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ANALYSIS OF SPEED RATIOS OF SIMPLE CYCLOID DRIVE WITH STEPPED PLANETS

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Abstract: Due to the complicated and costly construction, the use of drive train with cycloid gears was avoided in the past. With the development of the modern CNC machining centers, it is possible to make the production process of these gears cheaper and simpler. The drive trains with cycloidal profile gears are mainly planetary drive trains, which are used today as speed reducers. They can achieve high speed ratio in single stage and have many advantages, as compactness and simplicity of production. Simple cycloid drive with stepped planets is a special variant of planetary drive train. It is a type of high sensitivity dive train which can realize high speed ratio in single stage. In this paper are shown the basic equations of speed ratios for different working conditions. By theoretical analysis, it can be noticed that a simple cycloid drive with stepped gear can achieve very high speed ratio while achieving small overal dimensions.
Keywords: cycloid drive, speed ratio, planetary drive train

INTRODUCTION

The drive trains with cycloidal profile gears are mainly planetary drive trains, which are used today as speed reducers. They can achieve high speed ratio in single stage and have many advantages, as compactness and simplicity of production. In addition, by using special cycloid stepped planets (figure 1), the total weight of drive trains can be further reduced.

Figure 1. Small cycloid stepped planets

Due to the complicated and costly construction, the use of drive train with cycloid gears was avoided in the past. With the development of the modern CNC machining centers, it is possible to make the production process of these gears cheaper and simpler. Because of very wide area of application, production of cycloid drives has growing character and wide area of application: processing equipment, conveyors, presses, mixers, food industry, robots, automotive plants, spinning machines, cranes, etc.

Despite the very common use of cycloid drive trains as speed reducers, they can also be used as speed increasers. Therefore, it is necessary to examine all the possibilities of the cycloid drive train with stepped planets, in order to get a clear picture of its transmission capabilities.

SIMPLE CYCLOID DRIVE

In the analysis of a simple cycloid drive, it can be started from an elementary planetary mechanism with internal coupling, replacing, for example, classic involute gears with cycloid gears (figure 1a). Members of the planetary mechanism whose axis coincides with the central axis and receive the external torques are called the *basic members* [1].

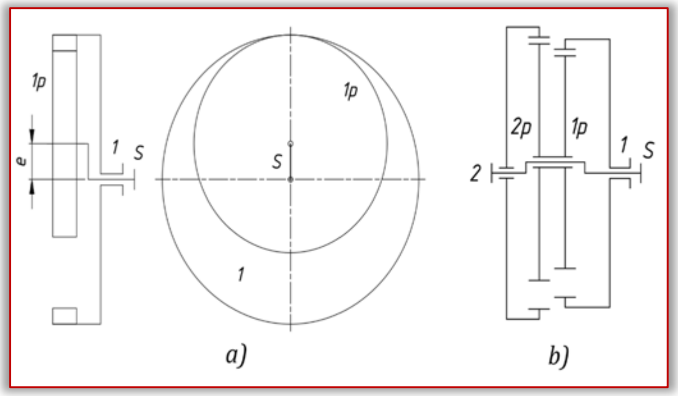

Figure 2. Transformation from elementary mechanism to simple cycloid drive with stepped planets

The members of the elementary mechanism, the central gear (*1*) and the carrier (*S*), whose axes of rotation coincide with the base axis, can't be used in this case for the transfer of energy. In order to achieve this, one elementary member must be added to the elementary planetary mechanism. This gives a *simple cycloid drive* or *three-shaft cycloid drive*.

This can be accomplished by adding another central ring gear (*2*) with the pins placed on the periphery, which meshes with the second cycloid gear (*2p*) (figure 1.b). The cycloid gears (*1p*) and (*2p*) are tightly connected in this case. In literature, such planets are called *stepped planets* [2, 3].

SPEED RATIOS

It will be analyzed only drives with the numbers of pins of ring gear by one greater than the numbers of teeth of cycloid planet gear. The gear drives shown in figure 2b have two degrees of freedom (DOF). By blocking one of the basic members, a *two-shaft cycloid drive* is provided, which has only one DOF.

When denoting the speed ratio, it is necessary to make a difference when denoting the speed ratios of three-shaft cycloid drive with two DOF from two-shaft cycloid drive with one DOF. Therefore, in this study, will be used proposal [4], that the symbol "*i*" means only a constant, design dependent speed ratios (with one DOF).

The order of two subscripts denote the order of input and output members. For the speed ratios of simple cycloid drive train with two DOF, will be used the symbol "*k*", so that, for example,

$$k_o = k_{12} = \frac{n_1}{n_2} = \frac{1}{k_{21}}, \quad (1)$$

represents the speed ratio between shafts 1 and 2.

The cycloid drive works as classical gearbox (with a fixed axle) when the eccentric shaft is stopped. This simple working mode can be termed as *the basic mode* whereby the *basic speed ratio* is realized:

$$i_o = i_{12} = \left(\frac{n_1}{n_2}\right)_{n_S=0}, \quad (2)$$

where is: n_1- speed of ring gear shaft *1*,
n_2- speed of ring gear shaft *2*,
n_S- speed of eccentric shaft *S*.

The complex general state of motion of a simple cycloid drive can be explained as the superposition of two partial motions. The first partial motion is the rotation of central ring rear (turning and meshing with planets), relative to the carrier. The second partial motion is an equal rotation of all shafts of basic members and it is same as rotation of carrier (eccentric shaft *S*).

If the two partial motion are superimposed, the total speed of each shaft is obtained as the algebraic sum of its partial speed. Thus the basic speed ratio become [3, 5]:

$$i_o = \frac{n_1 - n_S}{n_2 - n_S}, \quad \text{so that} \quad (3)$$
$$n_1 - i_o n_2 + (i_o - 1) n_S = 0,$$

From the equation (3), the shaft speed of a simple cycloid drive is obtained as follows:

$$n_1 = i_o n_2 + (i_o - 1) n_S,$$
$$n_2 = \frac{n_1 - n_S (1 - i_o)}{i_o}, \quad (4)$$
$$n_S = \frac{n_1 - i_o n_2}{1 - i_o}.$$

It is possible to derive the equations for all speed ratios of simple cycloid drive with stepped gear (Table 1).

Table 1. Equations of speed ratios of simple cycloid drive

Reduced notation	Speed ratio $f(k_o)$
$k_{12} = i_o + (1 - i_o) k_{s2}$	$k_{12} = k_o$
$k_{21} = \frac{1}{i_o} + \left(1 - \frac{1}{i_o}\right) k_{s1}$	$k_{21} = \frac{1}{k_o}$
$k_{1S} = (1 - i_o) + i_o k_{2S}$	$k_{1S} = \frac{1 - i_o}{1 - \frac{i_o}{k_o}}$
$k_{S1} = \frac{1 - i_o k_{21}}{1 - i_o}$	$k_{S1} = \frac{1 - \frac{i_o}{k_o}}{1 - i_o}$
$k_{2S} = \frac{k_{1S} - (1 - i_o)}{i_o}$	$k_{2S} = \frac{1 - i_o}{k_o - i_o}$
$k_{S2} = \frac{k_{12} - i_o}{1 - i_o}$	$k_{S2} = \frac{k_o - i_o}{1 - i_o}$

TWO-SHAFT CYCLOID DRIVE SPEED RATIOS

If the numbers of pins of ring gear by one greater than the numbers of teeth of cycloid planet gear, then:

$$i_o = i_{11p} i_{2p2} = \frac{n_1}{n_{1p}} \frac{n_{2p}}{n_2} = \frac{n_1}{n_2} = \frac{z_{1p}}{z_1} \frac{z_2}{z_{2p}} = \frac{z_2 (z_1 - 1)}{z_1 (z_2 - 1)}, \quad (5)$$

where is: $n_{1p} = n_{2p}$ – speed of stepped planets,
z_{1p} - the number of teeth on a cycloid gear *1*,
z_{2p} - the number of teeth on a cycloid gear *2*,
i_{11p} - speed ratio between gear *1* and cycloid *1*,
i_{2p2} - speed ratio between cycloid 2 and gear 2.

The speed ratios of the tree possible two-shaft cycloid drive can be obtained using equations from Table 1, by setting appropriate speed ratios equal to zero if shaft was stopped (Table 2).

Table 2. Speed ratios of two-shaft cycloid drive

Working mode	Speed ratio $f(z_1, z_2)$
Minimum increase	$i_{12} = \frac{z_2 (z_1 - 1)}{z_1 (z_2 - 1)}$
Minimum reduction	$i_{21} = \frac{z_1 (z_2 - 1)}{z_2 (z_1 - 1)}$
Maximum increase	$i_{1S} = \frac{z_2 - z_1}{z_1 (z_2 - 1)}$
Maximum reduction	$i_{S1} = \frac{z_1 (z_2 - 1)}{z_2 - z_1}$
Reversible increase	$i_{2S} = \frac{z_1 - z_2}{z_2 (z_1 - 1)}$
Reversible reduction	$i_{S2} = \frac{z_2 (z_1 - 1)}{z_1 - z_2}$

Equations that determine the speed of the shafts of the basic members, for two-shaft cycloid drive, can also be written in matrix form. If e.g. shaft 1 is input shaft, and shaft 2 is locked, then the following system of equations are valid:

$$\begin{aligned} n_1 - i_o n_2 + (i_o - 1) n_S &= 0 \\ n_1 &= n_{in} \\ n_2 &= 0 \end{aligned} \tag{6}$$

where is: n_{in}- speed of input shaft *1*,

This system of linear equations can be written in matrix form:

$$\begin{bmatrix} 1 & -i_o & (i_o - 1) \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} n_1 \\ n_2 \\ n_S \end{bmatrix} = \begin{bmatrix} 0 \\ n_{in} \\ 0 \end{bmatrix} \Rightarrow [C_N]\vec{n} = \vec{e_n} \tag{7}$$

where is: $[C_N]$ - coefficient matrix,

$\vec{n}$ - vector of unknown shaft speeds,

$\vec{e_n}$ - input shaft speed vector.

System (7) can be solved using mathematical programs for working with matrices. In order to obtain values of unknown speeds, the system must be set up as follows:

$$\vec{n} = [C_N]^{-1}\vec{e_n} \Rightarrow \begin{bmatrix} n_1 \\ n_2 \\ n_S \end{bmatrix} = \begin{bmatrix} n_{in} \\ 0 \\ \dfrac{n_{in}}{1 - i_o} \end{bmatrix} \tag{8}$$

ANALYSIS OF SPEED RATIOS

Basic speed ratio, given in equation (2), shows, if the condition $z_1 < z_2$ is satisfied, then $i_o < 1$. Also, simple cycloid drive is a positive drive train ($i_o > 0$) [5].

The analysis of speed ratios will be considered regardless of the possibility of self-locking, which is present in high-sensitivity planetary gear trains [6]. Self-locking can occur if the teeth numbers are equal $z_1 = z_2$ (the gearbox acts as a coupling) and if $i_o \geq \eta_o$ [7], where η_o is *basic efficiency*. The last case can occur when $z_2 - z_1 = 1$, but because $\eta_o \approx 1$ it is possible only for higher values of z_1.

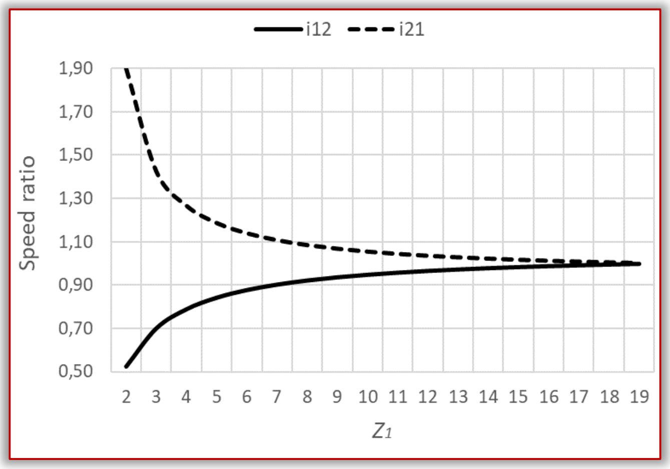

Figure 3. Basic speed ratios

In order to understand the nature of the change in speed ratios, the theoretical model of a simple cycloid drive with stepped planets will be considered, where $z_2 = 20$, while the number of pins of ring gear *1* are changing from $z_1 = 2 \div 19$.

In figure 3, the function of the change of the basic speed ratios is shown. It can be noticed that by approaching the number of pins z_1 to z_2, the basic speed ratio tends to $i_o = 1$ (self-locking occur).

— Reduction speed ratios

Cycloid drive train are mainly used as speed reducers. The variant with stepped planets is not used in practice for now, so it is very interesting to examine its possibilities.

Figure 4 shows the changing in speed ratios for maximum reduction (i_{S1}) and reversible reduction mode (i_{S2}). Number of pins of ring gear 2 is constant $z_2 = 10$ and number of pins of ring gear 1 are changing $z_2 = 2 \div 19$.

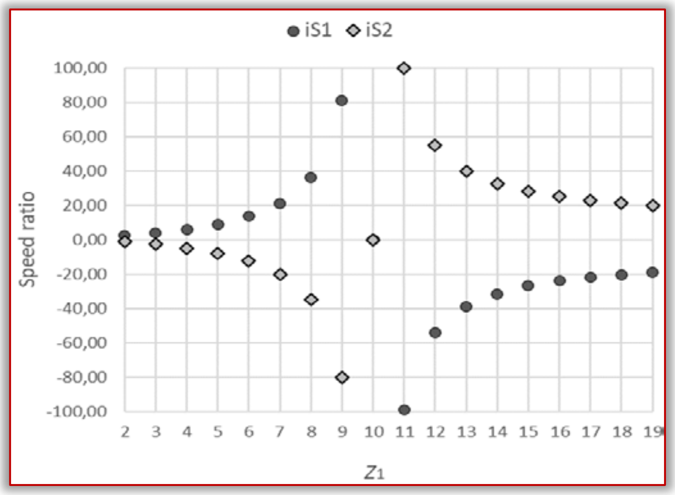

Figure 4. Reduction speed ratios

One can notice a sudden increase in the speed ratio, when number of pins z_1 is approaching to z_2.

— Increasing speed ratios

For the analysis of speed ratios in increase modes, the same settings will be used as for reducer modes, i.e. number of pins of ring gear 2 will be constant, while number of pins of ring gear 1 will change.

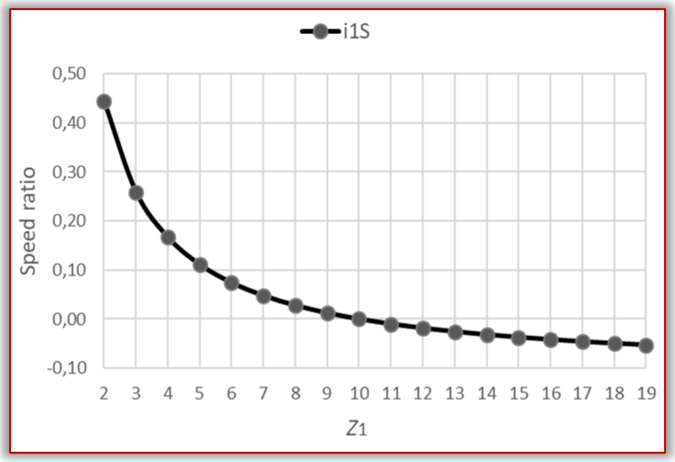

Figure 5. Maximum increase speed ratios

On figure 5 is shown the changing in the speed ratios for maximum increase mode (i_{1S}).

In figure 6, the function of the change of the speed ratios for reversible increase mode (i_{2S}) is shown.

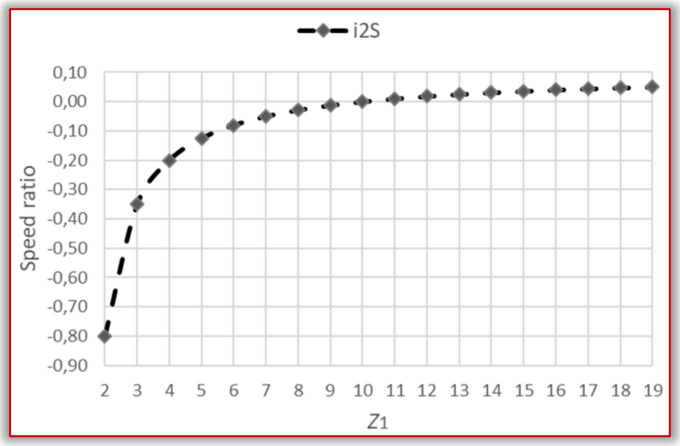

Figure 6. Reversible increase speed ratios

The speed ratio is equal to zero if $z_1 = z_2$. When $z_1 > z_2$ the sign of speed ratio is changing and shaft of ring rear 2 become summation shaft [7].

If the pins number of ring gear 2 is constant, it can be noted from an analysis, that there is no significant increase of speed ratio with increasing the pins number of ring gear 1. However, if the cycloid drive is loaded with higher torque, then it is desirable to use larger numbers of pins due to a more even distribution of forces on the ring gear.

CONCLUSION

The cycloid drive with stepped planets can achieve very large speed ratios, while using ring gears with a relatively small number of pins. This makes it possible to design high speed ratio cycloid drive train of small dimensions and mass.

Increasing the number of pins of ring gear 1, with a constant number of pins on the other ring gear, does not significantly increase the speed ratio. Therefore, when designing these drive train, it is necessary to first consider variants with smaller numbers of pins, with checking the total load capacity.

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