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Rotational Swashplate Pulse Continuously Variable Transmission Based on Helical Gear Axial Meshing Transmission

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Abstract: The current research on pulse continuously variable transmission(CVT) is mainly focused on reducing the pulse degree and making pulse degrees a constant value. Current research mainly confined to find out new design parameters by using the method of optimization, and reduce the pulse degree of pulse CVT and its range of variation. But the fact is that the reduction of the pulse degree is not significant. This article presents a new structure of mechanical pulse CVT—the rotational swashplate pulse CVT with driven by helical gear axial meshing. This transmission is simple and compact in structure and low in pulsatile rate (it adopts 6 guide rods), and the pulsatile degree is irrelevant to the transmission ratio. Theoretically, pulsatile rate could be reduced to zero if appropriate curved surface of the swashplate is used. Compared with the connecting rod pulse CVT, the present structure uses helical gear mechanism as transmission part and it avoids unbalanced inertial force in the former model. This paper analyzes the principle of driving of this transmission, presents its mechanical structure, and discusses its motion characteristics. Experimental prototype of this type of CVT has been manufactured. Tests for the transmission efficiency(when the rotational speed of the output shaft is the maximum) and the angular velocity of the output shaft have been carried out, and data have been analyzed. The experimental results show that the speed of the output shaft for the experimental prototype is slightly lower than the theoretical value, and the transmission efficiency of the experimental prototype is about 70%. The pulse degree of the CVT discussed in this paper is less than the existing pulse CVT of other types, and it is irrelevant to the transmission ratio of the CVT. The research provides the new idea to the CVT study.

Key words: pulse continuously variable transmission, pulsatile rate, motion analysis

1 Introduction

The structure of mechanical pulse continuously variable transmission(PCVT) is simple but offers reliable transmission. PCVT mainly includes the transmission mechanism, output mechanism(overrunning clutch) and the speed control mechanism. Easily manufactured, its transmission ratio is broad. The minimum speed of input axis can be zero, while the performance of speed control is stable. Speed of transmission mechanism can be changed at rest or in motion. Therefore, it is widely used in the textile, food and packaging industries[1–5].

The GUSA Ⅱ type pulse continuously variable transmission(CVT) was designed and manufactured by Heinrich Gensheimer & Sohne LTD. CO. It features wide transmission rate and easy speed control, while the rotational speed of output axis can be zero and the pulsation of rotational speed for output axis is small. With its compact structure, good manufacturability and reliable transmission rate, this type is widely used[6]. ZERO-MAX CVT designed and manufactured by the ZERO-MAX LTD. CO. has similar characteristics as of GUSA Ⅱ CVT. But its output power is small so it is fit for small workload. ZERO-MAX pulsatile CVT produced by MIKI LTD. CO. has reverse handle so two-way transmission can be achieved. All the pulsatile CVTs mentioned above use the connecting rod transmission mechanism. By changing proportional relationship for size of each rod in the linkage, stepless speed regulation of these pulse CVTs can be achieved[7–8]. If the lower pair in the linkage is replaced by the higher pair(cam), connecting rod pulsatile CVT will be changed into eccentric cam pulsatile CVT. Structure of cam-type pulsatile CVT is relatively simple compared with connecting rod pulsatile CVT. There are many combinations and improved pulsatile CVT besides these major types of pulsatile CVT mentioned above. For example, the Germany-made Philamat pulsatile CVT is a combination of fixed axis gear mechanism and connecting rod mechanism. Its pulsation is small, range of speed control is wide and transmission power is large. MORSE pulsatile CVT designed by MORSE LTD. CO. is a combination of cam mechanism and gear mechanism. KAZEM, et al[9], proposed a novel parallel disc pulse CVT, whose kinematic and dynamic characteristics had been

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analyzed. SUN, et al[10], proposed a novel connecting rod pulse CVT.

Impulse CVT used in practice has three main shortcomings. First, the inertia force produced by the movement of the connecting rod is difficult to balance. The vibration is obviously caused by the unbalanced inertia force and inertia moment when the speed of the connecting rod is high. Second, overrunning clutch in the output mechanism is the weak link in the transmission chain of the impulse CVT. Its bearing capacity and shock resistance is relatively poor and this limits the capacity of transferring power for impulse CVT[11]. Third, pulsation can not be completely eliminated[12].

The rotational swashplate pulse CVT described in this article presents a whole new design. It has the advantages not possessed by the existing pulse CVTs. Its transmission component is composed of a swash plate, a guide rod and a helical gear. More importantly, it overcomes the major shortcoming of the existing connecting rod pulse CVT or swing link pulse CVT, which is the inertia force or the inertia moment is difficult to balance. It should be noted that its pulsation is low and the value of the pulsation does not vary with the change of the transmission ratio.

2 Motion Principle of the Rotational Swashplate Pulse CVT

2.1 Mechanism diagrams

As shown in Fig. 1, 1 is axis of input and it is driving member. 2 is slider and it connects with axis of input in the form of sliding pair. 4 is a disk and its obliquity can be adjusted. Disk connects with axis of input at point C in the form of revolute joints(hinge). 3 is connecting rod and it connects with slider 2 in the form of hinge at the end of point A. On the other end of point B, it connects with swashplate 4 in the form of hinge. When the input shaft 1 rotates, the slider 2, the swashplate 3, and the connecting rod 3 are driven to rotate at the same speed. 11 is the nut and 12 is the screw which can adjust the speed of output shaft. 10 is the guide rod and the minimal number is 3(As shown in Fig. 2, the number of the guide rod is 4. If the number of the guide rod is less than 3, the motion of the output shaft will be discontinuous). The guide rods are uniform distribution around the axis of the input shaft. They can move only but can not rotate in the direction of the axis. The guide rods make contact with the surface of the disk 4 on the right end. Driving helical gear 8 is installed on the other end of the guide rods. Helical gear 9 connects with the guide rod 10 by means of the overrunning clutch 8. 7 is the driven helical gear which meshes with driving helical gear 9. Driven helical gear 7 connects with the output shaft 6 in the form of key joint. 5 is the rack.

2.2 Principle of rotational swashplate pulse CVT

When the input shaft 1 is rotating, it drives the swashplate 4 rotation synchronously(in the view of function, disk 4 is cylindrical cam). Then disk 4 pushes the guide rod 10 to move. Because the helical gear 9 connects with the guide rod 10 through the overrunning clutch 8 and the guide rod 10 cannot rotate, the helical gear 9 can not rotate when the guide rod 10 moves in one direction (Movement direction of the guide rod 10 and the helical gear 9 is decided by the installation direction of the overrunning clutch 8). Because the direction of the helical gear 9 tooth and its axis has a angle(helix angle β), when the helical gear 9 and the guide rod 10 move along their axis, driven helical gear 7 will mesh with helical gear 9 and it must turn an angle(at this time helical gear 9 is equivalent to driving gear). Helical gear 9 can rotate freely relative to the guide rod 10 when the guide rod 10 and the helical gear 9 move in the opposite direction because of one-way rotation property of the overrunning clutch 8.

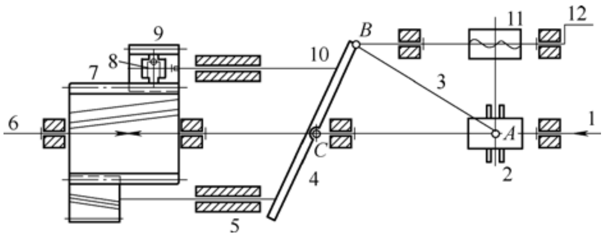

Fig. 1. Mechanism diagrams of rotational swashplate pulse

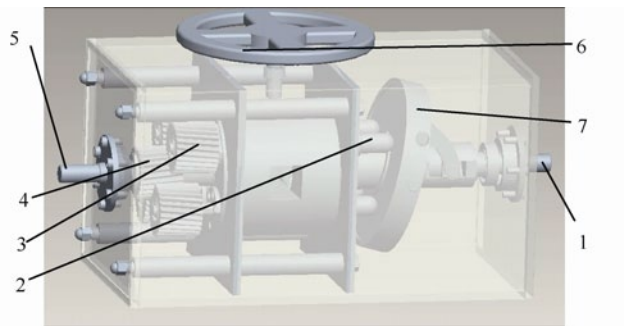

Fig. 2. Structure diagram of rotational swashplate pulse CVT

1. Input shaft 2. Guide rod 3. Driving helical gear 4. Driven helical gear 5. Output shaft 6. Speed-regulating handle 7. Swashplate

Single guide rod and helical gear only can make driven helical gear 7 do unidirectional intermittent rotation. If 3 or more guide rods and helical gears are installed evenly on circumferential position along the axis of the driving shaft, driven helical gear 7 will be able to do continuously unidirectional rotation.

2.3 Transmission principle of rotational swashplate pulse CVT

As shown in Fig. 1, no matter the input shaft 1 is in motion or not, the screw 12 can be revolved. If the screw revolves, the nut 11 must move along its axis. So the slider 2 moves by the driving of the shifting fork of the nut 11 synchronously. Then the linkage 3 is driven to move by the slider 2. Driven by the linkage 3, the disk 4 turns certain angles around point C on the left of the input shaft. Then the displacement of the guide rod 10 will be changed. The displacement of the guide rod is proportional to the rotational speed of the output shaft. The greater the displacement of the guide rod is, the higher the rotational speed of the output will be. When the plane of the disk 4 is perpendicular to the axis of the input shaft, the displacement of the guide rod 10 will be zero. As a result, the rotational speed of the output shaft will be zero too.

3 Structure of Rotational Swashplate Pulse CVT

The authors of this paper designed the drawings and the prototype of this CVT was produced. Three-dimensional structure diagram of this CVT is shown in Fig. 2. As shown in Fig. 2, the input shaft is the driving part. Disk is jointed to the input shaft and its tilt angle can be adjusted. Tilt angle of the disk is adjusted by the turn of the speed-regulating handle. Disk rotates synchronously by the driving of the input shaft. Then the disk pushes the guide rod to move(there are 4 guide rods in the model as shown in Fig. 2). Driving gear is installed on the left of the guide rod. Overrunning clutch is installed between the drive gear and the guide rod(not shown in Fig. 2). Each of the driving gears on the guide rod respectively drives the driven gear to rotate continuously. The driven helical gear is installed into the output shaft by the form of the flat key. So the output shaft can be driven by the driven gear. Fig. 3 shows a photograph of the experimental prototype.

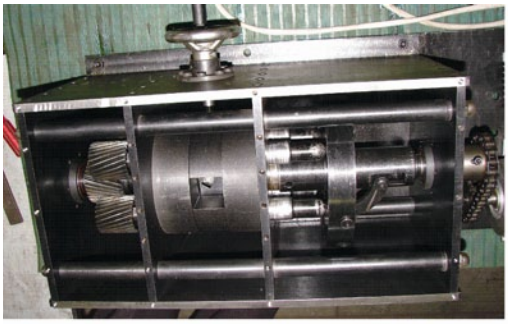

Fig. 3. Experimental prototype of rotational swashplate pulse CVT

4 Main Performance Parameters of Rotational Swashplate Pulse CVT

The more the number of the guide rods in this pulse CVT is, the smaller the impulse rate of the output shaft is. After theoretical analysis and calculation, main performance parameters of this rotational swashplate pulse CVT are as follows.

4.1 Angular displacement and angular velocity of the output shaft

4.1.1 Rotational angle of the output shaft

When the number of the guide rod is 1 in this CVT, relation formula between angular displacement of the output shaft and angular displacement of the input shaft is

$$\phi_2 = \frac{d}{d_2}\tan\beta\tan\theta(1-\cos\phi_1),\ 0 \leqslant \phi_1 \leqslant \pi, \qquad (1)$$

where β is helical angle of reference circle, θ is angle between the plane of the swashplate and the vertical section of the input shaft, D is diameter of the distributed circle of the guide rod, d_2 is diameter of the helical gear's reference circle in the output shaft, ϕ_1 is angle displacement of the input shaft ($\phi_1=\omega_1 t$), ω_1 is angle velocity of the input shaft (constant).

4.1.2 Angular velocity of the output shaft

Because each guide rod works in turn, curves about angular velocity of the output shaft can be different if the number of the guide rod is different. According to Eq. (1), if the number of the guide rod in this rotational swashplate pulse CVT is 4, angular velocity of the output shaft is

$$\omega_2 = \frac{\mathrm{d}\phi_2}{\mathrm{d}t} = \omega_1\frac{d}{d_2}\tan\beta\tan\theta\sin\left(\phi_1 - \frac{\pi}{2}i\right).$$

When $\pi/4 \leqslant \phi_1 < 3\pi/4$, i equals 0; when $3\pi/4 \leqslant \phi_1 < 5\pi/4$, i equals 1; when $5\pi/4 \leqslant \phi_1 < 7\pi/4$, i equals 2; when $0 \leqslant \phi_1 < \pi/4$ or $7\pi/4 \leqslant \phi_1 < 2\pi$, i equals 3.

In Fig. 4 curve above the shadow line is the graph of the angular velocity vs. time where the number of guide rod is 4. The point of intersection between the curves is speed intersection between adjacent guide rods.

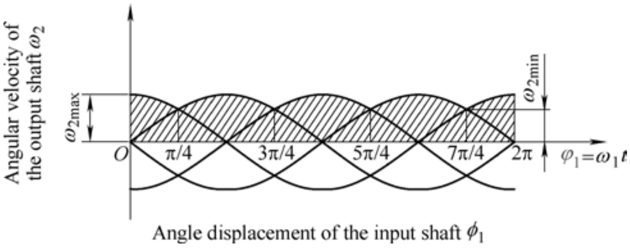

Fig. 4. Angular velocity of the output shaft

4.2 Pulsation of rotational swashplate pulse CVT (uneven coefficient of velocity)

Pulsatile rate is used to evaluate stationarity of the angular velocity of output shaft. Only instances of this pulse CVT whose number of the guide rod is between 3 and 6 are discussed in this article.

4.2.1 Maximum angular velocity of the output shaft

No matter how many the guide rods the transmission has, the maximum angular velocity they have will be the same. And the position of the maximum angular velocity is at 90° of ϕ_1, namely,

$$\omega_{2\max} = \omega_1\frac{d\tan\beta\tan\theta}{d_2}\sin 90° = \omega_1\frac{d\tan\beta\tan\theta}{2d_2}.$$

4.2.2 Minimum angular velocity of the output shaft and uneven coefficient of velocity

The minimum angular velocity of the output shaft is located in speed intersection between adjacent guide rods. The number of the guide rods of the transmission is different; the phase of speed intersection must be different too. The detailed information can be found in papers that will be published soon. By definition, uneven coefficient of velocity for pulse CVT is expressed as follows:

$$\delta = \frac{\omega_{\max} - \omega_{\min}}{\omega_{\mathrm{m}}} = 2 \bullet \frac{\omega_{\max} - \omega_{\min}}{\omega_{\max} + \omega_{\min}},$$

where $\omega_{\min}$ is the minimal angular velocity of the output shaft, $\omega_{\max}$ is the maximum angular velocity of the output shaft, ω_{m} is the average angular velocity of the output shaft.

If the number of the guide rods the transmission has is different, the minimum angular velocity will be different too. The minimum angular velocity and uneven coefficient of velocity are shown in Table 1.

Table 1. Main characteristic parameters

Parameter	Value			
Number of the guide rod N	3	4	5	6
Maximum rotational velocity of the output shaft $\omega_{2\max}$	$A\omega_1$	$A\omega_1$	$A\omega_1$	$A\omega_1$
Minimum rotational velocity of the output shaft $\omega_{2\min}$	$0.5\omega_{2\max}$	$0.707\omega_{2\max}$	$0.809\omega_{2\max}$	$0.866\omega_{2\max}$
Pulsatile rate $\delta/\%$	66.7	34.3	21.1	14.4
Average transmission rate i_{12}	$2.598B$	$2.828B$	$2.94B$	$3B$
Variable ration R	∞	∞	∞	∞

Note: $A=d\tan\beta\tan\theta/(2d_2))$, $B=d\tan\beta\tan\theta/(d_2\pi))$.

4.3 Average transmission ratio and variable ratio of rotational swashplate pulse CVT

4.3.1 Average transmission ratio of rotational swashplate pulse CVT

Definition: average transmission ratio of rotational swashplate pulse CVT whose number of the guide rod is n is expressed by

$$i_{12}^{n} = \frac{n_{1\mathrm{ave}}}{n_{2\mathrm{ave}}} = \frac{2\pi}{n\Delta\phi_{2n}},$$

where n is the number of the guide rod, $n_{1\mathrm{ave}}$ is average rotational velocity of the input shaft, $n_{2\mathrm{ave}}$ is average rotational velocity of the output shaft, $\Delta\phi_{2n}$ is corresponding angular displacement of the output shaft when the input shaft rotates angle of the $2\pi/n$.

4.3.2 Maximum angular velocity of the output shaft

CVT's variable ratio equals to the ratio of the maximum transmission ratio to the minimum transmission ratio. It also equals the ratio of the maximum rotational velocity of the output shaft to the minimum rotational velocity of the output shaft. In this article it is indicated by the letter:

$$R = \frac{i_{\max}}{i_{\min}} = \frac{n_{2\max}}{n_{2\min}} = \frac{\omega_{2\max}}{\omega_{2\min}}.$$

Variable ratio of rotational swashplate pulse CVT discussed in this paper is infinity because the minimum rotational velocity of the output shaft can be zero. So the variable ratio in this rotational swashplate pulse CVT is irrelevant to the number of the guide rod.

Characteristic parameters of rotational swashplate pulse CVT whose number of the guide rods is between 3 and 6 are shown in Table 1.

As shown in Table 1, pulsatile rate of the rotational swashplate pulse CVT is decreased obviously with increased number of the guide rods. When other conditions are not changed, with a limited increase of the number of the guide rod, the weight of the CVT increases a little, with no change in the volume of the CVT. When the number of the guide rod is 6, compared with other types of the pulse CVT, pulsatile rate decreases obviously[1]. Furthermore, pulsatile rate is irrelevant to the transmission ratio of this kind of CVT. It is a unique characteristic which is not possessed by other kinds of pulse CVT.

4.4 Transmission efficiency of the experimental prototype

Transmission efficiency is related to many factors, such as the form of the mechanical structure, material, roughness of the contact surface and lubrication mode. Due to the lack of sealed structure with good lubrication and the point contact between the guide rod and the disk of obliquity, the transmission efficiency of the experimental prototype discussed in this paper is low. A preliminary test shows that the transmission efficiency is about 70% when the rotational speed of the output shaft reaches the maximum. Since the transmission efficiency of CVT used in engineering nowadays typically ranges between 70% and 75%[13–16], the pulse CVT discussed in this paper has certain application prospect in engineering.

Theoretical analysis and experiment of transmission efficiency of the present pulse CVT will be elaborated in other paper by the author, where good lubrication and structural form with low friction coefficient will be adopted.

4.5 Comparison analysis between experimental data of the prototype and theoretical data

Angular velocity of the output shaft of the four-rod prototype was tested and conditions of the testing were as follows: Angular velocity of the input shaft(ω_1) is 100 rad/s, the diameter of the distributed circle of the guide rod(d) is 108 mm, the diameter of the reference circle possessed by the helical gear of the output shaft(d_2) is 48 mm. Angle between swashplate surface and cross-section of the input shaft(θ) is 2°, 5°, 10°, and 15° (different θ represents different transmission ratio).

Results of the testing are shown in Fig. 5. Comparison relationship between experimental data and theoretical data is similar when θ is 2°, 5°, 10°, and 15°, so only the data of θ equaling to 10° is shown in Fig. 5. Actual rotational velocity is always less than the theoretical value because the roller in overrunning clutch has some clearance.

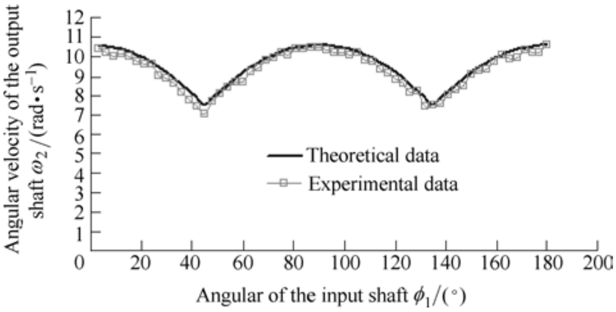

Fig. 5. Angular velocity curve of output shaft

Actual values of pulsatile rate at different angles of θ(transmission ratio) are shown in Table 2. Actual result of testing is larger than the theoretical value of 34.3%. It is mainly caused by the clearance of roller, measurement error and manufacturing installation error of parts.

Table 2. Pulsatile rate at different rotation angle of swashplate

Rotation angle of swashplate θ/(°)	2	5	10	15
Pulsatile rate δ/%	35.1	35.2	34.8	34.9

5 Conclusions

The rotational swashplate pulse CVT discussed in this paper is an original design. It is based on a new transmission principle and structure. It is the combination of a cylindrical cam(swashplate-guide rod mechanism) and the parallel-shaft helical cylindrical gear mechanism, which is in planetary layout and axial meshing. It achieves non-traction, continuously variable transmission.

The rotational swashplate pulse CVT has the following characteristics:

(1) Uneven coefficient of velocity is irrelevant to the transmission ratio of this pulse CVT. It overcomes the shortcoming that pulsatile rate changes dramatically when the rotational velocity of the output shaft is low;

(2) When the number of the guide rod is 6, uneven coefficient of velocity is less than the existing pulse CVT;

(3) Theoretically, uneven coefficient of velocity could be reduced to zero if appropriate surface of the swashplate is used;

(4) Gear mechanism is adopted as the transmission component, and it avoids the unbalanced inertial force of connecting rod pulse CVT.

Invention patents on the transmission discussed in this paper have been filed in China and abroad. A prototype of this transmission has also been produced. Running tests of this prototype have proved that the principle of rotational swashplate pulse CVT described in this paper is feasible. Performance characteristics of the prototype are close to the value of the theoretical analysis.

The motion and dynamic analysis as well as the calculation of the performance parameters of this transmission will soon be published in other papers.

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