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Output speed and flow of double-acting double-stator multi-pumps and multi-motors*

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Abstract: The primary focus of this study was to investigate a series of novel motors and pumps, based on a new type of structure called double-stator. The double-stator structure can be used as pump or motor just based on the application requirements. A certain amount of pumps or motors can be formed in one shell, and these sub-pumps or sub-motors can work alone or be combined without influence on each other. So this kind of double-stator pump (motor) is called a multi-pump (multi-motor). Through the analysis of multifarious connection modes of the double-acting double-stator multi-pumps and multi-motors, the mathematical expressions of the output flow rate and the rotational speed are acquired. The results indicate that a quantity of different flow rates can be provided by one fixed-displacement multi-pump under the condition of unalterable driven speed by electromotor. Likewise, when supplied by settled input flow, without complex variable mechanism, the functions of double-speed, multiple-speed, and even differential connection can be obtained by employing the use of a double-stator multi-motor. The novel hydraulic transmission is made of such a double-stator multi-pump and multi-motor, and has broad application prospects.

Key words: Multi-pumps, Multi-motors, Flow rate, Rotational speed, Hydraulic transmission, Differential motor
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1 Introduction

Hydraulic motors and pumps are important core components in hydraulic systems. In recent years, higher demands for the output flow rate and pressure of hydraulic pumps, and the rotational speed and torque of motors have been required. The noise level, efficiency, service life, impact resistance, control method, and specific power are other factors that industry has greater demands for. Hydraulic motors are usually divided into two groups: low-speed high-torque ones and high-speed low-torque ones. It is difficult to obtain a wide range of rotation velocity regulation for the current fixed-displacement motors. For pumps, pressure-reducing valves are needed when more than two different pressures exist in one hydraulic transmission with great energy loss. The desire to improve the shortages mentioned above has increased rapidly, and a considerable amount of research has been performed in this field during the past five years (Zhang *et al.*, 2009). To improve the performances and increase the ratings of pumps and motors, many different aspects of study on hydraulic components have received attention (Wang and Zhang, 2003).

The main research performed on hydraulic pumps and motors is concentrated on pressure distribution, temperature change, friction analysis, advanced materials application, manufacturing process, tightness methods, and lubrication. Three-dimensional model simulation and optimization designs on the key friction pairs are hot topics today, and much research work has been performed in this area too. For

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example, the single-cylinder and multi-cylinder pumping dynamics models of a swash plate piston pump were improved. Particular attention has been paid to the design influences of key parts of the valve plate. The cross angle and the pre-compression angle of the valve plate were optimized, based on the pumping dynamics model (Manring, 2003; Ma *et al*., 2010). Advances in variable frequency technology have improved the energy-saving level and response speed. The variable speed electro-hydraulic technology can control hydraulic systems by varying pump speeds and output flow rates (Jahns and Owen, 2001; Peng *et al*., 2004). Significant amounts of work regarding various control algorithms, expert systems, optimal design method, and advanced 3D-application software have been applied in hydraulic industry (Azadeh *et al.*, 2009; Spence and Amaral-Teixeira, 2009; Wang *et al.*, 2009; Shin and Sung, 2010; Xue and Shi, 2010). In addition, the demand for more environmental and fuel-efficient construction machinery, especially for hydraulic excavators, has been increased in response to growing environmental and energy-saving concerns. A method of how to regenerate the potential energy for a hybrid hydraulic excavator was discussed in detail by Lin *et al.* (2010). Moreover, a virtual prototype technology was used in the hydraulic industry. The flow, pressure, and power controls of hydraulic components were studied in the way of simulation of the virtual prototype. The virtual prototype technology can well predict the pump performance and would be a good choice for designing and optimizing the components (Yang *et al*., 2010). In addition, research on reducing the noise level is a hot topic today, and much research work has been performed (Yang *et al*., 2009). Advances in materials and seizure technology have improved contamination tolerance and fatigue technology (Bobzin *et al*., 2004; Nilsson and Prakash, 2009), including nanostructured materials as a new class of engineering materials with enhanced properties and structural length scale between 1 and 100 nm, which have a broad application when producing novel components (Chawla *et al*., 2007). However, little attention is paid to the operating principles of the existing pumps or motors to improve their characteristics (Wen, 2011).

The design of the double-stator structure offers a lower-cost alternative in comparison to other fluid-power and fluid-transfer mechanisms over a broad range of applications. Designers of engines, compressors, machine tools, tractors, and other equipments requiring hydraulic systems can use an integrally designed double-stator pump and motor for a more compact and lower weight unit. In most cases, it will also run more quietly for no variable mechanisms are required.

It is a significant and challenging issue to study the theory of multi-pump and multi-motor hydraulic systems based on the existing structures and operating principles of hydraulic components. For this reason, we made an innovation in the field of structure and operating principles of components and developed a series of novel ones.

2 Structure and operating principles

Generally, the hydraulic transmission systems consist of single pumps and single motors, whose basic structures require the use of one rotator corresponding to one stator in a single shell (Lei, 1998). Different from the common ones, there are two stators corresponding to one rotator for this novel double-stator structure. The specific configuration of a double-acting double-stator multi-pump (multi-motor) with double-roller and connecting-bar is shown in Fig. 1. The basic structure includes a rotator, inner and outer stators, inner and outer rollers, and connecting-bars. The rotator is a concentric cylinder on which several thorough grooves are installed. For each groove, there is a group of double-rollers and connecting-bars. The inner and outer stators are stationary. Four pairs of the inlet and the outlet ports, used for suction and delivery action, are installed on the shell. The inlet and outlet segments are controlled by the valve plate located on the two side plates. The distance between the inner and the outer stators is equal, and both of their fringes resembled curves.

Here, we suppose that it is used as a pump to account for the operating principle. The variable volume of the two outer pumps is formed by the outer stator, the group of rollers and connecting-bar, the rotator, the outer valve plate, and two side plates. Likewise, the inner variable volume of the two inner pumps is composed of the group of rollers and connecting-bar, the inner stator, the rotator, the inner valve plate, and two side plates. There are four pumps

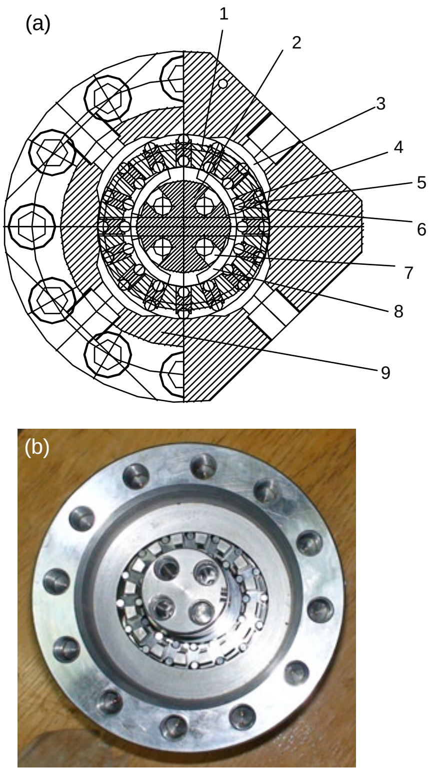

Fig. 1 Structure section (a) and prototype (b) of the double-acting double-stator multi-pump with double-rollers and connecting-bar

1: Rotator; 2: Inner stator; 3: Valve plate of the outer pump; 4: Outer roller; 5: Connecting-bar; 6: Inner roller; 7: Inlet or outlet port of the inner pump; 8: Valve plate of the inner pump; 9: Outer stator

in one shell for a double-acting double-stator multi-pump. Each of these sub-pumps can work alone or be combined depending on the actual requirement. A certain number of different output flow rates can be provided by one double-stator fixed-displacement pump, and it can work at various hydraulic system pressures at the same time. There is a proportional relationship between each of the output flow rates and the ratio of the displacement of the inner pump to that of the outer one. When compared with the pump, using the same action times and volume, two pumps appeared in one shell. Hence, the displacement is enlarged, and the specific power is increased as well as with the advantages of small size and light weight. Moreover, the radial forces balance well for the double-acting double-stator structure, and the rolling frictions among rollers and stators can reduce the damages due to friction.

Similarly, under the condition of the same input flow and without complex variable mechanism, a certain amount of different output rotational speeds can be acquired when it is used as a motor. Likewise, the proportional relationship exists between the output rotational speeds (Wen, 2003a; 2003b; 2008).

Furthermore, if we change the shape of the inner and the outer stators, the single-acting, triple-acting, and even the multiple-acting double-stator multi-pumps (multi-motors) can be acquired. The double-roller setup with a connecting-bar can be designed as a rectangle slider, single-roller, and concentric circle vane, etc.

Simulation, theoretical analysis, test results, structure parameters, performance standards, and graphic symbols of these novel hydraulic components as well as the definition of multi-pumps and multi-motors were discussed in detail (Wen *et al*., 2008; 2011; Wen, 2009).

3 Modeling of double-stator multi-pumping dynamics

According to the description above, the main moving parts of double-stator multi-pump are the rotator and the roller group (including two rollers and a connecting-bar). The rotational speed of the rotator is the speed of the electric motor, which is approximately a constant. Thus, the primary focus of the dynamics analysis is to study the movement of the roller group. The outer curve of the inner stator and the inside curve of the outer stator are concentric and similar, and the distance between the two curves is equal in distance. Therefore, no radial movement exists between the two curves for the roller group. So, the absolute movement of the roller group is the rotational motion around the center of the stator, which is composed of the rotational and the radial elastic motions of the roller group that follows the rotator. The rotational velocity is the same as the rotational speed of the rotator driven by the motor. Besides, the motion of the roller group has a close relationship with the shape of the two curves mentioned above. The two curves are composed of four working curves and four transition curves. The four working curves consist of two large and two small circular arcs, which are all concentric arcs and symmetrically located. The equivalent acceleration and deceleration models are selected as the mathematical expression of the four transition curves, which are also symmetrically distributed. In the study of the pumping dynamics of the double-acting double-stator multi-pump, the motion of the roller group can be better described by means of polar coordinates. The mathematical model of polar radius should be acquired first. Since the structure of the double-acting double-stator is centrosymmetric, a quarter of the movement will be used as an example (Fig. 2).

Firstly, some common parameters are explained as follows: 2γ and 2β are the large and the small circular arc angles of the outer stator respectively, α is the transition curve angle, ϕ is the polar angle of the center of the roller group, ω is the rotation speed of the rotator, and ρ is the polar radius of the center of the roller group, which can be expressed as

$$\rho=\begin{cases} R-\dfrac{L}{2}, & 0\le\phi\le\beta, \\ R+\dfrac{2(R_1-R)}{\alpha^2}(\phi-\beta)^2-\dfrac{L}{2}, & \beta<\phi\le\beta+\dfrac{\alpha}{2}, \\ R_1-\dfrac{2(R_1-R)}{\alpha^2}(\alpha+\beta-\phi)^2-\dfrac{L}{2}, & \beta+\dfrac{\alpha}{2}<\phi\le\alpha+\beta, \\ R_1-\dfrac{L}{2}, & \alpha+\beta<\phi\le\alpha+\beta+\gamma, \end{cases} \tag{1}$$

where L is the length of the roller group, R and R_1 are the small and the large circular arc distribution radii, respectively.

The absolute speed of the roller group V_a consists of the following velocity V_e, which comes from the rotational speed of the rotator, and the relative velocity V_r, and is calculated by

$$\begin{aligned} &V_a=V_e+V_r,\, V_a=\sqrt{V_e^2+V_r^2}, \\ &V_r=\frac{d\rho}{dt},\, V_e=\rho\omega, \end{aligned} \tag{2}$$

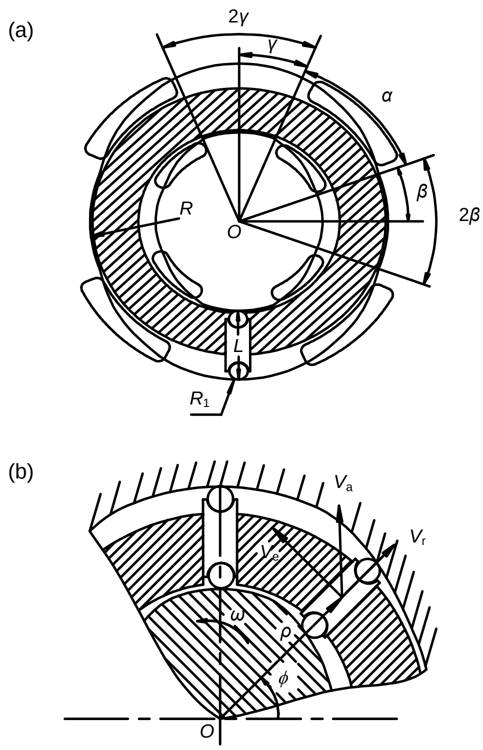

Fig. 2 Diagrammatic sketch of dynamics analysis
(a) Parameters of the rotator distribution; (b) Polar coordinates and velocity resolution

where the forward direction of V_r is the outward motion of the roller group, and the direction of V_e is the tangential direction of the revolving rotator.

Substituting Eq. (1) into Eq. (2), the absolute speed of the roller group is given as Eq. (3) (see the bottom of this page).

The acceleration of the roller group a_a is composed of the relative acceleration a_r, the following acceleration a_e, and Coriolis acceleration a_k, and can be expressed by

$$\begin{aligned} &a_a=a_r+a_e+a_k,\quad a_a=\sqrt{(a_r-a_e)^2+a_k^2}, \\ &a_r=\frac{d^2\rho}{dt},\, a_e=\rho\omega^2,\, a_k=2\omega V_r. \end{aligned} \tag{4}$$

$$V_a=\begin{cases} (R-L/2)\omega, & 0\le\phi\le\beta, \\ \sqrt{\left[R+2(R_1-R)(\phi-\beta)^2/\alpha^2-L/2\right]^2\omega^2+\left[4(R_1-R)(\phi-\beta)\,\omega/\alpha^2\right]^2}, & \beta<\phi\le\beta+\dfrac{\alpha}{2}, \\ \sqrt{\left[R_1-2(R_1-R)(\alpha+\beta-\phi)^2/\alpha^2-L/2\right]^2\omega^2+\left[4(R_1-R)(\alpha+\beta-\phi)\omega/\alpha^2\right]^2}, & \beta+\dfrac{\alpha}{2}<\phi\le\alpha+\beta, \\ (R_1-L/2)\omega, & \alpha+\beta<\phi\le\alpha+\beta+\gamma. \end{cases} \tag{3}$$

Based on Eqs. (1), (2), and (4), the composition of acceleration of the roller group is given as Eq. (5) (see the bottom of this page).

4 Connection modes and speed of double-acting multi-motors

Different output and input flows can be acquired by changing the connection mode of multi-pumps and multi-motors, respectively.

To facilitate explication, we suppose that the input flow rate is always the same as Q, and the displacements of the two inner and two outer motors as q_{11}, q_{12}, q_{21}, and q_{22}.

For double-acting double-stator multi-motors, two major combination categories exist: the common connection and the differential connection. The connection features for each of the two different connection modes are discussed in detail.

4.1 Common connection

Fig. 3a indicates that only one of the outer motors is working, while Fig. 3b shows that two outer motors are working with no load on the inner motors. In the term of double-acting double-stator multi-motor structure, the next mathematical expression can be obtained:

$$\frac{q_{21}}{q_{11}}=\frac{q_{22}}{q_{12}}=C,\ \ q_{11}=q_{12},\ \ q_{21}=q_{22}, \tag{6}$$

where C is a constant dependant on the design of the inner and outer motors' displacements.

When only one of the inner motors is working, the output rotational speed is expressed by

$$n_1=\frac{Q}{q_{11}}. \tag{7}$$

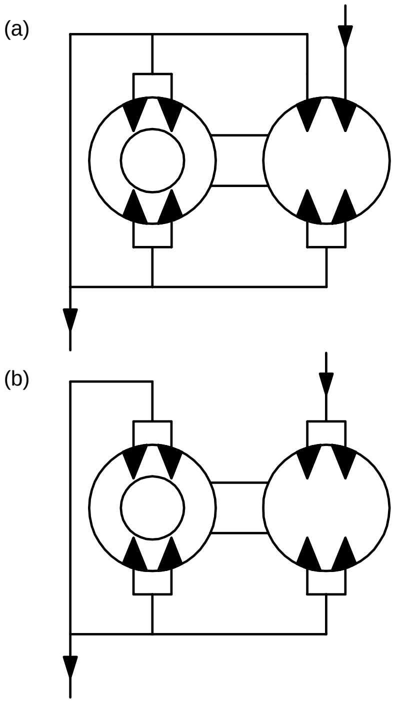

Fig. 3 Schematic drawings of double-acting double-stator multi-motor connection with one outer motor (a) and two outer motors (b) working

Eq. (7) is the basic expression of the rotational speed of the multi-motors. The other output rotational speeds listed in Table 1 in different connection modes have a certain proportional relationship with n_1, and the calculation method is similar with Eq. (7). A similar explanation can be used to describe Tables 2 and 3.

4.2 Differential connection

Because of the double-stator structure, a novel differential connection of double-stator multi-motors, which is similar to differential hydraulic cylinder can be acquired. When a double-acting double-stator multi-motor is working, the torque provided by one

$$a_{\rm a}=\begin{cases}(R-L/2)\omega^2, & 0\le\phi\le\beta,\\ \sqrt{\left\{\dfrac{4(R_1-R)\omega^2}{\alpha^2}-\left[R+\dfrac{2(R_1-R)}{\alpha^2}(\phi-\beta)^2-\dfrac{L}{2}\right]\omega^2\right\}^2+\left[\dfrac{8(R_1-R)}{\alpha^2}(\phi-\beta)\omega^2\right]^2}, & \beta<\phi\le\beta+\dfrac{\alpha}{2},\\ \sqrt{\left\{\left[\dfrac{-4(R_1-R)\omega^2}{\alpha^2}\right]-\left[R_1-\dfrac{2(R_1-R)}{\alpha^2}(\alpha+\beta-\phi)^2-\dfrac{L}{2}\right]\omega^2\right\}^2+\left[\dfrac{8(R_1-R)}{\alpha^2}(\alpha+\beta-\phi)\omega^2\right]^2}, & \beta+\dfrac{\alpha}{2}<\phi\le\alpha+\beta,\\ (R_1-L/2)\omega^2, & \alpha+\beta<\phi\le\alpha+\beta+\gamma.\end{cases} \tag{5}$$

Table 1 Rotational speeds of the double-acting multi-motors in common connections

CM	N_{in}	N_{out}	Output rotational speed (r/min)
1	1	0	$n_1=Q/q_{11}$
2	2	0	$n_2=Q/2q_{11}=n_1/2$
3	0	1	$n_3=Q/q_{21}=Q/Cq_{11}=n_1/C$
4	0	2	$n_4=Q/(q_{21}+q_{22})=n_1/2C$
5	1	1	$n_5=Q/(q_{11}+q_{21})$ $=Q/(q_{11}+Cq_{11})=n_1/(1+C)$
6	1	2	$n_6=Q/(q_{11}+q_{21}+q_{22})=n_1/(1+2C)$
7	2	1	$n_7=Q/(2q_{11}+q_{21})=n_1/(2+C)$
8	2	2	$n_8=Q/(2q_{11}+2q_{21})=n_1/(2+2C)$

CM: connection mode; N_{in}: number of the inner working motors; N_{out}: number of the outer working motors

Table 2 Rotational speeds of the double-acting multi-motors in differential connections

CM	N_{in}	N_{out}	Output rotational speed (r/min)
1	1	1	$n_9=Q/(q_{21}-q_{11})=n_1/(C-1)$
2	1	2	$n_{10}=Q/(2q_{21}-q_{11})=n_1/(2C-1)$
3	2	1	$n_{11}=Q/(q_{21}-2q_{11})=n_1/(C-2)$
4	2	2	$n_{12}=Q/(2q_{21}-2q_{11})=n_1/(2C-2)$

CM: connection mode; N_{in}: number of the inner working motors; N_{out}: number of the outer working motors

Table 3 Output flow rates of the double-acting multi-pumps

CM	N_{in}	N_{out}	Output flow rate (L/min)
1	1	0	$Q_1=q'_{11}n_d$
2	2	0	$Q_2=2q'_{11}n_d=2Q_1$
3	0	1	$Q_3=q'_{21}n_d=C'Q_1$
4	0	2	$Q_4=2q'_{21}n_d=2C'Q_1$
5	1	1	$Q_5=(q'_{11}+q'_{21})n_d=(1+C')Q_1$
6	1	2	$Q_6=(q'_{11}+2q'_{21})n_d=(1+2C')Q_1$
7	2	1	$Q_7=(2q'_{11}+q'_{21})n_d=(2+C')Q_1$
8	2	2	$Q_8=(2q'_{11}+2q'_{21})n_d=(2+2C')Q_1$

CM: connection mode; N_{in}: number of inner pumps; N_{out}: number of outer pumps; n_d: rotational speed of the electromotor

outer motor is larger than that by one inner motor. So the rotation direction is determined by the outer motor. Then the inner motor is used as the pump in differential connection to provide hydraulic oil to the outer motor. Therefore, the total input flow for double-stator multi-motors is enlarged. The differential function of double-stator multi-motors is suited for high-speed working conditions.

Fig. 4 shows that two inner motors and one outer motor are combined as one kind of differential connections.

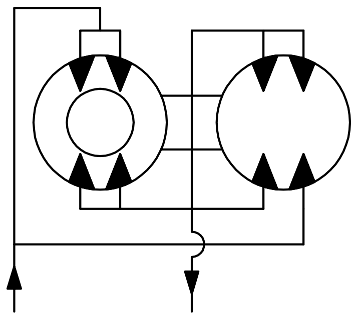

Fig. 4 Schematic drawing of double-acting multi-motor in differential connections

The mathematical expression of the output rotational speed in a differential connection composed by one inner motor and one outer motor is

$$n_9=\frac{Q}{q_{21}-q_{11}}=\frac{1}{C-1}n_1. \quad (8)$$

The above description shows that a double-motor fixed-displacement multi-motor can output twelve different rotational speeds under the condition of the same input flow rate and without a complex variable displacement mechanism (Tables 1 and 2).

5 Connection modes and flow of double-acting multi-pumps

One fixed-displacement multi-pump can output a certain number of different flows driven by a constant speed, and can work at diverse system pressures without the use of a pressure-reducing valve. All of these functions are based on the various combinations of the multi-pumps.

Using the double-acting fixed-displacement multi-pumps as an example, there are eight different connection methods available (Table 3), two of which are shown in Fig. 5.

Based on the structure of double-stator, the following relational expression can be obtained:

$$\frac{q'_{21}}{q'_{11}}=\frac{q'_{22}}{q'_{12}}=C',\ q'_{11}=q'_{12},\ q'_{21}=q'_{22}, \quad (9)$$

where q'_{11}, q'_{12}, q'_{21}, and q'_{22} are the displacements of the two inner pumps and the two outer pumps, and C' is a constant, depending on the ratio of the inner and outer pumps' displacements.

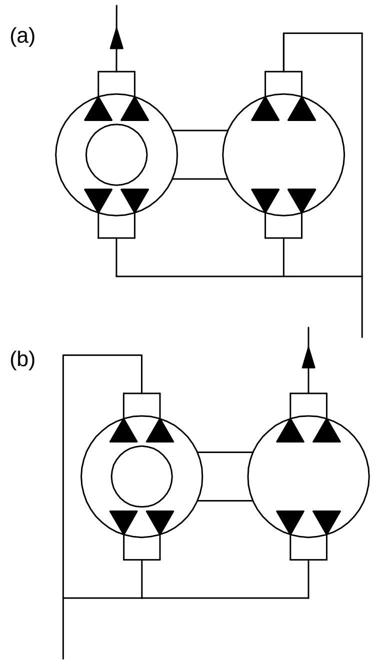

Fig. 5 Connection modes of double-acting multi-pumps with two inner pumps (a) and two outer pumps (b) working

6 Speed analysis of multi-motors

After obtaining the various connection methods of the multi-pumps and multi-motors, a novel hydraulic transmission has come into being, which is called multi-pump and multi-motor transmission. Since there are many connection modes for the multi-pumps and multi-motors, the connection of double-acting multi-pumps with multi-motors is taken as an instance to illustrate the advantage of the new type of transmission.

Through the above analysis, one double-acting fixed-displacement multi-motor can output twelve different rotational speeds under the same input flow rate. For a single double-acting multi-pump, eight connection modes are possible. In other words, eight different flow rates can be provided. Therefore, there are 96 connection configurations, when such pump and motor are combined. That is to say, 96 output rotational speeds can be acquired for a double-acting multi-pump combined with a multi-motor transmission. Every mathematical expression of the output rotational speed can be obtained by performing the following matrix multiplication:

$$\begin{aligned}\boldsymbol{M} &= \boldsymbol{M}_1\times\boldsymbol{M}_2\\ &=\left[n,\frac{1}{2}n,\frac{1}{C}n,\frac{1}{2C}n,\frac{1}{1+C}n,\frac{1}{1+2C}n,\frac{1}{2+C}n,\right.\\ &\qquad\left.\frac{1}{2+2C}n,\frac{1}{C-1}n,\frac{1}{2C-1}n,\frac{1}{C-2}n,\frac{1}{2C-2}n\right]^{\mathrm{T}}\\ &\qquad\times\left[1,2,C',\ 2C',1+C',1+2C',2+C',\ 2+2C'\right]^{\mathrm{T}},\end{aligned}$$

where $\boldsymbol{M}_1$ is the calculational result of the output rotational speed of double-acting multi-motors, $\boldsymbol{M}_2$ is the coefficient matrix of the results of the flow rate for double-acting multi-pumps, and $\boldsymbol{M}$ is an 8×12 matrix, and represents the calculational result of the output rotational speed of double-acting multi-motors with multi-pumps.

7 Conclusions

In this paper, some conclusions can be drawn based on the analysis above:

1. The basic structure of the novel hydraulic pumps (motors) is that there is one rotor corresponding to two stators, and thus more than two motors or pumps can be configured for use in a single shell. This paper lays the groundwork for multi-pump and multi-motor hydraulic transmission research and adds a new series of hydraulic components.

2. A certain number of different flows can be provided by one of this kind of fixed-displacement pump without the need for use of a variable mechanism or other assisting components. Furthermore, there is a type of proportional relation for every two output flows.

3. Differential motors are acquired, which expand the range of applications and improve the adaptability for hydraulic motors. As the distance between the inner and outer stators is equal, no returning springs and such mechanisms are required.

4. Comparing the pumps with the same action times and volume, two pumps are formed in one shell for double-acting double-stator structure. So it takes

the advantages of small size, light weight, and high efficiency in specific power.

5. Ninety-six different rotational speeds from low to high in a wide range of speed regulation can be achieved by such a novel hydraulic transmission. All of these indicate that the novel hydraulic transmissions have a wide range of industrial applications.

In summary, this paper presents a new structure design that is capable of generating large numbers of possible design concepts of hydraulic components automatically for specified operation requirements.

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References

Azadeh, A., Ebrahimipour, V., Bavar, P., 2009. A fuzzy inference system for pump failure diagnosis to improve maintenance process: the case of a petrochemical industry. *Expert Systems with Applications*, **37**(1):627-639. [doi:10.1016/j.eswa.2009.06.018]

Bobzin, K., Lugscheidera, E., Maesa, M., Goldb, P.W., Loosb, J., Kuhnb, M., 2004. High-performance chromium aluminium nitride PVD-coatings on roller bearings. *Surface & Coatings Technology*, **188-189**:649-654. [doi:10.1016/j.surfcoat.2004.07.030]

Chawla, V., Prakash., S., Sidhu, B.S., 2007. State of the art: applications of mechanically alloyed nanomaterials—a review. *Materials and Manufacturing Processes*, **22**(4): 469-473. [doi:10.1080/10426910701235900]

Jahns, T.M., Owen, E.L., 2001. AC adjustable-speed drives at the millennium: how did we get here? *IEEE Transactions on Power Electronics*, **16**(1):17-25. [doi:10.1109/63.903985]

Lei, T.J., 1998. New Compilation of Hydraulic Engineering Manual. Beijing Institute of Technology Press, Beijing, China, p.313-318 (in Chinese).

Lin, T.L., Wang, Q.F., Hu, B.Z., Gong, W., 2010. Research on the energy regeneration systems for hybrid hydraulic excavators. *Automation in Construction*, **19**(8):1016-1026. [doi:10.1016/j.autcon.2010.08.002]

Ma, J.N., Fang, Y.T., Xu, B., Yang, H.Y., 2010. Optimization of cross angle based on the pumping dynamics model. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, **11**(3):181-190. [doi:10.1631/jzus.A0900417]

Manring, N.D., 2003. Valve-plate design for an axial piston pump operating at low displacements. *Journal of Mechanical Design*, **125**(1):200-205. [doi:10.1115/1.1541632]

Nilsson, D., Prakash, B., 2009. Investigation into the seizure of hydraulic motors. *Tribology International*, **43**(1-2):92-99. [doi:10.1016/j.triboint.2009.05.001]

Peng, T.H., Xu, B., Yang, H.Y., 2004. Development and research overview on variable frequency hydraulic technology. *Journal of Zhejiang University (Engineering Science)*, **38**(2):215-221 (in Chinese).

Shin, S.J., Sung, H.J., 2010. Three-dimensional simulation of a valveless pump. *International Journal of Heat and Fluid Flow*, **31**(5):942-951. [doi:10.1016/j.ijheatfluidflow.2010.05.001]

Spence, R., Amaral-Teixeira, J., 2009. A CFD parametric study of geometrical variations on the pressure pulsations and performance characteristics of a centrifugal pump. *Computers & Fluids*, **38**(6):1243-1257. [doi:10.1016/j.compfluid.2008.11.013]

Wang, Y.Q., Zhang, W., 2003. Summary of fluid power transmission and control technology. *Chinese Journal of Mechanical Engineering*, **39**(10):95-99 (in Chinese).

Wang, W., Yang, H.Y., Zou, J., Ruan, X.D., Fu, X., 2009. Optimal design of Stewart platforms based on expanding the control bandwidth while considering the hydraulic system design. *Journal of Zhejiang University-SCIENCE A*, **10**(1):22-30. [doi:10.1631/jzus.A0820329]

Wen, D.S., 2003a. Double-Stator Torque Pump/Motor. China Patent 02144407.2 (in Chinese).

Wen, D.S., 2003b. Quantitative Same Width and Curvilinear Double-Stators Pump. China Patent 02144406.4 (in Chinese).

Wen, D.S., 2008. Quantitative Same Width and Curvilinear Double-Stators Axial Pump with Sliders. China Patent 200710139642.X (in Chinese).

Wen, D.S., 2009. Innovation and Application for Hydraulic Component. Aviation Industry Press, Beijing, China, p.375-384 (in Chinese).

Wen, D.S., 2011. Theoretical analysis of output speed of multi-pump and multi-motor driving system. *Science China Technological Sciences*, **54**(4):992-997. [doi:10.1007/s11431-011-4321-4]

Wen, D.S., Lu, S.J., Liu, X.C., Cai, X.Z., 2008. Theoretic research on variable displacement of equal-width double-stators pump and motor. *Journal of Harbin Institute of Technology*, **40**(11):1840-1844 (in Chinese).

Wen, D.S., Zhang, Y., Wang, Z.L., Lu, S.J., Tsukiji, T., 2011. Rotating speed and torque of triple-acting multi-pump and multi-motor. *Journal of Xi'an Jiaotong University*, **45**(3): 81-84 (in Chinese).

Xue, Z.F., Shi, L., 2010. Modeling and experimental investigation of a variable speed drive water source heat pump. *Tsinghua Science and Technology*, **15**(4):434-440. [doi:10.1016/S1007-0214(10)70084-5]

Yang, H.Y., Ma, J.N., Xu, B., 2009. Research status of axial piston pump fluid—borne noise. *Journal of Mechanical Engineering*, **45**(8):71-79. [doi:10.3901/JME.2009.08.071]

Yang, Z.W., Xu, B., Zhang, B., 2010. Study on control performance of digital piston pump based on virtual prototype technology. *Journal of Zhejiang University (Engineering Science)*, **44**(1):1-7 (in Chinese).

Zhang, B., Xu, B., Xia, C.L., Yang, H.Y., 2009. Modeling and simulation on axial piston pump based on virtual prototype technology. *Chinese Journal of Mechanical Engineering*, **22**(1):84-90. [doi:10.3901/CJME.2009.01.084]