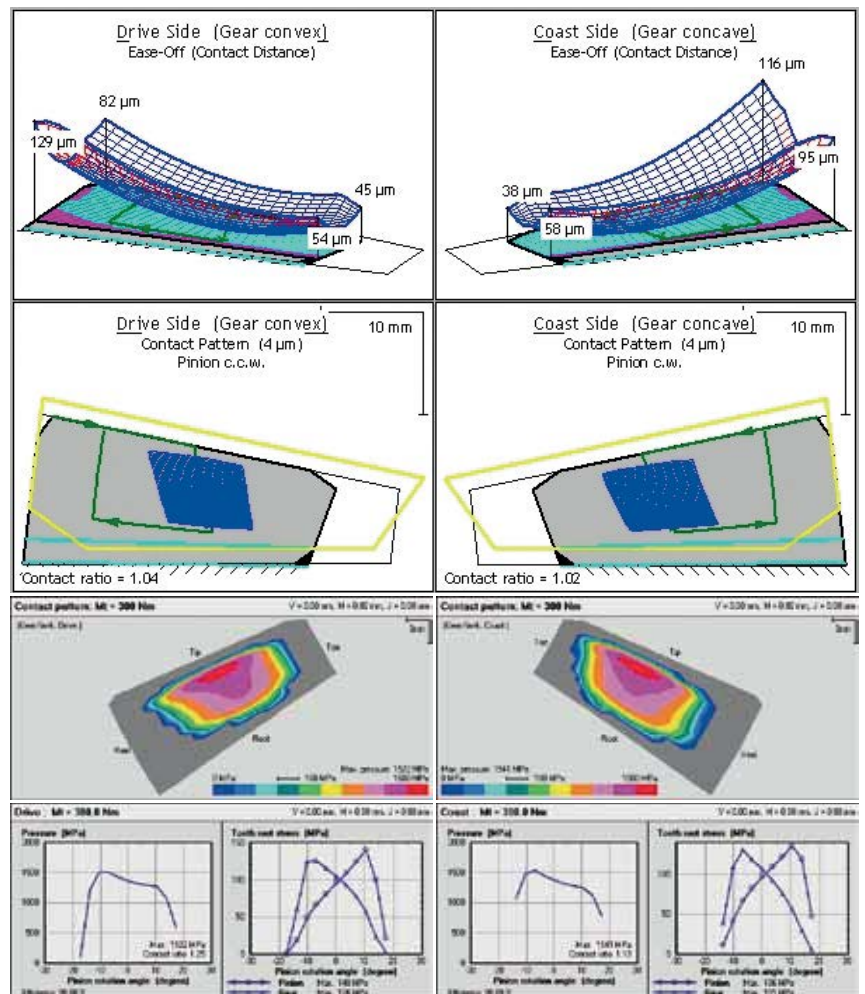


Fig. 6: Results of contact analysis

What are Cycloids?

A cycloid is the path which a point on a circle describes if it is rolled off without sliding on a guiding curve, for instance a straight line or a circle. Cycloids, for which the guiding curve is a circle, are particular interest in the bevel gears because they can be accomplished through a machine technology which combines the rotations of the tool and the workpiece. Cycloids do not describe the profile of the tooth in the height axis, but the longitudinal curve of the tooth on the crown gear.

The circle that rolls is normally named the rolling circle, with the E_b radius, and the fixed circle is called the base circle, with the E_y radius.

If the rolling circle is rolled off externally on the base circle, an epicycloid is created. If the generating point in this process is inside the rolling circle, i.e. if $r_c < E_b$, the result is referred to as a shortened epicycloid, otherwise ($r_c > E_b$) it is termed an extended epicycloid. The parameters for a general epicycloid are:

$$x = (E_y + E_b) \cdot \cos \alpha - r_c \cdot \cos \left(\frac{E_y + E_b}{E_b} \cdot \alpha \right)$$

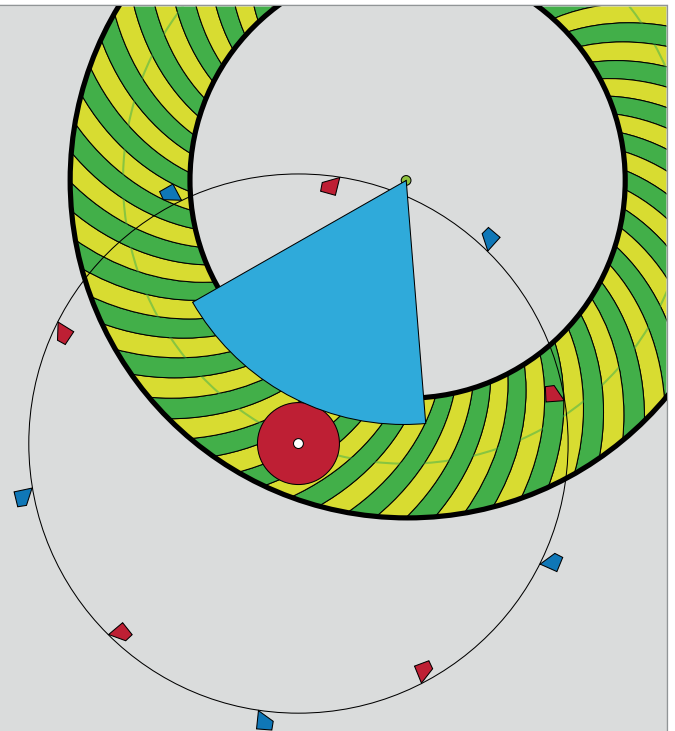
$$y = (E_y + E_b) \cdot \sin \alpha - r_c \cdot \sin \left(\frac{E_y + E_b}{E_b} \cdot \alpha \right)$$

in which α is the angle on the base circle.

When the cutting spiral bevel gears in a continuous process, the tooth traces on the crown gear are sections of extended epicycloids. The ratio of the number of starts to the number of teeth may be regarded as an indexing ratio of the gear making machine.

The circular arcs resulting from the single indexing process can be understood as special forms of the epicycloid, in which the radius of the rolling circle goes down to zero. The number of starts and hence the partial transmission ratio are then also zero.

If the rolling circle is rolled off on the inside of the base circle, a hypocycloid is created. This is equivalent to reversing the direction of rotation of the cutter head during cutting, and the partial transmission ratio has a sign opposite to that for epicycloids.



Hypocycloids may again be extended or shortened, depending on the position of the generating point with the r_c radius. The parameters of a general hypocycloid are:

$$x = (E_y - E_b) \cdot \cos \alpha + r_c \cdot \cos \left(\frac{E_y - E_b}{E_b} \cdot \alpha \right)$$

$$y = (E_y - E_b) \cdot \sin \alpha - r_c \cdot \sin \left(\frac{E_y - E_b}{E_b} \cdot \alpha \right)$$

How can a straight line and hence a straight gear be generated? In the special case in which the radius of the rolling circle E_b is exactly equal to half the radius of the base circle E_y , all the points generated by a point on the rolling circle will be located on a straight line. In this case, shortened and extended hypocycloids become ellipses.

Given appropriate tool parameters, i.e. a number of starts which corresponds to half the number of crown gear teeth, a straight line is generated as the lengthwise tooth form of the tooth in the continuous process.

Literature

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