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An Unordinary Gear Pump with Flexspline

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Abstract: In order to solve the problem of radial pressure existed in current gear pumps, an unordinary pump called flexspline gear pump is invented in this study where the pumping function for fluid is achieved by the inner gearing between two gears of flexspline and circular spline. The necessary aspects regarding the composition, operating principle, features and calculation of the new gear pump are provided. Excellent performances of the new pump are respresented by its balanced radial pressure on the drive shaft, double displacement and longer service life of the pump. The proposed new pump offer innovative ideas for upgrading the classical gear pumps.

Key words: Gear pump, radial pressure, harmonic gear drive, flexspline, internal gear pump

INTRODUCTION

Gear pumps are the preferred solution to perform the mechanical-hydraulic energy conversions in many fluid power applications (Vacca and Guidetti, 2011), in particular in automotive industry for engine oil lubrication and transmission systems (Bonandrini *et al*., 2012). Throughout gear pumps all over the world at present, many designs are available depending on the application, nevertheless the gear pumps are structurally nothing more than two types: The external gear pump and the internal gear pump, they are all composed of two rigid gears or circular splines (Feature, 1999; He, 1982; Zhu, 1988).

The pressure in the inlet port is lower in the operating process of the gear pump, the pressure in the outlet port is higher. Radial force, caused by the pressure difference between the inlet and outlet ports, acts vertically on the pump shaft. Bending deformation of the shaft is inevitable and internal leakage will increase because of variation in the sealing clearance. Gears will come in contact with the casing in a zone near the lower pressure chamber, friction and wear of moving pairs and bearing load are increased. There is bigger radial force with the escalating output pressure, as a result, the bearings wear out faster and the pump will be scrapped in advance (Zhu and Min, 1999; Zhu, 2002).

To reduce the influence caused by the radial pressure, researchers have specifically come up with following ways, for instance narrowing the discharge chamber, expanding the suction chamber, milling relief grooves in the internal face of bearing blocks to communicate with the high or low pressure chambers, shortening the tooth width and diameter of addendum circle, increasing modulus of gears and reducing the tooth number or using flexible bearing as individually (He, 1982; Zhu, 1988; Zhu and Min, 1999). Although, there are certain effects for these measures, the results were less than optimal. The problem has not been solved fundamentally. The service lives of gear pumps are far from the setting values up to now.

THE CONCEPTION OF FLEXSPLINE GEAR PUMP

Based on the combination of current gear pump with gear train transmission, a planetary gear pump, having several planetary gears arranged symmetrically around the center gear was invented to balance the radial pressure (Li, 2003). Complicated geometric construction of the planetary gear pump introduces difficulties in its design and manufacturing associated with more number of components, the volume and weight of the pump are greatly increased. Nonetheless, the planetary gear pump gave us a revelation: Symmetric structure is an effective method to ensure even load bearing and to achieve force balance on a component. Therefore in this study, an unordinary pump called flexspline gear pump is presented to settle the problem of radial pressure based on the symmetry principle and inspired by the balanced vane pump (He, 1982; Giuffrida and Lanzafame, 2005).

Flexspline gear pump, an innovative idea borrowed from the principle of harmonic gear (Rathindranath, 2004; Rao, 1994) is mainly composed of external circular spline (i.e., rigid gear), flexspline (i.e., flexible internal gear), sealing blocks, rollers, casing and end cover as shown in Fig. 1. The circular spline and flexspline rotate and mesh each other, two mating gears

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have the same tooth width and circular pitch but different tooth number (the tooth number of flexspline is slightly more than that of circular spline). Flexspline, a thin wall ring gear which can produce large elastic deformation, becomes an oval-shape bound by two roller. Crescent-shaped sealing blocks are set in radial direction between the addendum arc surfaces of two gears matching closely with two side plates (Fig. 1) in the axial direction. The two gears, two sealing blocks and two side plates separate the space between the circular spline and flexspline into two chambers a for oil absorption and two chambers b for oil extrusion. Accordingly, there are two oil supply holes (corresponding to lower pressure chamber a) and two oil drain holes (corresponding to higher pressure chamber b) on the side plates symmetrically and the holes are connected with inlet and outlet hoses outside of the pump, respectively.

Similar to the process of pumping in the internal gear pump, flexspline gear pump inhales and extrudes fluid by means of periodic variation of sealing volume with the rotation of two meshing gears. While, the circular spline rotates counterclockwise driven by the flexspline is driven to rotate in the same direction (Fig. 1). A partial vacuum is produced in the chambers a arranged symmetrically where the teeth on two gears separate because the sealing volume between teeth glows bigger gradually. So, the oil in a tank is forced by atmospheric pressure into two suction chambers a through the intake hose, two axial suction holes on the side plates. Teeth grooves are then full of oil which is trapped between the teeth of two gears and sealing blocks.

As the gear turn towards two chambers b arranged symmetricaly, the trapped oil increases progressively its pressure up to the high pressure. In the gear meshing area when two tooth pairs come in contact, a trapped volume could undergo a sudden volume reduction. Continued rotation of gears carries the oil to chambers b where the volume in isolated space grows smaller, forces the oil between grooves out of the chambers b to drain hose through two axial discharge holes on the side plates. This is the working principle of the flexspline gear pump.

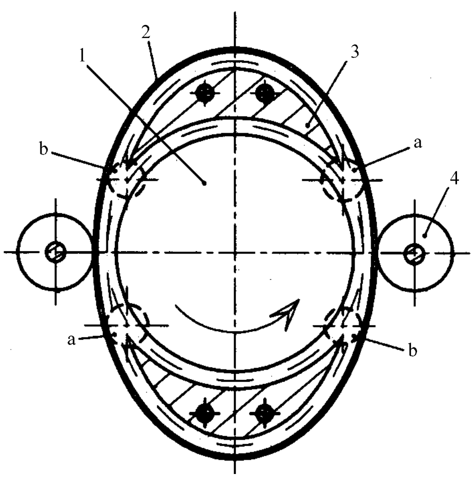

Fig. 1: Principle diagram of flexspline gear pump: 1) Circular spline; 2) Flexspline; 3) Sealing block; 4) Wheel; a) Suction chamber; b) Extrusion chamber

BASIC PARAMETERS OF FLEXSPLINE GEAR PUMP

Structural scheme: The structure design on the flexspline gear pump is related to its motion pattern. There are mainly three kinds of motion patterns in the new gear pump:

The circular spline is a driving gear and the flexspline is a driven gear, the wheel spins *in situ* (Fig. 1). Both gears rotate in the same direction, however at different speeds because of the relation between the teeth, being slightly faster for the circular spline than the flexspline. The angular velocity ratio is Z_2/Z_1 where Z_1 and Z_2 are tooth number of circular spline and flexspline, respectively.

The flexspline is a driving one while the circular spline is driven, the wheel spins around its original position. Two gears rotate in the same direction, being slightly faster for the flexspline than the circular spline at this time. The angular velocity ratio is Z_1/Z_2 now.

The wheel is a driving one and the flexspline is a driven gear, the circular spline holds still. The flexspline rotates slowly in the same direction with the wheel. The speed ratio of wheel to flexspline is $Z_2/(Z_2-Z_1)$.

Distribution mechanism for oil in the pump is simpler in the first two transmission patterns and the oil distribution is relatively difficult in the final case. The structural schemes are very different for the lateral plates, sealing arrangement and casing of pump in different patterns which must be seriously considered. The first case is adopted in this study.

Essential meshing parameters: A pair of involute gears within the new gear pump are the core components, the parameters of the gears (such as the tooth number, module and tooth width of gears) are main factors determining the performance of the new pump. Variety of design schemes could be obtained for the combination of different parameters, the displacement and the volume of the pump to be designed are different.

The structure calculation of the new pump in a first stage of design should not only conform to the principles of gear pump design but also meet the requirements in

Table 1: The basic meshing parameters of gears

Form of gear drive		Cylindrical gear drive	Harmonic gear drive	
Types of gear	Symbol	Standard cylindrical gear	Flexspline	Circular spline
Addendum coefficient	h^*_a	1.00	0.65	1.0
Coefficient of dedendum	h^*_f	1.25	1.35	1.2
Whole depth coefficient	h^*	2.25	2.00	2.2
Bottom clearance coefficient	c^*	0.25	0.70	0.2

harmonic gear drive. Formulas well-known in general gear transmission cannot be completely applied to parameters calculation for gears in the new gear pump since the internal gear is a flexible component.

For example, as far as the normal teeth with involute tooth profile and a pressure angle of 20° on the reference circle are concerned, the addendum coefficient, coefficient of dedendum, whole depth coefficient and bottom clearance coefficient of standard cylindrical gear in conventional cylindrical gear drive are different from those of flexspline (or flexible gear) and circular spline (or rigid gear) in harmonic gear drive (Fan and Cao, 1995). The comparison of these parameters is given in Table 1.

Undergoing alternating stress in the operating process of the new gear pump, flexspline must have enough fatigue strength in designing of the new pump which is the basis to calculate the tooth number of the flexspline. Tooth number of >40 for the flexspline is recommend from the point of view to reduce the deformation of flexspline and to ensure its fatigue strength (Zhu *et al*., 2013). Tooth number difference between the circular spline and flexspline should be equal to the number of deformation wave or integral times of the wave-number in flexspline to harmonic gear drive (Rao, 1994; Zhu *et al*., 2013). It seems more appropriate to take 4 or 6 as the tooth number difference, considering that two sealing blocks need to be installed between the circular spline and flexspline in the new pump. Modulus of gears is determined by desired displacement of the new pump, bearing capacity and meshing performance of two gears.

Calculation on geometric size for gears: Decomposing the gears in the new pump into two kinds of gears: External circular spline and flexible internal gear and if the meshing parameters of gears are determined, geometric size for two gears could be calculated based on the formulas in general gear transmission and harmonic gear drive, respectively. These geometric calculations are now arranged in Table 2, to guide the designer to conduct structure design of the new pump.

Table 2: Equations of geometrical size for gears

Parameters and dimensions	Symbols	Equations: Circular spline	Equations: Flex spline
Number of teeth	Z	Z_1	Z_2
Module (mm)	m	m	m
Pressure angle at reference circle (deg)	α	$\alpha = 20°$	$\alpha = 20°$
Addendum (mm)	h_a	$h_{a1} = m$	$h_{a2} = 0.65$ m
Dedendum (mm)	h_f	$h_{f1} = 1.2$ m	$h_{f2} = 1.35$ m
Tooth depth (mm)	h	$h_1 = 2.2$ m	$h_2 = 2$ m
Diameter of reference circle (mm)	d	$d_1 = mZ_1$	$d_2 = mZ_2$
Diameter of base circle (mm)	d_b	$d_{b1} = d_1\cos\alpha$	$d_{b2} = d_2\cos\alpha$
Diameter of addendum circle (mm)	d_a	$d_{a1} = d_1+2h_{a1}$	$d_{a2} = d_2-2h_{a2}$
Diameter of dedendum circle (mm)	d_f	$d_{f1} = d_1-2h_{f1}$	$d_{f2} = d_2+2h_{f2}$
Pressure angle at addendum circle (deg)	α_a	$\alpha_{a1} = \cos^{-1}(d_{b1}/d_{a1})$	$\alpha_{a2} = \cos^{-1}(d_{b2}/d_{a2})$
Tooth thickness at addendum circle (mm)	S_a	$S_{a1} = [0.5\pi/Z_1-(\text{inv}\alpha_{a1}-\text{inv}\alpha)]\, d_{a1}$	$S_{a2} = [0.5\pi/Z_2+(\text{inv}\alpha_{a2}-\text{inv}\alpha)]d_{a2}$

Volumetric characteristics: Volumetric characteristics mainly contain instantaneous flow, volume variation or flow pulsation rate, displacement and theoretical flow rate. The method to calculate the volumetric characteristics is the derivative approach which are summarized as follows (He, 1982):

Instantaneous flow: The volume of liquid discharged in an instant is called the instantaneous flow of the pump. By using the equations (He, 1982), the instantaneous flow of the new pump can be derived as:

$$Q_{inst} = \frac{1}{30}\pi B m^2 n \begin{bmatrix} 1.65Z_1 + 1 - 0.4225\frac{Z_1}{Z_2} - \\ 0.2208\left(1-\frac{Z_1}{Z_2}\right)(Z_1\varphi_1)^2 \end{bmatrix} \quad (1)$$

Where, φ_1 is the rotation angle of the circular spline, rad.

Flow pulsation rate: During the process of gears engagement, rate of change in volumetric capacity is not constant in the suction and discharge chambers. Therefore, instantaneous flow rate is fluctuating for the gear pump. Flow pulsation rate σ is commonly used to evaluate the fluctuant situations of instantaneous flow. The flow pulsation rate is defined as:

$$\sigma = \frac{Q_{max} - Q_{min}}{Q_{ave}} \quad (2)$$

According to He (1982) and using the Eq. 1 and 2, the flow pulsation rate of the new pump is given by:

$$\sigma = \frac{3.2667(Z_2 - Z_1)}{Z_1 + 2.4734Z_2Z_1 - 0.1343Z_2} \quad (3)$$

It was clear that the flow pulsation rate is a function of tooth number of two gears, f (Z_1, Z_2).

Displacement: Without considering the leakage in the new gear pump, the volume of liquid extruded per revolution of the circular spline is referred to as the displacement of the pump (also known as geometric displacement). From Eq. 1, the displacement of the new pump is obtained by:

$$q = 2\pi Bm^2\left(\frac{1.65Z_1 + 0.3038Z_1}{Z_2 + 0.2737}\right) \quad (4)$$

It is shown that the displacement, based on five design parameters is a function of f (B, m, Z_1, Z_2).

Theoretical flow rate: Without considering the leakage in the new gear pump, the volume of liquid output per unit time is called the theoretical flow rate of the pump. It is associated with the speed n of pump shaft and the displacement q and can be calculated as:

$$Q_{th} = \frac{qn}{60} \quad (5)$$

Where, q is displacement of the new pump, computed according to Eq. 4. It is visible from above, the volumetric characteristics of the new gear pump can be based on basic design parameters (He, 1982).

Advantages of flexspline gear pump: Flexspline gear pump achieves the function to inhale and extrude fluid based on a pair of circular spline and flexspline which are meshing properly with each other, two radial sealing blocks and side plates in axial direction. The new gear pump conceived in this study has the following advantages compared with current gear pumps composed of two rigid gears widely used in the world.

Radial forces are balanced: The radial force on gears, caused by higher pressure liquid in two delivery chambers are hydraulically balanced because of the symmetrical structure and two higher pressure chambers placed symmetrically which decreases greatly the bearing on drive shaft of loads and helps to improve the service life of the pump.

Displacement is doubled: The displacement of the new pump is 2 times that of conventional internal gear pump, since there are two delivery chambers and two suction chambers. The pumping efficiency of one new pump is equivalently that of two internal gear pumps. Two ways of output flows can converge and the flow pulsation is improved with stable operation.

Contact stress between the gear teeth is smaller: Flexspline is a thin wall ring gear which can produce larger elastic deformation. The profile of the flexspline is pressed into an oval-shape by two rollers. Teeth near two ends of the short axis of the oval on the flexspline mesh with the teeth on circular spline in a way of surface contact. The load per unit area of each tooth is smaller and the load carrying capacities are higher for the teeth, since more teeth participate in meshing process simultaneously. The magnitude of wear and noise are less because of lower relative sliding velocities on teeth surfaces of gears for the new pump.

It is visible that the new gear pump not only solved the problems of unbalanced radial pressure and bigger flow pulsation existed in current gear pumps with two rigid gears but also overcame the shortcomings of more parts, complex structure and larger volume in planetary gear pump with more gears. The new pump, therefore possesses better performance advantages can be used for upgrading the gear pump products now-a-days.

CONCLUSION

Unbalanced radial pressure, inherent in current gear pump due to its structure, is difficult to eliminate no matter what measures are taken. This fact increases the interests in developing a new way using unordinary strategy on the basis of symmetry principle and knowledge of harmonic gear drive. The new gear pump, characterized by flexspline could guide the future development in the technology of gear pump due to a number of its superiorities in performance. Several superiorities are hydraulic balance on its own, double displacement, few components, less noise and smaller pulsation in flow.

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NOMENCLATURE

Z = Tooh number of gear
m = Module of gear (m)
q = Displacement of the pump ($m^3 r^{-1}$)
B = Axial width of circular spline (m)
Q_{th} = Theoretical flow rate of the pump ($m^3 sec^{-1}$)
Q_{inst} = Instantaneous flow of the pump ($m^3 sec^{-1}$)
Q_{max} = Maximum instantaneous flow of the pump ($m^3 sec^{-1}$)
Q_{min} = Minimum instantaneous flow of the pump ($m^3 sec^{-1}$)
Q_{ave} = Average flow rate of the pump ($m^3 sec^{-1}$)
n = Rotate speed of the pump (rpm)
h^*_a = Addendum coefficient
h^*_f = Coefficient of dedendum
h^* = Whole depth coefficient
h_a = Addendum (m)
h_f = Dedendum (m)
h = Tooth depth (m)
d = Diameter of reference circle (m)
d_b = Diameter of base circle (m)
d_a = Diameter of addendum circle (m)
d_f = Diameter of dedendum circle (m)
S_a = Tooth thickness on addendum circle (m)
α_a = Pressure angle on addendum circle
α = Pressure angle on the reference circle
σ = Flow pulsation rate

Subscripts:

- External circular spline (rigid gear)
- Flexspline (flexible gear)

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