Paradigm Academic Press
Innovation in Science and Technology
ISSN 2788-7030
JAN. 2023 VOL.2, NO.1

Torque Ripple Analysis of Double Rotor Eccentric Shell Rotating Multi-Speed Motor with Equal Width Curve

Guoqiang Zhao[1], Shitong Ren[1], Zhixin Wang[1], Junhua Lu[1], Zi Yang[1] & Yongjie Xing[1]

[1] Air Force Logistics Academy

Correspondence: Guoqiang Zhao, Air Force Logistics Academy.

doi:10.56397/IST.2023.01.03

Abstract

With the rapid development of hydraulic technology, the type and performance of hydraulic motor are put forward higher requirements. In the actual working condition, the motor needs to have more than one stable torque and torque output, but the existing motor cannot be realized. In order to solve this problem, a series of new hydraulic motors based on double rotor structure are developed, thus further developing the multi-speed motor with equal width curve double rotor eccentric shell. One stator and two rotors cooperate with each other and enter through different inputs. The connection of the oil outlet can output a variety of different speed and torque, which realizes the function that multiple motors work synchronously and independently of each other in one shell. This paper mainly introduces the structural characteristics and working principle of the motor, and deduces the instantaneous torque and torque pulsation coefficient of the motor when working alone and in combination. At the same time, in order to understand the torque pulsation law of the internal and external motor more intuitively, the torque of the motor is analyzed and verified by Matlab software. It is concluded that the motor can realize many different speed and torque analysis. At the same time, through the analysis of instantaneous torque and torque pulsation coefficient, it can be concluded that the variation law of instantaneous torque output of internal and external motor combination is the best and the torque fluctuation is the smallest compared with that of internal and external motor alone.

Keywords: equal width curve, double rotor, instantaneous torque, torque ripple coefficient

1. Introduction

In recent years, hydraulic transmission has developed rapidly in the mechanical industry. It can not only achieve low speed and high torque transmission, but also achieve high speed and high torque transmission. Hydraulic transmission technology is irreplaceable in many fields and is an important symbol to measure a country's industrial level (Yang Huayong, Zhang Bin, Xu Bin, et al., 2008). With the continuous development of industrial technology, the requirements for some hydraulic components are also increasing, especially the hydraulic motor (Yang Erzhuang, 2001; Xu Yangzeng, 2010). The existing motors cannot achieve multiple stable torque and torque output, but also have a series of problems such as noise level and service life (Zhao Wu & Du Changlong, 2004; Wen Desheng, 2009; Furustiu J, Almqvist A, Bates C A, et al., 2015; Furustig J, Larsson R, Almqvist A, et al., 2015). In response to these problems, Professor Wen Desheng of Yanshan University (Zhou Cong, 2017; Wen Desheng, Gao Junfeng, Zhou Ruibin, et al., 2014; Wen Desheng, 2011; Deng Haishun, Huang Ran, Wang Chuanli, et al., 2016; Zhang Jun, XuXianliang & Zhang Xiaofei, 2004) and others first proposed a constant width curve double rotor eccentric housing rotation multi speed motor. Compared with traditional hydraulic motors, this motor can realize synchronous operation of multiple motors and separate operation of motors, so that the motor can output a variety of different torques and speeds at the same time (He Cunxing, 1982), making the hydraulic system easier to achieve automation, systematization and standardization (Lei Tianjue, 1990).

The structure and principle of this new type of double rotor eccentric housing rotation multi speed motor is proposed for the first time at home and abroad. It is an innovative basic hydraulic component and a new independent branch of hydraulic components (Wen Desheng, Wang Zhili, Gao Jun, Zhang Yong, Lyu Shijun & Tetsuhiro Tsukiji, 2011; Li Ruitao, Fang Mei, Zhang Wenming, et al., 2000). It is extremely important for the research and development of hydraulic motors in the future. This paper mainly studies the working performance of this new hydraulic motor.,

2. Structure Characteristics and Working Principle of Motor

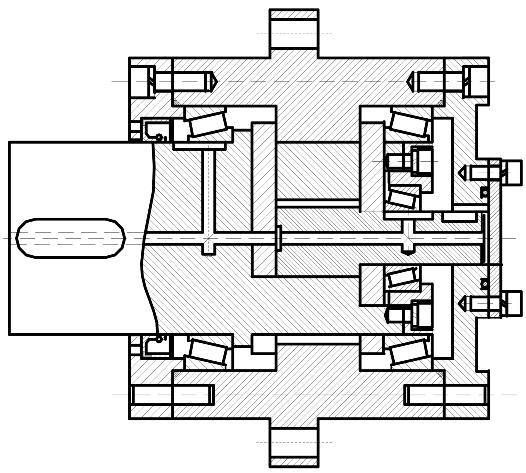
2.1 Structural Characteristics

Figure 1 shows the structural diagram of the new motor. The innovation of the motor is that two rotors (outer rotor 1 and inner rotor 5) and one stator 6 are designed in the motor housing. The stator 6, the outer rotor 1, the upper roller 7, the connecting rod 2, and the left and right side plates form a closed volume that can change periodically. We call it the outer motor; The stator 6, the inner rotor 5, the lower roller 10, the connecting rod 2 and the left and right side plates form a closed volume that can change periodically, which is called the inner motor. The enclosed volume of the internal and external motors is equal, so the displacement of the internal and external motors is also equal. Compared with the traditional single stator motor, the new motor has an internal motor, which improves the overall output torque and speed of the motor, increases the total displacement and improves the specific power.

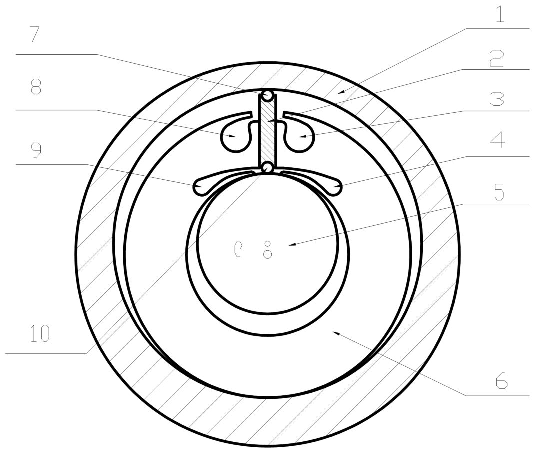
Rolling friction exists between roller 7 and 10 and inner rotor 5, outer rotor 1 and connecting rod 2. Each friction pair is lubricated when the motor is working. The clearance between connecting rod 2 and roller 7 and 10 is compensated, which can greatly improve the sealing characteristics, mechanical efficiency and service life of the motor (Xu Tian, 2012).

2.2 Working Principle

Because there are two rotors in a motor body, the internal and external two closed volumes that can change periodically are formed, which are called internal and external motors. The main working principle is as follows: when the pressure oil enters the closed working chamber of the internal and external motors, the hydraulic pressure generated by the high-pressure oil acts on the internal and external rotors of the high-pressure working chamber and drives the internal and external rotors to rotate with the rotating torque generated from the stator to the force point; When rotating, the connecting rod slides up and down along the internal and external curves of the internal and external rotors in the stator connecting rod slot, the roller rolls along the internal and external surfaces of the internal and external rotors in the connecting rod roller slot, and moves up and down with the connecting rod at the same time. At the same time, the internal and external rotors of the connecting rod roller component group and the high and low pressure working chambers remain sealed. The volume of adjacent connecting rod rollers, rotors, stators and side plates in the high-pressure oil chamber expands with the rotation direction. At this time, the high-pressure oil area is connected to the oil outlet to form a low-pressure oil area. The low-pressure oil area decreases with the volume of the motor rotation area, and the oil is discharged through the oil outlet. At the same time, the high-pressure oil area continues to enter the next cycle. Since the internal and external rotor curves of the new motor are in equal proportion, the internal and external motor displacement is also in equal proportion, so as to form two equal proportion motors in one motor housing (Xu Tian, 2012).



(a) Motor structure diagram I



(b) Motor structure diagram II

Figure 1. Schematic diagram of double rotor eccentric shell rotating multi-speed motor with equal width curve

Description: 1 - Outer rotor 2 - Connecting rod 3 - Outer motor oil inlet 4 - Inner motor oil inlet 5 - Inner rotor 6 - Stator 7 - Upper roller 8 - Outer motor oil outlet 9 - Inner motor oil outlet 10 - Lower roller

3. Torque Analysis of Motor

3.1 Kinematics Analysis of Connecting Rod Inner Ball and Outer Ball

Now, the kinematics of the inner ball and the outer ball is specifically analyzed (Wen Desheng, 2009; 2002). As shown in Figure 2, the inner ball will move up and down in the connecting rod slot during the operation of the motor, and rotate at high speed at the same time. Let a point on one side of the high-pressure chamber be the analysis point P, the distance from the stator axis to point P is a, the distance from the stator axis to eccentric e is b, the distance from eccentric e to point P is c, and the angle corresponding to distance a is ∠ A. The radius of the outer surface of the inner rotor is r 2. Small radius of stator r 1.

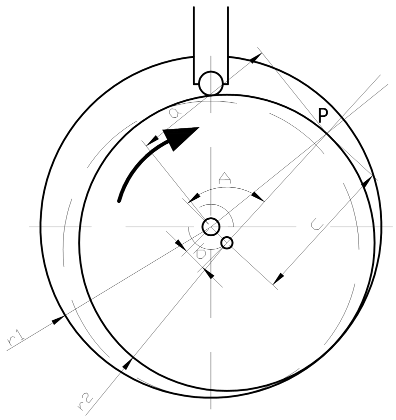


Figure 2. Diagram of motion analysis of inner roller

Here, the distance a is the polar radius we find ρ; As shown in the figure, it is obvious that the inner motor pole radius ρ. The cosine formula is satisfied.

$$a^2 = b^2 + c^2 - 2bc \cos \angle A \tag{1}$$

Among, $a = \rho$, $b = e$, $c = r_2$

Substitute to obtain the polar radius ρ Expression for:

$$\rho^2 = e^2 + {r_2}^2 - 2er_2 \cos \angle A \tag{2}$$

In the same way, as shown in Figure 3, the schematic diagram of outer ball motion analysis (R1 is the inner surface radius of the outer rotor, R2 is the large radius of the stator), and the triangle cosine theorem can be obtained:

$$\rho^2 = e^2 + {R_1}^2 - 2eR_1 \cos \angle A \tag{3}$$

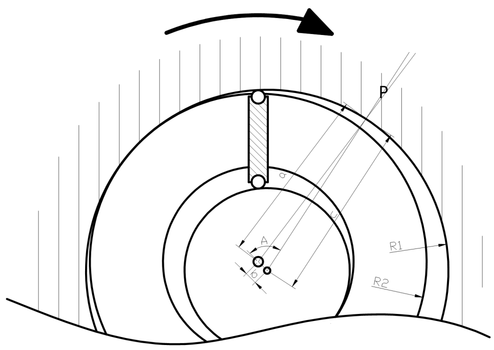


Figure 3. Diagram of motion analysis of external roller

3.2 Motor Torque Calculation

According to the basic formula of the motor:

Speed n:

$$n = \frac{q}{V}\eta_v \tag{4}$$

Where q —Input flow of motor port (ml/min)

V —displacement (ml/r)

η_v—Volumetric efficiency (%)

Average torque *T*

$$T = \frac{\mathrm{pV}}{2\pi}\eta_m \tag{5}$$

Where η_m— Mechanical efficiency of motor (%)

Theoretical torque T_L

$$T_L = \frac{PV}{2\pi} \tag{6}$$

3.3 Torque Analysis of Internal Motor and External Motor with Double Rotor Eccentric Housing

Firstly, the torque of internal motor is analyzed. A force bearing point is set in the inner rotor high-pressure chamber of the inner motor to establish a coordinate system centered on this point. Due to the existence of eccentric e, the force bearing point generates torque relative to the stator center during the rotation of the inner rotor. The direction of the torque is along the tangent direction of the inner rotor rotation.

When the eccentricity of the inner rotor is at different positions, the output torque of the motor will change in each instant because the connecting rod roller and the closed volume are constantly changing (Li Zhuangyun, 2005).

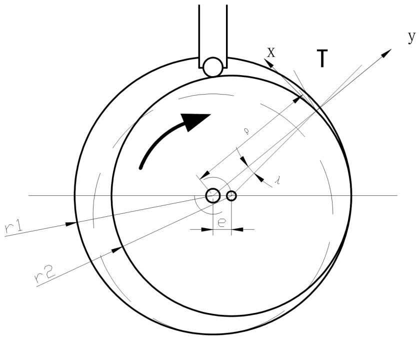


Figure 4. Internal rotor force analysis diagram

Figure 4 shows the force diagram of the inner rotor of the inner motor. If the pressure of high-pressure oil fed into the internal motor is p1, the instantaneous torque received by the internal motor is:

$$dM_1 = T\rho = P\sin\lambda * \rho = (p_1 B ds)\sin\lambda * \rho \tag{7}$$

Where p_1—Inlet pressure of motor (MPa);

B—Rotor width (mm);

λ—Polar diameter ρ Angle from normal (°).

The distance from the stator axis to the stress point, the distance from the rotor axis to the stress point, and the eccentricity e in Figure 4 meet the trigonometric cosine theorem.

Now it is critical to find out the instantaneous displacement ds and eccentric e diagonal λ And extreme diameter of stress point ρ,The instantaneous torque of the internal motor can be obtained.

If the inner rotor rotates through a segment of arc in ds, the approximate value is taken according to the relationship in the following figure $\mathbf{ds} = \sqrt{dx^2 + dy^2}$, among: $x = \rho\sin\varphi$,$y = \rho\cos\varphi$.

Middle angle φ as shown in Figure 5

You can see:

$$ds = \sqrt{\rho'^2 + \rho^2 d\varphi^2} \tag{8}$$

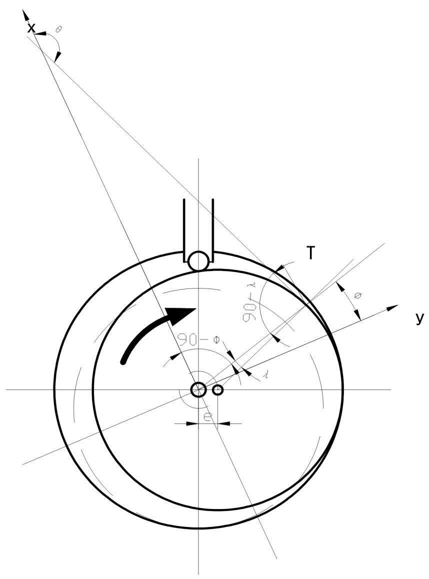


Figure 5. Analysis diagram of internal rotor stress angle

Calculate the angle according to Figure 5 above:

$$\theta = (90° - \lambda) + (90° - \varphi)$$

$$\lambda = 180° - (\theta + \varphi) \tag{9}$$

$$sin\,\lambda = sin(\phi + \theta) = \frac{sin\,\phi + cos\,\phi * tg\theta}{\sqrt{1+tg\theta}} \tag{10}$$

$$\text{tg}\theta = \frac{dy}{dx} = \frac{\rho' \,cos\,\phi - \rho\,sin\,\phi}{\rho' \,sin\,\phi + \rho\,cos\,\phi} \tag{11}$$

Substitute equation (10) into equation (9) to get:

$$sin\,\lambda = \frac{\rho'}{\sqrt{\rho'^2 + \rho^2}} \tag{12}$$

Substitute Eq. (8) and (12) into Eq. (7) to get:

$$dM_1 = p_1 B \rho d\rho \tag{13}$$

When $0 \le \phi \le \pi$:

$$M_1 = \int_{R_{内}}^{\rho} p_1\, B\rho d\rho = \frac{1}{2} p_1 B(\rho^2 - R_{内}{}^2) \tag{14}$$

From the triangle cosine theorem,

$$a = \rho = \sqrt{b^2 + c^2 - 2bc * cos\,\angle A} \tag{15}$$

Where: $a = \rho, b = e, c = r_2$

If equation (15) is brought into equation (14)

$$M_1 = \frac{1}{2} p_1 B(\rho^2 - r_1{}^2) = \frac{1}{2} p_1 B\left(e^2 + r_2{}^2 - 2er_2 * cos\,\angle A - r_1{}^2\right) \tag{16}$$

Because ρ< R1, so M1 is a negative value, which means that M1. Direction and ϕ. The steering direction of is opposite, which is expressed as a positive value, so that

$$M_1 = -\frac{1}{2} p_1 B(\rho^2 - r_1{}^2) = -\frac{1}{2} p_1 B(e^2 + r_2{}^2 - 2er_2 * cos\,\angle A - r_1{}^2) \tag{17}$$

When $\pi \le \phi \le 2\pi$, The torque output of the motor is:

$$M_1 = -\frac{1}{2} p_1 B(r_1{}^2 - \rho^2) = -\frac{1}{2} p_1 B\left[r_1{}^2 - (e^2 + r_2{}^2 - 2er_2 * cos\,\angle A)\right] \tag{18}$$

Similarly, the instantaneous torque of the external motor can be calculated:

$$\begin{cases} M_3 = \frac{1}{2} p_1 B \\ \left(e^2 + R_1{}^2 - 2eR_1\,cos\,\angle A - R_2{}^2\right) 0 \le \phi < \pi \\ M_4 = \frac{1}{2} p_1 B \\ \left[R_2{}^2 - \left(e^2 + R_1{}^2 - 2eR_1\,cos\,\angle A\right)\right] \pi \le \phi \le 2\pi \end{cases} \tag{19}$$

4. Analysis of Torque Ripple of Double Rotor Eccentric Housing Motor

From the above analysis, it can be seen that this constant width curve double rotor eccentric housing rotation multi speed motor can work separately and simultaneously with the internal and external motors. In order to more intuitively understand the torque pulsation law of the internal and external motors, Matlab software is now used to analyze the motor torque, and then calculate the torque pulsation coefficient through their instantaneous torque to analyze the pulsation.

4.1 Calculation of Torque Output and Torque Ripple Coefficient When Internal Motor Works Alone

When the oil inlet of the inner motor is filled with high-pressure oil, the inner motor starts to work independently. It can be seen from the above torque equation that the torque ripple of the inner motor is an equation close to the sine curve within a period of motion of the inner motor. As shown in Figure 6.

According to the above analysis, the instantaneous torque of the internal motor is:

$$\begin{cases} M_1 = -\frac{1}{2}p_1B \\ \left(e^2 + r_2{}^2 - 2er_2\cos\angle A - r_1{}^2\right) 0 \le \phi < \pi \\ M_2 = -\frac{1}{2}p_1B \\ \left[r_1{}^2 - \left(e^2 + r_2{}^2 - 2er_2\cos\angle A\right)\right] \pi \le \phi \le 2\pi \end{cases} \tag{20}$$

When $\cos\angle A = 0$, the instantaneous torque of the inner motor is the minimum value:

$$T_{1min} = -\frac{1}{2}p_1B[r_1{}^2 - (e^2 + r_2{}^2)] \tag{21}$$

When $\cos\angle A = 1$, the instantaneous torque of the internal motor is the maximum value:

$$T_{1max} = -\frac{1}{2}p_1B[r_1{}^2 - (e^2 + r_2{}^2 - 2er_2)] \tag{22}$$

The torque ripple coefficient of the internal motor is:

$$\delta_1 = \frac{T_{1max} - T_{1min}}{T_{1max}} = \frac{2er_2}{r_1{}^2 - (e^2 + r_2{}^2 - 2er_2)} \tag{23}$$

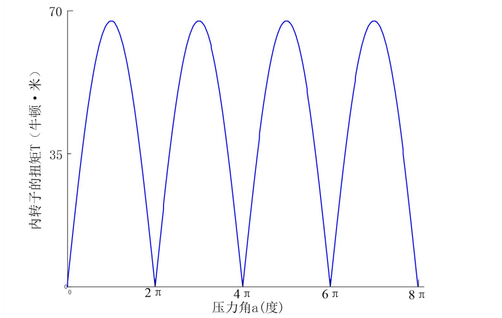


Figure 6. Motor Torque Ripple Diagram

4.2 Calculation of Torque Output and Torque Ripple Coefficient When External Motor Works Alone

When high pressure oil is fed into the oil inlet of the external motor, the external motor starts to work independently. It can be seen from the above torque equation that the torque ripple of the external motor is an equation close to the cosine curve within a period of movement of the external motor. As shown in Figure 7.

According to the above analysis, the instantaneous torque of the external motor is:

$$\begin{cases} M_3 = \frac{1}{2}p_1B \\ \left(e^2 + R_1{}^2 - 2eR_1\cos\angle A - R_2{}^2\right) 0 \le \phi < \pi \\ M_4 = \frac{1}{2}p_1B \\ \left[R_2{}^2 - \left(e^2 + R_1{}^2 - 2eR_1\cos\angle A\right)\right] \pi \le \phi \le 2\pi \end{cases} \tag{24}$$

When $\cos\angle A = 0$,the instantaneous torque of the external motor is the minimum value:

$$T_{2min} = \frac{1}{2}p_1B\left[{R_2}^2 - \left(e^2 + {R_1}^2\right)\right] \tag{25}$$

When $\cos\angle A = 1$,the instantaneous torque of the external motor is the maximum value:

$$T_{2max} = \frac{1}{2}p_1B\left[{R_2}^2 - \left(e^2 + {R_1}^2 - 2eR_1\right)\right] \tag{26}$$

The torque ripple coefficient of the external motor is:

$$\delta_2 = \frac{T_{2max} - T_{2min}}{T_{2max}} = \frac{2eR_1}{{R_2}^2 - \left(e^2 + {R_1}^2 - 2eR_1\right)} \tag{27}$$

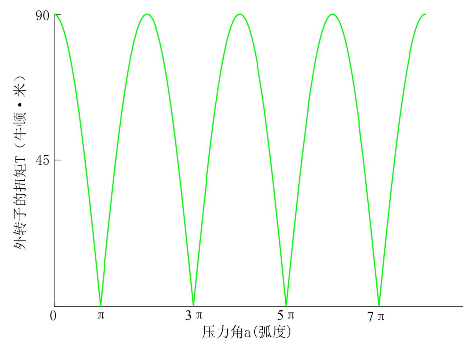


Figure 7. Torque pulsation diagram of external motor

4.3 Torque Output When Internal and External Motors Work at the Same Time

When the two oil inlets of the internal and external motors are connected with high-pressure oil at the same time, the internal and external motors in the motor body work at the same time, and the motor performance reaches the best. The motion torque of internal and external motors is simulated and analyzed through Matlab simulation software. As shown in Figure 8.

For the internal and external motors working at the same time, the instantaneous torque of the internal and external motors working separately is added to obtain the instantaneous torque of the internal and external motors working at the same time:

$$\begin{cases} M_5 = \frac{1}{2}p_1B\begin{bmatrix} {R_1}^2 - {R_2}^2 + ({r_1}^2 - {r_2}^2) \\ +2e\cos\angle A(r_2 - R_1) \end{bmatrix} \\ \quad 0 \le \phi < \pi \\ M_6 = \frac{1}{2}p_1B\begin{bmatrix} {R_2}^2 - {R_1}^2 + ({r_2}^2 - {r_1}^2) \\ +2e\cos\angle A(R_1 - r_2) \end{bmatrix} \\ \quad \pi \le \phi \le 2\pi \end{cases} \tag{28}$$

When $\cos\angle A = 0$,The instantaneous torque when the internal and external motors work at the same time is the minimum value:

$$T_{3min} = \frac{1}{2}p_1B\left[{R_2}^2 - {R_1}^2 + ({r_2}^2 - {r_1}^2)\right] \tag{29}$$

When $\cos\angle A = 1$, the instantaneous torque when the internal and external motors work at the same time is the maximum value:

$$T_{3\max} = \frac{1}{2}p_1B\left[{R_1}^2 - {R_2}^2 + ({r_1}^2 - {r_2}^2) + 2e(r_2 - R_1)\right] \tag{30}$$

When the internal and external motors work at the same time, the torque ripple coefficient is:

$$\delta_3 = \frac{T_{3max} - T_{3min}}{T_{3max}} = \frac{2e(r_2 - R_1)}{{R_1}^2 - {R_2}^2 + ({r_2}^2 - {r_1}^2) + 2e(R_1 + r_2)} \tag{31}$$

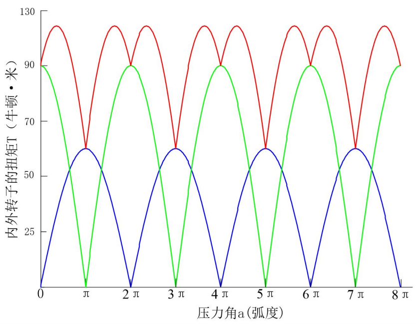


Figure 8. Joint working torque pulsation diagram of internal and external motors

In the figure, the blue curve is the torque ripple curve when the internal motor works alone, the green curve is the torque ripple curve when the external motor works alone, and the red curve is the torque ripple curve when the internal and external motors work simultaneously; From the torque simulation figure 8 generated by Matlab, it can be seen that the change rule of instantaneous torque output is the best when the internal and external motors work simultaneously; The torque ripple is small, and there is no dead point position, so the maximum output torque becomes larger.

5. Experiment Content

The output torque experiment is conducted for the constant width curve double rotor eccentric housing rotation multi speed motor. Table 1 shows the main dimensions of the experimental prototype, Figure 9 shows the experimental connection diagram of the motor, Figure 10 shows the assembly of the motor prototype used in this experiment, and Figure 11 shows the experimental platform built for this experiment.

Table 1. Main size parameters of prototype

Parameter	Symbol	Numerical value
Eccentricity	e	7mm
Motor double rotor spacing	B	24mm
Diameter of inner surface of motor outer rotor	R1	84mm
Diameter of external surface of MADA inner rotor	r_2	28mm
Motor stator outer diameter	R2	80mm
Inner diameter of motor stator	r_1	32mm
Rated pressure	P_1	15MPa
Rated speed of motor	n	150-800r/min
Theoretical discharge capacity	V	35mL/r

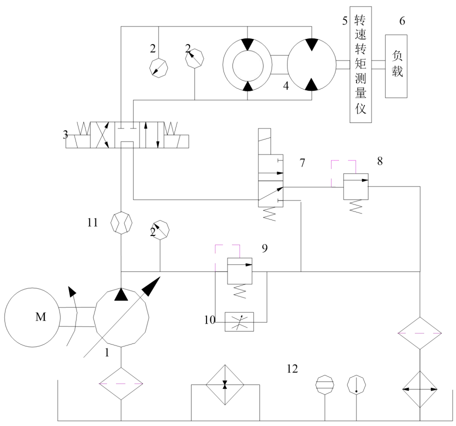


Figure 9. Experimental connection diagram of a wide-curve double-rotor eccentric shell rotating multi-speed motor

Description: 1 - Variable displacement pump 2 - Pressure gauge 3 - M functional three-way reversing valve 4 - Experimental motor 5 - Speed and torque measuring instrument 6 - Experimental load 7 - Two position three-way reversing valve 8 - Back pressure valve 9 - Overflow valve 10 - Throttle valve 11 - Flow meter 12 - Oil tank

Figure 10. Physical prototype of double rotor eccentric shell rotating multi-speed motor

Figure 11. Experimental system of double-rotor eccentric casing rotating multi-speed motor with constant width curve

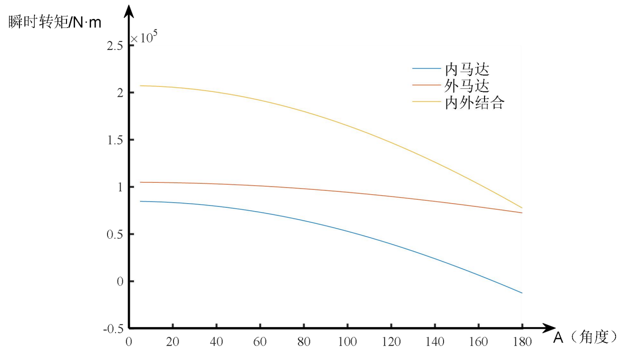


Figure 12. Instantaneous torque diagram of motor

Figure 12 is a half cycle instantaneous torque diagram of the motor made by Matlab software. From the diagram, the instantaneous torque of the internal motor when working alone is the minimum, the instantaneous torque of the external motor when working alone is the second, and the instantaneous torque of the internal and external motors when working simultaneously is the maximum.

Table 2. Motor Torque Ripple Coefficient

pattern	Torque ripple coefficient
Inner motor	0.67238
External motor	2.49682
Simultaneous internal and external motors	0.39516

The parameters are introduced into the torque ripple coefficient calculation formula to obtain the torque ripple coefficients of each mode in Table 2. It can be seen that when the internal and external motors work at the same time, the torque ripple coefficient is the smallest and the effect is the best.

6. Conclusion

(1) Compared with the traditional motor, the constant width curve double rotor eccentric housing rotation multi speed motor can use the limited motor volume to output a variety of stable torques without installing energy consuming elements such as pressure reducing valve and throttle valve. It reduces the dependence of the traditional motor on the hydraulic system, expands the application range of the circuit, and reduces the energy loss.

(2) Due to the dual rotor structure of the new motor, a variety of different speeds and torques can be achieved through the connection of different input oil inlet and outlet ports.

(3) Through the analysis of the output torque and torque ripple coefficient of the motor, it is known that when the internal and external motors work at the same time, the instantaneous torque output is the largest, the torque ripple coefficient is the smallest, and the variation law is the best.

References

Yang Huayong, Zhang Bin, Xu Bin, et al. (2008). Development of Axial Piston Pump/motor Technology. *Journal of Mechanical Engineering, 44*(10), 1-8.

Yang Erzhuang, (2001). Some developing trends of international fluid power industries and market. *Hydraulics Pneumatics & Seals,* (1), 66-69.

Xu Yangzeng, (2010). Strategy thinking on development of hydraulic industry and its technology. *Hydraulics Pneumatics & Seals,* (8), 1-5.

Zhao Wu, Du Changlong, (2004). Research status and development trend of hydraulic components. *Coal Science and Technology, 34*(14), 71-73.

Wen Desheng, (2009). *Innovation and development of hydraulic components*. Beijing: Aviation Industry Press, 375-383.

Furustiu J, Almqvist A, Bates C A, et al. (2015). A Two Scale Mixed Lubrication Wear in Model, Applied to

Hydraulic Motors. *Tribology International, 90*, 218-256.

Furustig J, Larsson R, Almqvist A, et al. (2015). A Wear Model for EHL. Contacts in Gerotor Type Hydraulic Cotors. *Proc. Inst. Mech. Part C: J. Mech. Eng., 229*(2), 254-264.

Zhou Cong, (2017). The design and research of double inclined plate multi row axial piston motor. Qinghuangdao: Yanshan University.

Wen Desheng, Gao Junfeng, Zhou Ruibin, et al. (2014). Analysis of torque pulsation for multi-acting double-stators couple hydraulic motor. *Transactions of the Chinese Society for Agricultural Machinery, 45*(10), 319-325

Wen Desheng, (2011). Theoretical Analysis of Output Speed of Multi-pump and Multi-motor Driving System. *Science China Technology Science, 54*(4), 992-997.

Deng Haishun, Huang Ran, Wang Chuanli, et al. (2016). Torque ripple analysis of a double-sided axial piston motor. *Journal of Zhejiang University (Engineering Science), 50*(03), 436-441+484.

Zhang Jun, XuXianliang, Zhang Xiaofei, (2004). Study on the Mechanism of Low Speed and High Torque I Type Compound Gear Rotor Motor. *Transactions of the Chinese Society of Agricultural Machinery*, (02), 44-47.

He Cunxing, (1982). *Hydraulic element*. Beijing: Machinery industry press, 51-66.

Lei Tianjue, (1990). *Hydraulic Engineering Manual*. Beijing: Machinery industry press, 11-30.

Wen Desheng, Wang Zhili, Gao Jun, Zhang Yong, Lv Shijun, Tetsuhiro Tsukiji, (2011). Output speed and flow of double-acting multi-pump and multi-motor. *Journal of Zhejiang University-Science A*, 5-20.

Li Ruitao, Fang Mei, Zhang Wenming, et al. (2000). Virtual Prototype Technology and Its Application Prospect in Mining Machinery. *Mining Machinery*, (5), 11-14.

Xu Tian, (2012). Theoretical Study on Equal-width Curved Dual-rotor Eccentric Shell-to-Multi-speed Motor. Qinhuangdao: Yanshan University.

Wen Desheng, (2009). *Innovation and Development of Hydraulic Components*. Beijing: Aviation Industry Press, 56-70.

Wen Desheng, (2002). *Open-circuit plunger pump*. Beijing: Aviation Industry Press, 45-52.

Li Zhuangyun, (2005). *Hydraulic Components and Systems*. Beijing: Machinery industry press, Machinery industry press, 55-60.