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Design and Performance Analysis of a new Rotary Hydraulic Joint

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Abstract. To improve the driving torque of the robots joint, a wobble plate hydraulic joint is proposed, and the structure and working principle are described. Then mathematical models of kinematics and dynamics was established. On the basis of this, dynamic simulation and characteristic analysis are carried out. Results show that the motion curve of the joint is continuous and the impact is small. Moreover the output torque of the joint characterized by simple structure and easy processing is large and can be rotated continuously.

1. Introduction

As an important part of robots, robots joint has a great effect on the performance of robots. At present the drive device of robots with drive of servo motor and reducer, is heavy and limited in load capacity, which has seriously restricts on the practicability of robots [1].Therefore robot joints with the advantages of small size, light weight and strong load capacity etc. have become a main studying interest.

There have been a few approaches to improve the load capacity of the robot joint, without increasing the mass. The one which enhance the joint performance is to use high power density motor and reducer. For example the robot Cheetah uses a planetary gear reducer and an EM motor whose power mass density is 7kw/kg [2]. The motor is small, high precision and no pollution, but they are expensive.

Compared with the motor drive, hydraulic driving have much predominance, such as big driving power. Therefore many high-load hydraulic actuators are designed to use on robots. Professor Liang [3] has proposed a rotary actuator based on screw device, which has an advantage of bigger output torque $(\geq 2.5kN\ m)$, but the corner is only 60 degrees. In the literature [4], a straight hydraulic cylinder is used to drive the hinge joint, the structure of the joint is simple, but the angle range of the joint is limited. Ref. [5] shows a kind of joint which adopts rope to drive pulley. It's easy to arrange this joint on robots, but the flexible wire rope is easy to deformation. In addition, there are other types of hydraulic joints, such as gear and rack rotary hydraulic cylinder [6], screw rotary cylinder [7] etc. These joints are not good choice for robots, due to leakage, larger size, and other reasons.

According to the characteristics of the robot joints described above, a new kind of hydraulic joint is proposed and can convert the reciprocating linear motion of the piston into the rotary motion of the output shaft. With a compact structure, driving capacity strongly, and being rotated continuously, this new joint can be applied especially for mobile robot which need large load driving capacity.

2. Design of the wobble plate hydraulic joint

In this section, the mechanism of the new hydraulic joint is presented, and the structure of the joint is designed.

2.1. Structure design of the hydraulic joint

The structure of the wobble plate hydraulic is shown in figure 1, which is mainly composed of the base, the cylinder, the wobble shaft, the piston, the rod, and the output shaft (Z axis). The two bases are connected by connecting rods, the linear hydraulic cylinders are evenly distributed on the circular base, two symmetrical rods and the fixing device are connected by screw threads. The linear bearing is installed on the linear bearing seat, there is a rotation pair between the linear bearing and the fixing device. Two perpendicular swing rod which constitute wobble plate are mounted on the output shaft through the bearing, the swing rod and the output shaft form a rotating pair, and a cylindrical pair are formed between swing rod and linear bearing simultaneously.

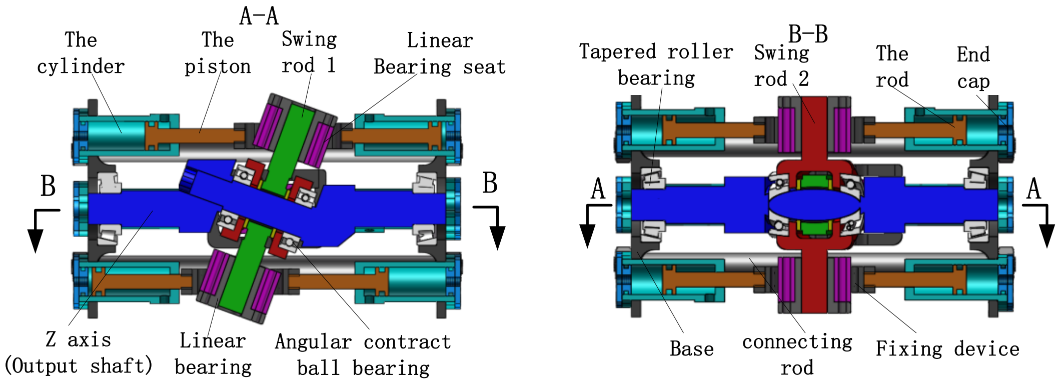

Figure 1. The structure of the joint.

2.2. Principle of the hydraulic joint

As shown in the figure 2, the servo valve causes the rods on both sides of the swing rod to produce a linear motion in the opposite direction by controlling the flow direction of the oil. Under the action of the rod, the swing rods are rotated in the plane A-A and B-B, which also drives Z axis to rotate. At the same time, the swing rod is also rotated relative to its own axis. In this way, the reciprocating linear motion of the piston is converted into rotary motion of the output shaft. However, when the piston is moved to the limit position, the corresponding swing rod is in the same plane with the bent portion of the output shaft. At this point, no matter how big the piston thrust is, the output shaft can't be driven, this point is called the dead point of the mechanism. In order to remove dead point, similar structures are arranged on the plane A-A and B-B, when the swing axis of the A-A plane is at the dead point, the swing axis of the B-B plane can rotates the output shaft. Thus the continuous rotation of the hydraulic joint is achieved.

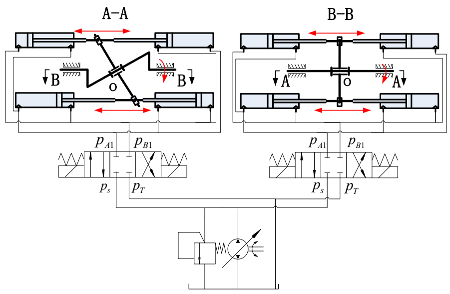

Figure 2. The principle of the joint.

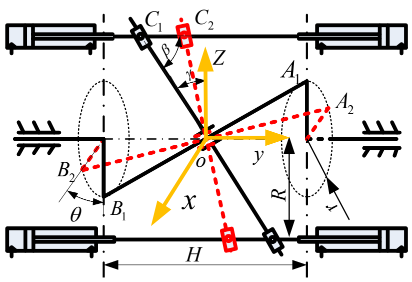

Figure 3. The mathematical model of the joint.

3. Mathematics model of the new joint

3.1. Kinematics model

The geometric relationship and some parameters of the internal structure of wobble plate hydraulic joint are shown in figure 3. The relationship between displacement of the ith piston $y_i (i = 1,2,3,4)$ and angle θ can be expressed as follows. The meanings of R, r, β, γ and H are shown in figure 3.

$$\begin{cases} y_1 = -\dfrac{2Rr}{H}\cos\theta \\ y_2 = -\dfrac{2Rr}{H}\sin\theta \\ y_3 = \dfrac{2Rr}{H}\cos\theta \\ y_4 = \dfrac{2Rr}{H}\sin\theta \end{cases} \tag{1}$$

3.2. Dynamic model

Before the establishment of the dynamic model by using Lagrange equation, the swing plate hydraulic joints are divided into four modules. Module 1 includes piston, rod, and fixing device. Module 2 contains linear bearings and linear bearing seat. Module 3 comprises swing rod 1 and swing rod 2. The last module is the Z axis. Respectively, calculate the kinetic energy of each module as follows.

$$T_1 = \sum_{i=1}^{4} \frac{1}{2} m_1 \dot{y}_i^2 \tag{2}$$

$$T_2 = \sum_{i=1}^{4} \frac{1}{2} m_2 \dot{y}_i^2 + \sum_{i=1}^{4} \frac{1}{2} I_{2x} \dot{\beta}_i^2 \tag{3}$$

$$T_3 = \frac{1}{2} I_{31x} \gamma_1^2 + \frac{1}{2} I_{31z} \gamma_2^2 + \frac{1}{2} I_{32x} \gamma_2^2 + \frac{1}{2} I_{32z} \gamma_1^2 \tag{4}$$

$$T_4 = \frac{1}{2} I_{4y} \dot{\theta}^2 \tag{5}$$

Where I_{2x} is the moment of inertia of module 2 relative to the x-axis, I_{4y} is the moment of inertia of Z axis relative to the y-axis, I_{3ij} $(i = 1, 2; j = x, z)$ is the moment of inertia of swing rod i relative to the j-axis. γ_i is the angle between the swing rod i and the Z-axis, β_i is the angle between the rod i and swing rod, and the expressions of γ_i and β_i are as follows.

$$\gamma_i = \arctan\frac{y_i}{R} (i = 1, 2) \tag{6}$$

$$\begin{cases} \beta_i = \dfrac{\pi}{2} + \gamma_i (i = 1, 2) \\ \beta_i = \beta_{i-2} (i = 3, 4) \end{cases} \tag{7}$$

The kinetic energy of system T is obtained.

$$T = \sum_{i=1}^{4} T_i \tag{8}$$

Because the joints are symmetrical about the origin of the coordinate system, the potential energy of the system V can be obtained.

$$V = 0 \tag{9}$$

From equations (3) to (11), The Lagrange is obtained as:

$$L = T + V = \sum_{i=1}^{4} T_i \tag{10}$$

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{\theta}} - \frac{\partial L}{\partial \theta} = Q \tag{11}$$

Assuming that the joint is affected only by the fluid force F_i and torque τ , the power generated by F_i and τ is equal to the power produced by the generalized force Q .

$$\tau\theta + \sum_{i=1}^{N} F_i \dot{y}_i = Q\theta \tag{12}$$

From equations (2) and (14), the generalized force Q .can be obtained.

$$Q = M + F_1 \frac{2Rr}{H}\sin\theta - F_2 \frac{2Rr}{H}\cos\theta - F_3 \frac{2Rr}{H}\sin\theta + F_4 \frac{2Rr}{H}\cos\theta \tag{13}$$

The meaning of F_i $(i = 1,2,3,4)$ is the output force of the ith cylinder.

4. Simulation

The new hydraulic joint is modeled in MATLAB/Simulink. In order to verify the wobble plate hydraulic joint can output a large torque, the servo valve is fully opened, and the external force of each swing rod is shown in the figure 4. Meanwhile the displacement of Z axis is $\theta = \pi t / 6$. Shown in Figure 5, the piston motion curve is continuous, which is consistent with the mathematical model.

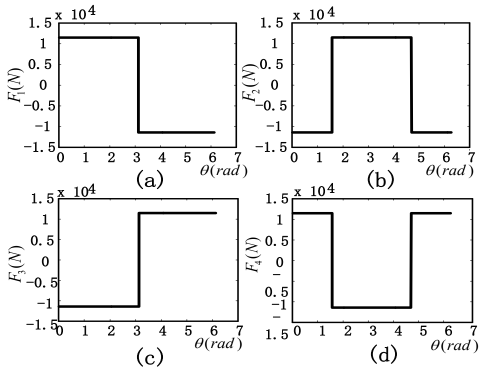

Figure 4. The external force of swing rod.

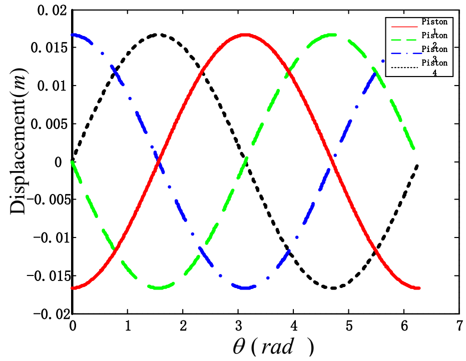

Figure 5. The displacement of each piston.

Figure 6 shows the output torque curve of the joint. It can be seen that the output torque of the joint is at least 380 $N\bullet$, and the output torque varies with the rotation angle of the output shaft. In order to verify the validity of the mathematical model, Adams virtual prototype simulation is carried out after MATLAB simulation. The results of Adams simulation is shown in Figure. 7.

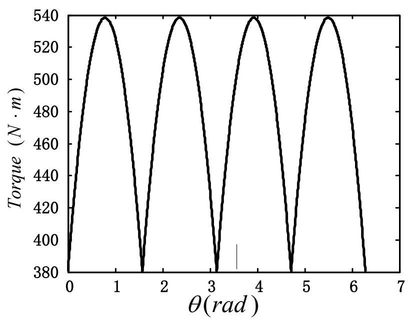

Figure 6. The output torque of the joint.

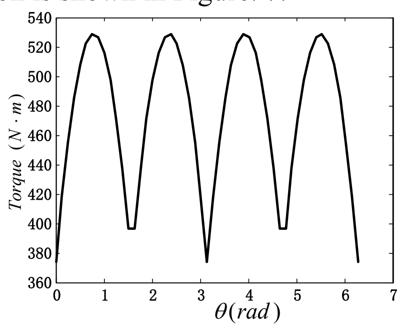

Figure 7. Adams Simulation Result.

By comparison, it is found that the output torque in Figure 7, is smaller than that in Figure 6, at any point. The reason is that the influence of frictional resistance and the inertial force of eccentric mass are ignored in the mathematical model. On the whole, two sets of curves are basically consistent, which proves that the mathematical model and simulation are correct.

5. Conclusion

In the present paper, a new joint is proposed. With advantages of compact structure, continuous rotation, and small mass, this joint, whose maximum output torque can be more than 380 $N\bullet$, is just about 4.75kg. In addition, through the movement and dynamic simulation of the joint, it’s found that the joint motion curve was continuous and the maximum output torque is related to the rotation angle of the joint.

Acknowledgement

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