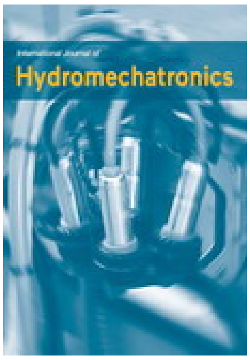


International Journal of Hydromechatronics

ISSN online: 2515-0472 - ISSN print: 2515-0464
https://www.inderscience.com/ijhm

Low-pulsation design of motion structure in cam-lobe hydraulic motor

Chao Zhang, Yiman Duan, Pengpeng Dong, Hao Tan, Xiaolong Zhang, Min Han, Zhijian Zheng, Junhui Zhang, Bing Xu

DOI: 10.1504/IJHM.2024.10067913

Article History:

Received:	21 July 2023
Last revised:	02 September 2023
Accepted:	07 September 2023
Published online:	06 December 2024

Low-pulsation design of motion structure in cam-lobe hydraulic motor

Chao Zhang and Yiman Duan

State Key Laboratory of Fluid Power and Mechatronic Systems,
Department of Mechanical Engineering,
Zhejiang University,
Hangzhou, 310027, China
Email: chao.zhang@zju.edu.cn
Email: ymduan@zju.edu.cn

Pengpeng Dong

Hangzhou Applied Acoustics Research Institute,
Hangzhou, 310027, China
Email: 383451152@qq.com

Hao Tan, Xiaolong Zhang and Min Han

State Key Laboratory of Fluid Power and Mechatronic Systems,
Department of Mechanical Engineering,
Zhejiang University,
Hangzhou, 310027, China
Email: 22025186@zju.edu.cn
Email: zhang.xl@zju.edu.cn
Email: 12325001@zju.edu.cn

Zhijian Zheng

National Intelligent Manufacturing Equipment Quality Supervision and Inspection Center,
Ningbo, 315800, China
Email: zjzhengnb@126.com

Junhui Zhang* and Bing Xu

State Key Laboratory of Fluid Power and Mechatronic Systems,
Department of Mechanical Engineering,
Zhejiang University,
Hangzhou, 310027, China
Email: benzjh@zju.edu.cn
Email: bxu@zju.edu.cn
*Corresponding author

Abstract: Cam-lobe hydraulic motors are widely used in high-end equipment due to their low speed and high output torque. The motion structure composed of piston assemblies and cam ring is the key component that converts hydraulic power into mechanical rotational speed, which directly affects the hydraulic motor rotational speed pulsation. Yet, there is little research on the low-pulsation motion structure design. For that, this study proposed the low-pulsation design approach of motion structure to achieve the hydraulic motor with good speed stability. In general, the piston assembly number and the action number design should ensure that the total angle distribution coefficient is not less than 2, but it should be greater than 3 when the asymmetric distribution coefficient is 2. Finally, several hydraulic motors are used to validate the effectiveness of the low-pulsation design. This study can provide theory guidelines for the low-pulsation motion structure design.

Keywords: hydraulic motors; low-pulsation; motion structure; cam ring curve; speed stability.

Reference to this paper should be made as follows: Zhang, C., Duan, Y., Dong, P., Tan, H., Zhang, X., Han, M., Zheng, Z., Zhang, J. and Xu, B. (2024) 'Low-pulsation design of motion structure in cam-lobe hydraulic motor', *Int. J. Hydromechatronics*, Vol. 7, No. 4, pp.310–327.

Biographical notes: Chao Zhang received his BS degree in 2012 and MS degree in 2015 from Northwestern Polytechnical University, Xi'an, China. He received his PhD degree in 2019 from University of Lyon, Lyon, France. He is currently an Associate Research Fellow at the Institute of Mechatronics and Control Engineering, Zhejiang University. His research interests include high-performance electro-hydrulic actuators and robotics. He published more than 40 papers indexed by SCI.

Yiman Duan received her BS and MS degrees from Yanshan University, Qinghuangdao, China in 2019 and 2022. She is currently working toward her PhD degree in the College of Mechanical Engineering, Zhejiang University, Hangzhou, China. Her main research interests include the design and optimisation of high-performance hydraulic components and system.

Pengpeng Dong received his BS in Mechanical Engineering from Wuhan University, Wuhan, China in 2009, and PhD degree from Zhejiang University, Hangzhou, China, in 2016. He is currently an Engineer at Hangzhou Applied Acoustics Research Institute.

Hao Tan received his BS in Mechanical Engineering from Xiamen University, Xiamen, China in 2020, and MS degree from Zhejiang University, Hangzhou, China in 2023. His research interests include the design and optimisation of high-efficient hydraulic motors.

Xiaolong Zhang received his BEng in Mechanical Engineering from Yanshan University, Qinghuangdao, China in 2019. He is currently working toward his PhD in Mechanical Engineering with Zhejiang University, Hangzhou, China. His research focuses on the design of high-efficient hydraulic motors.

Min Han received his BEng in Mechanical Design and Manufacturing and Automation from the Huazhong University of Science and Technology, Wuhan, China in 2021. She is currently working toward her Master's in Mechatronics Engineering with the State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou, China. Her research interests include laser cladding and surface design of hydraulic motor parts.

Zhijian Zheng received his MS degree in 2011 and PhD degree in 2017, both from Zhejiang Sci-Tech University, Hangzhou, China. He is currently a Senior Engineer at the National Intelligent Manufacturing Equipment Quality Supervision and Inspection Center (Zhejiang). His research interests include the inspection and quality evaluation on hydraulic pumps, motors and valves. He published more than 30 papers indexed by SCI or EI, and granted 12 national invention patents. He is the Vice Chairman the of the National Hydraulic and Pneumatic Standardization Technical Committee (SAC TC3).

Junhui Zhang received his BS degree in 2007 and PhD degree in 2012, both from Zhejiang University, Hangzhou, China. He is currently a Professor at the Institute of Mechatronics and Control Engineering and the Deputy Director of the State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University. His research interests include high-speed hydraulic pumps/motors, and hydraulic robots. He published more than 40 papers indexed by SCI, and applied more than 20 national invention patents with 18 granted. He is supported by the National Science Fund for Excellent Young Scholars.

Bing Xu received his PhD in Fluid Power Transmission and Control from Zhejiang University, Hangzhou, China in 2001. He is currently a Professor and Doctoral Tutor in the Institute of Mechatronic Control Engineering, and the Director of the State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University. He has authored or co-authored more than 200 journal and conference papers and authorised 49 patents. He is a Chair Professor of the Yangtze River Scholars Programme, and a science and technology innovation leader of the Ten Thousand Talent Programme.

1 Introduction

Hydraulic motors are the key components of the hydraulic rotary drive system of various types of large machinery and equipment (Tao et al., 2019; Zhang et al., 2021a, 2022a; Dasgupta et al., 2012; Pettersson and Jacobson, 2007; Wang et al., 2022; Olsson and Ukonsaari, 2003; Chao et al., 2023). Cam-lobe hydraulic motors, as a type of typical low-speed high-torque hydraulic motors, so can provide excellently low speed and ultrahigh torque for large equipment, such as shield machines, winches, drilling machines, shredders, and wind turbines (Zhang et al., 2022b; Darnet and Bideaux, 2022; Fan et al., 2022; Skaare et al., 2013; Zhang et al., 2023; Sjödin and Olofsson, 2003). In order to avoid damage or poor work quality caused by large equipment vibration, the output speed of the cam hydraulic motor is usually required to have good stability, that is, low pulsation. In the cam-lobe hydraulic motor, the output speed is achieved through the motion structure consisting of the piston assemblies and cam ring curve since the motion structure is a core component that converts hydraulic power into mechanical motion (Ceschini et al., 2013; Kelley and Hagan, 2020; Kleckner and Kress, 1973; Dasgupta et al., 2012; Liu et al., 2017). It can be concluded from this the output-speed stability of the cam-lobe hydraulic motor is mainly affected by the design of the motion structure (Wang et al., 2022; Zhang et al., 2023). Thus, it is very important to design a low-pulsation motion structure for the cam-lobe hydraulic motor to avoid the severe vibration of the large equipment.

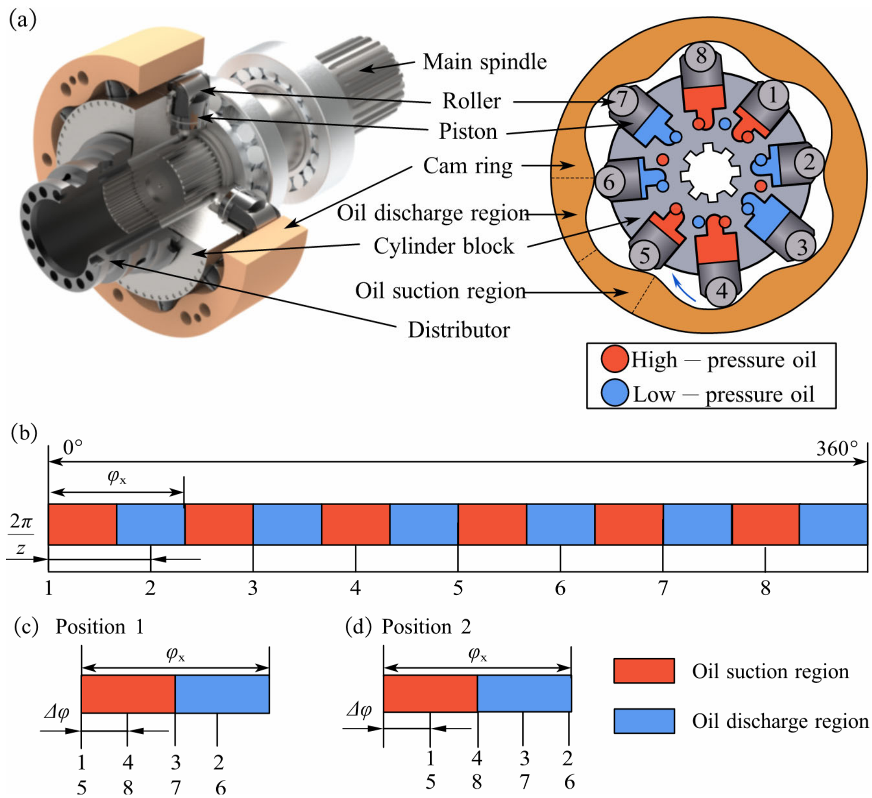
To date, a large number of scientists and engineers have made much effort to design the motion structure of hydraulic motors for improving speed stability and reducing speed pulsation. Most scholars attach much importance to designing and optimising the cam ring curve of hydraulic motors. The design methodology of the cam ring curve could be roughly grouped into four types: geometric-based curve design, kinematics-based curve design, contact force-based curve design, and other innovative curve design (Zhang et al., 2021b). Based on the above design methodology, a lot of innovative curves are proposed to improve low-speed stability, including the parabolic curve, sine curve, equal acceleration curve, and other modified curves. In addition, there are still some optimisation methods of the cam ring curve for low-speed stability, such as the high-order constant acceleration and constant deceleration cam ring curve based on a genetic algorithm, elliptical cam ring curve, and modified heart-shaped cam ring curve (Zhang et al., 2021b; Qiu et al., 2005; Nguyen and Kim, 2007; Nguyen et al., 2019). Meanwhile, the performances of these cam ring curves have been analysed. It is discovered that the equal acceleration cam ring curve has relative speed stability (Huang et al., 2013; Gao et al., 2012; Zhao, 2017). The existing research on the motion structure is mainly confined to the design and optimisation of the cam ring curve, and there is little complete and universal design for the speed stability of the hydraulic motors (Lin et al., 2010; Liu et al., 2018, 2017).

For that, this study proposes a low-pulsation design approach of motion structure for cam-lobe hydraulic motors. The motion structure design consists of two parts: the piston assembly number and the action number design and the cam ring curve design. The piston number and the action number design is responsible for determining whether the cam-lobe hydraulic motor can achieve low speed pulsation and speed stability. The cam ring curve design is used to further reduce output speed pulsation of hydraulic motors. The structure of this study is as follows. Section 2 introduces the typical structure and working principle of the cam-lobe hydraulic motor and the working process of the motion structure. The pulsation evaluation criterion and the basic conditions with free pulsation and the low-pulsation motion structure design is presented in Section 3. In Section 4, a case study on the structure parameters of the actual hydraulic motor products is carried out to validate the effectiveness of the design approach. Finally, Section 5 summarises this study.

2 Configuration and working principle of cam-lobe hydraulic motor

A typical configuration of the cam-lobe hydraulic motor is illustrated in Figure 1(a), which consists of the motion structure (i.e., a cam ring and several piston assemblies), an oil distributor, a cylinder block, etc. During the rotation of the hydraulic motor, the pressurised hydraulic oil flows into the piston chamber and acts on the bottom of the piston, which drives the piston assembly (i.e., roller and piston) along the cam ring curve. Meanwhile, a tangential force is generated between the cam ring and roller, resulting in the rotation of both the cylinder block and main spindle. Thus, the cam-lobe hydraulic motor can continuously convert the hydraulic pressure to rotational motion and torque.

Figure 1 Typical configuration and working principle of a cam-lobe hydraulic motor (see online version for colours)



To further illustrate the working process of the motion structure, the corresponding expanded view of the cam ring is depicted in Figure 1(b). It schematically shows eight piston assemblies (as indicated by Roman numerals 1, 2, 3, 4, 5, 6, 7, and 8) in different positions (the oil suction region is indicted as red region, while the oil discharge region is indicted as blue region). The distance between adjacent piston assemblies is $2\pi/z$ and z represents the number of piston assemblies. The total angle of both an oil suction region and an oil discharge region is the action angle φ_x, which can be expressed as:

$$\varphi_x = \frac{2\pi}{x} \tag{1}$$

where x is the action number (i.e., the number of concave and convex in cam ring curve).

All the piston assemblies are put into the same oil suction region and oil discharge region, as depicted in Figures 1(c) and 1(d). It is apparent that the piston assemblies can be classified as two groups, which have the same working process. The motion distance from positions 1 to 2 is considered as the minimum motion period of the piston assemblies $\Delta\varphi$, which is given by:

$$\Delta\varphi = \frac{\varphi_x}{z'} \tag{2}$$

where z' is the number of piston assemblies in each piston assemblies group, which can be expressed as:

$$z' = \frac{z}{m} \tag{3}$$

where m is the number of piston assemblies groups, which can be represented as the minimum common divisor between the action number x and piston assemblies number z.

From the above, it can distinctly show that the output characteristics of cam-lobe hydraulic motor is influenced by the motion law of the piston assemblies. The motion law of the piston assemblies is constrained by the motion structure (i.e., the action number x, the piston assemblies number z, and the cam ring curve). Thus, the low pulsation design of the motion structure is important to improve the performance of the hydraulic motor, especially its speed stability.

3 Low pulsation design of the motion structure

To evaluate the influence of low-pulsation design approach of motion structure for cam-lobe hydraulic motors, a reasonable pulsation evaluation criterion needs to be given. In this section, the pulsation evaluation criterion of the cam-lobe hydraulic motor is introduced first, and develop the low-pulsation design approach of motion structure. The motion structure design is mainly determined by the action number x, the piston assemblies number z, and the cam ring curve. Thus, the design of the action number x and the piston assemblies number z are analysed in detail, and the low-pulsation cam ring curve about the constant acceleration and constant deceleration cam ring curve has been developed.

3.1 Pulsation evaluation criterion of cam-lobe hydraulic motor

The speed pulsation of the hydraulic motor is equal to the torque pulsation when power loss is ignored. Therefore, in this study, the theoretical speed pulsation of the cam-lobe hydraulic motor δ can be expressed as:

$$\delta = \frac{\max\left(\sum_{i=1}^{z} v_{\varphi i}\right) - \min\left(\sum_{i=1}^{z} v_{\varphi i}\right)}{mean\left(\sum_{i=1}^{z} v_{\varphi i}\right)} \tag{4}$$

where $v\varphi_i$ is degree velocity of the piston assembly. The free pulsation condition of cam-lobe hydraulic motor is that the sum of all piston assemblies degree velocity is constant, which is given by:

$$\sum_{i=1}^{z} v_{\varphi i} = constant \tag{5}$$

It is known that the piston degree velocity can be obtained by integrating the piston degree acceleration $a\varphi_i$, thereby the condition of the free pulsation can also be expressed as:

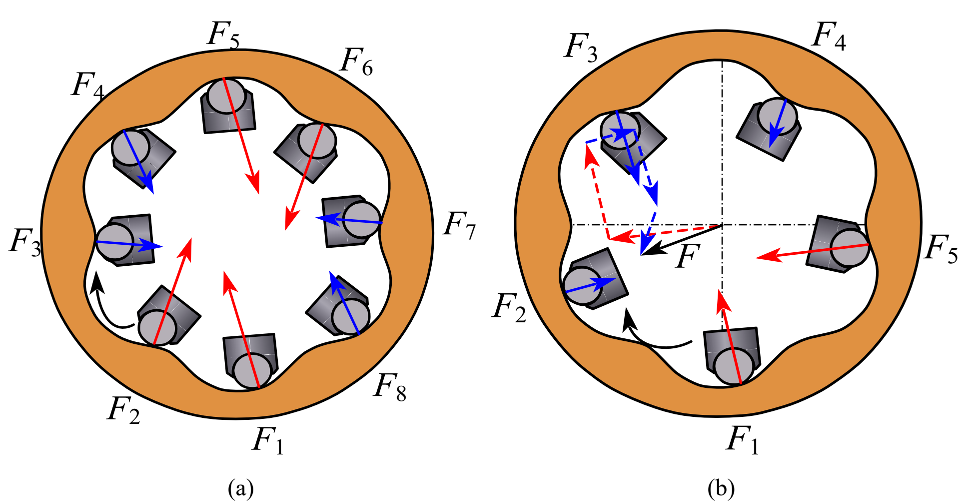
$$\sum_{i=1}^{z} a_{\varphi i} = 0 \tag{6}$$

In general, the theoretical free pulsation evaluation criterion of the cam-lobe hydraulic motor can be expressed that the sum of all piston assembly degree velocity is constant or the assembly degree acceleration is zero.

3.2 Low pulsation design of the piston number x and the action number z

The piston number x and the action number z, play a crucial role in determining whether the cam-lobe hydraulic motor can achieve low pulsation performance. It is worth to known that the design of the piston number x and the action number z must be satisfied the radial force balance first, because the unbalanced load would cause the speed instability of hydraulic motors. Thus, we first analyse the radial force under different combination of the piston number x and the action number z. Subsequently, the design of the action number x and the piston assemblies number z are analysed. The radial force plays a key role in the motion structure design, which is the premise of low-speed stability. The radial force analysis of the piston assemblies in the movement is illustrated in Figure 2. In Figure 2(a), it is observed that F_1 and F_5, F_2 and F_6, F_3 and F_7, F_4 and F_8 are the reaction forces of the cam ring on the whole internal rotating body. They are equal in magnitude and opposite in direction, that is, the radial forces are completely balanced. In comparison, it can be seen that the resultant force points to the lower left corner and the radial force is unbalanced based on the vector superposition method in Figure 2(b). The unbalanced load would cause the speed pulsation of hydraulic motors. Thus, the design of the piston number x and the action number z should ensure radial force balance first.

Figure 2 Force analysis of cam-lobe hydraulic motor (see online version for colours)



The relationship between the action number x and the piston assemblies number z can be expressed as the total angle distribution coefficient K. The physical meaning of the total angle distribution coefficient K is that an action angle can be divided into K equal angles. The total angle distribution coefficient K can be calculated as follows:

$$K = \frac{\varphi_x}{\Delta\varphi} \tag{7}$$

The common combinations of the piston number and the action number are listed in Table 1, where the number in the table is the total angle distribution coefficient K. The unbalanced combinations of radial forces (indicated by '×') that fail to achieve complete balance should be disregarded entirely when selecting the piston number and the action number. To further analyse the influence of the total angle distribution coefficient on speed pulsation, selecting five different radial force balanced combinations, as shown in Table 2.

Table 1 The common combinations of the piston number and the action number

x \ z	5	6	7	8	9	10	11	12	13	14	15	16	17	18
3	×	×	×	×	×	×	×	×	×	×	×	×	×	×
4	×	1.5	×	×	×	2.5	×	×	×	3.5	×	×	×	4.5
5	×	×	×	×	×	×	×	×	×	×	×	×	×	×
6	×	×	×	2	1.5	2.5	×	×	×	3.5	×	4	×	×
7	×	×	×	×	×	×	×	×	×	×	×	×	×	×
8	×	1.5	×	×	×	2.5	×	3	×	3.5	×	×	×	4.5
9	×	1	×	×	×	×	×	2	×	×	2.5	×	×	×
10	×	1.5	×	2	×	×	×	3	×	3.5	1.5	4	×	4.5
11	×	×	×	×	×	×	×	×	×	×	×	×	×	×
12	×	×	×	2	1.5	2.5	×	×	×	3.5	2.5	4	×	4.5

Note: '×' is radial force unbalanced combinations.

Additionally, different speed zones of the cam ring curve are designed for different combinations based on the total angle distribution coefficient. The speed pulsation rate of the cam-lobe hydraulic motor under different speed zone distribution is calculated respectively, as indicated in Figure 3. It can be seen that free pulsation can be achieved through appropriate speed zone distribution under different x and z. The range of optional speed zone distribution that meets the low-pulsation design criteria increases significantly as the total angle distribution coefficient rises. In other words, a higher total angle distribution coefficient resulting from the combination of the piston number and the action number is more favourable for designing a low-pulsation cam-lobe hydraulic motor. However, a higher total angle distribution coefficient implies the multiple pistons, leading to more complex structure, higher costs, increased failure rates, etc. To sum up, considering various factors, this study suggests that the total angle distribution coefficient should not be less than 2 to achieve a simple structure and meet the requirements of low pulsation when designing the overall motion structure.

Figure 3 Pulsation rate of different amplitude distribution under different *x* and *z* (see online version for colours)

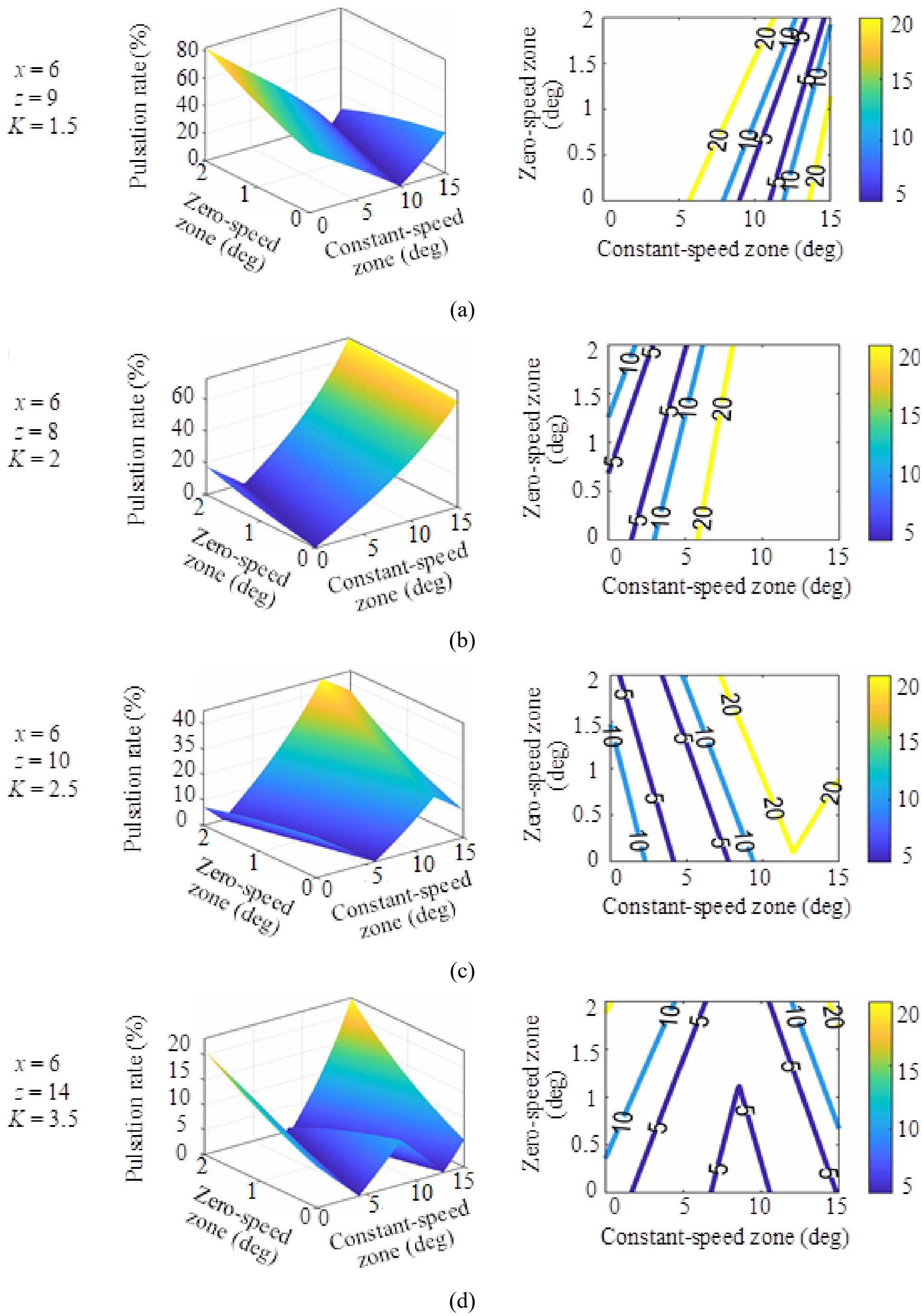
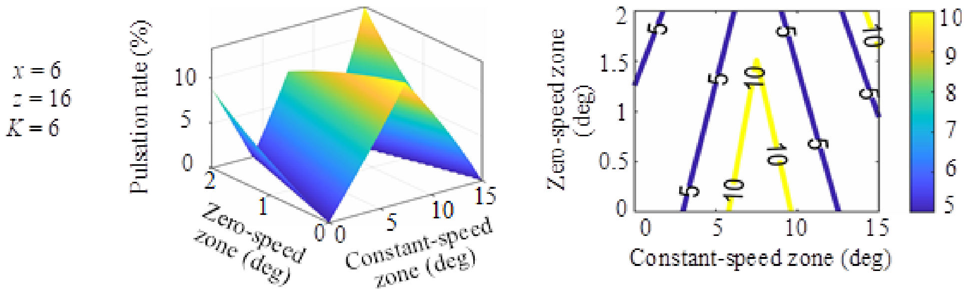


Figure 3 Pulsation rate of different amplitude distribution under different x and z (continued) (see online version for colours)



(e)

Table 2 Combination of radial force balance

Number	*x*	*z*	*m*	*K*
1	6	9	3	1.5
2	6	8	2	2
3	6	10	2	2.5
4	6	14	2	3.5
5	6	16	2	4

3.3 Low pulsation design of the cam ring curve

To further reduce the speed pulsation of the cam-lobe hydraulic motor, the cam ring curve is designed in detail. The constant acceleration and constant deceleration cam ring curve is one of the typical cam ring curve among cam-lobe hydraulic motors. The typical cam ring curve consists of the acceleration zone, deceleration zone, zero-speed zone, and constant-speed zone. In this section, the influence of different speed zones of the cam ring curve on speed pulsation is analysed and developed.

3.3.1 Influence of the acceleration zone and the deceleration zone on pulsation

Figure 4 is the constant acceleration and constant deceleration cam ring curve. The symmetrical distribution of acceleration and deceleration zones can realise the free pulsation design, yet the acceleration zones and deceleration zones are designed by the asymmetric distribution to improve the performance of hydraulic motor in some conditions. In practice, the asymmetric distribution characterised by a wider acceleration zone than the deceleration zone is beneficial in reducing the contact force on the cam ring and oil back pressure. However, an excessively high asymmetry coefficient may lead to excessive acceleration within the deceleration zone, so it is recommended that the asymmetric distribution coefficient is between 1 and 2.5. Generally, the asymmetric distribution coefficient C can be expressed as:

$$C = \frac{\varphi_1}{\varphi_3} \tag{8}$$

where φ_1 and φ_3 are acceleration zone and deceleration zone of the cam ring curve, respectively.

Figure 4 The constant acceleration and constant deceleration cam ring curve (see online version for colours)

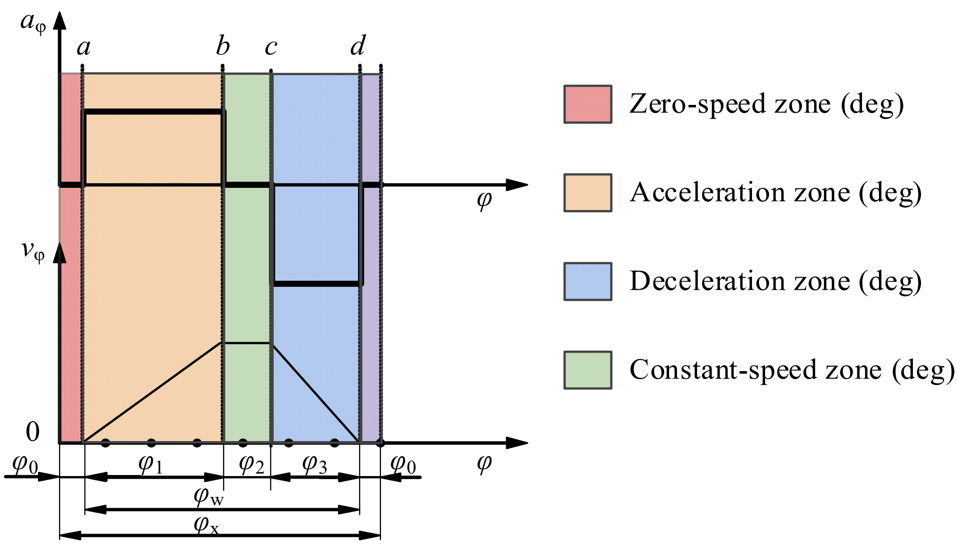
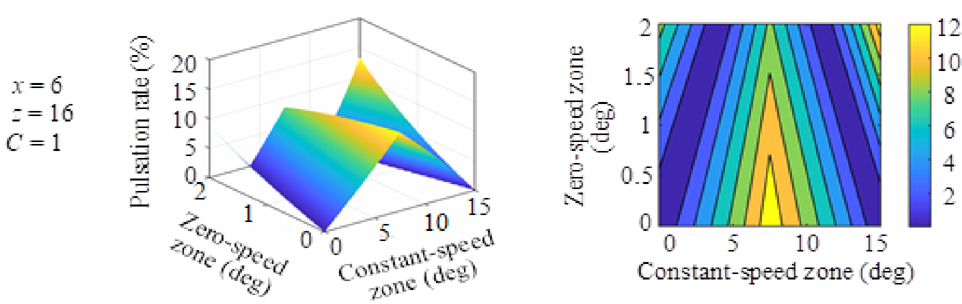
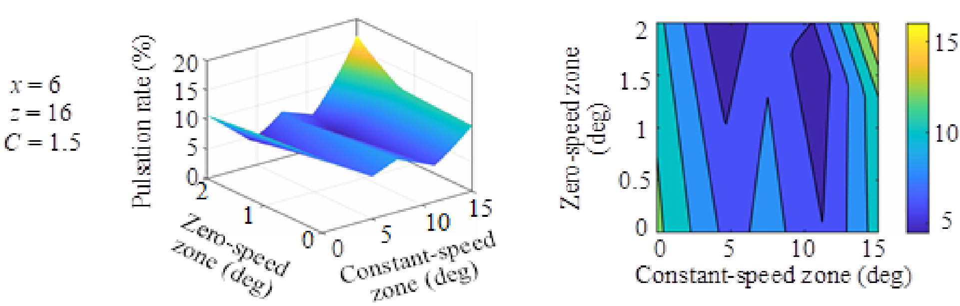


Figure 5 The influence of asymmetry distribution coefficient on pulsation (see online version for colours)

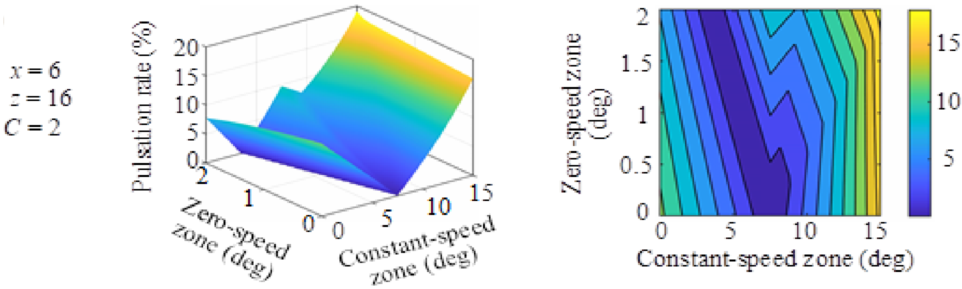


(a)

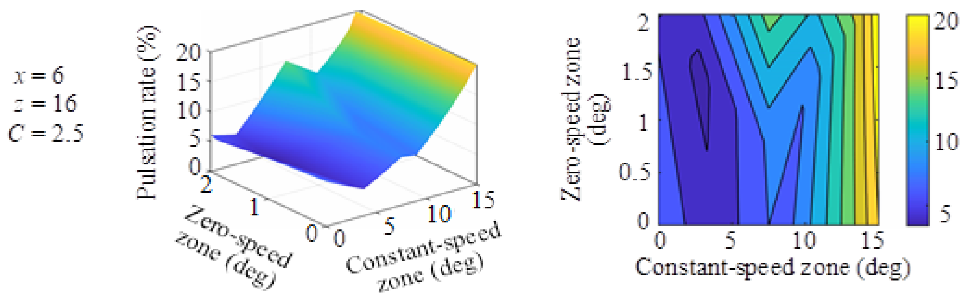


(b)

Figure 5 The influence of asymmetry distribution coefficient on pulsation (continued) (see online version for colours)

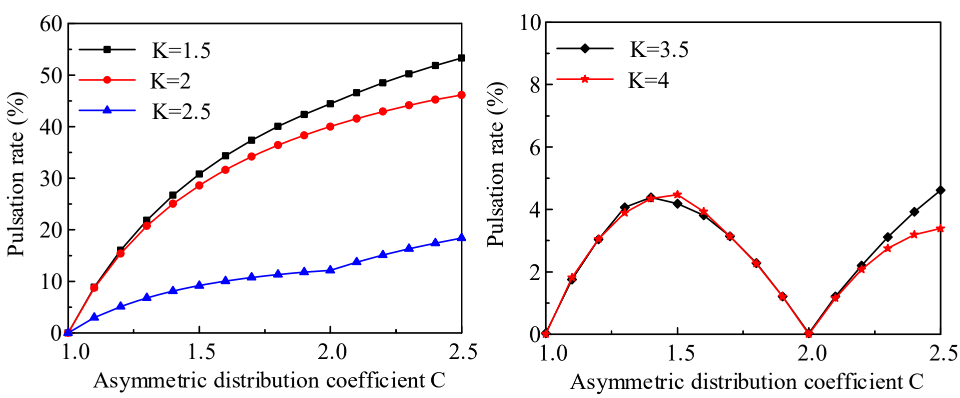


(c)



(d)

Figure 6 Influence of asymmetry distribution coefficient on pulsation (see online version for colours)



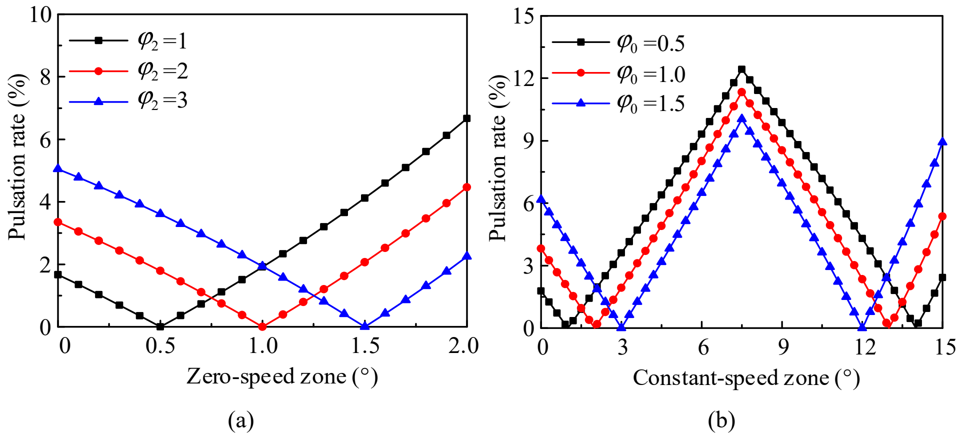
(a) (b)

The speed pulsation rate of the cam-lobe hydraulic motor under different asymmetry distribution coefficients is indicated in Figure 5. It is evident that free pulsation can be obtained when the asymmetric distribution coefficient is 1 or 2, yet, the angle distribution cannot satisfy free pulsation in any case when the asymmetric distribution coefficient is 1.5 or 2.5. In addition, the achievable minimum pulsation under different asymmetric distribution coefficients from Table 2 is calculated, as indicated in Figure 6. It can be concluded that the free speed pulsation condition includes two parts:

a the asymmetric distribution coefficient *C* is 1 and the total angle distribution coefficient is greater than 2

b the asymmetric distribution coefficient *C* is 2 provided that the total angle distribution coefficient should be greater than 3.

Figure 7 Influence of constant-speed zone and zero-speed zone on pulsation (see online version for colours)



3.3.2 *Influence of the zero-speed zone and the constant-speed zone on pulsation*

The zero-speed zone is used to prevent oil trapping and increase the effective action angle, which is commonly set to less than 2°. The constant-speed zone plays an important role in reducing the velocity impact of the transition between the acceleration zone and the deceleration zone. Thus, the zero-speed zone and the constant-speed zone have greater adjustability as functional zones, which have the following linear relationship:

$$\varphi_2 = a\varphi_0 + b \tag{9}$$

where a = 2 or –2, b is the constant coefficient related to angle distribution, φ_2 is constant-speed zone of the cam ring curve, and φ_0 is zero-speed zone of the cam ring curve.

To further illustrate the influence of zero-speed zone and constant-speed zone on pulsation, the speed pulsation under three different distributions of the zero-speed zone and constant-speed zone are analysed respectively in Figure 7. The slope of the curve is calculated and the slope of Figure 7(a) is 4.5 and that of Figure 7(b) is 2.2, indicating that the speed pulsation rate is more sensitive on the changes in zero-speed zone. Thus, the constant-speed zone should be optimised first, when designing the angle distribution of cam ring curve to enhance other performance.

4 Case study

To validate the effectiveness of the low-pulsation design approach for cam-lobe hydraulic motors, a case study on the structure parameters of the actual hydraulic motor products is carried out. The piston number x and the action number z can be determined by observation, while the cam ring curve requires a three-coordinate scanner as depicted in Figure 8. Table 3 shows the fundamental parameters of the actual hydraulic motor products. In addition, Figure 9 show the specific reverse analysis process of the cam ring curve, which is used to obtain the width and asymmetry coefficient of each speed interval. Thus, the structural parameters and speed zone distribution of seven cam-lobe hydraulic motors are obtained in Table 4. It can be seen that the total angle distribution coefficients of all hydraulic motors are not less than 2, which confirms the motion structure design approach of the piston number x and the action number z. In addition, the asymmetric distribution coefficient of the hydraulic motors is close to 1 except the seventh hydraulic motor. The asymmetric distribution coefficient of the seventh hydraulic motor is close to 2 as well as the total angle distribution coefficient is greater than 3, which is consistent with the analysis of the cam ring curve design.

Meanwhile, to further prove the design approach of the cam ring curve, the speed pulsation under different distributions of the zero-speed zone and constant-speed zone are calculated in Figure 10, respectively. It can be seen that these hydraulic motors are distributed in the low pulsation zone (pulsation rate < 5%). Thus, the above analysis verify the effectiveness of the low-pulsation design approach for cam-lobe hydraulic motors in this study.

Figure 8 The cam ring curve measured by coordinate measuring machine (see online version for colours)

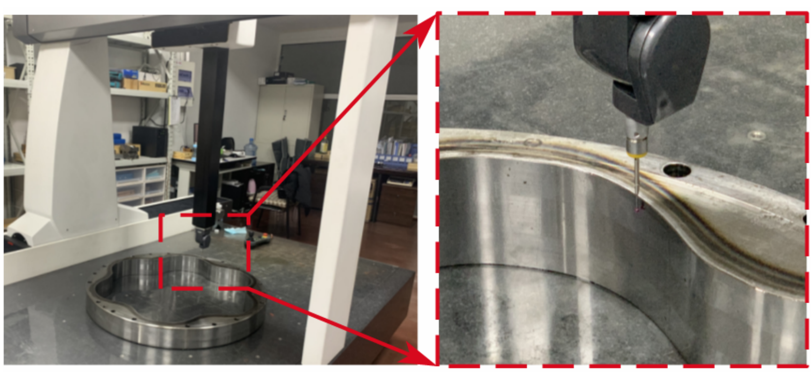


Table 3 Basic parameters of three coordinate scanners

Parameters	*Value*
Machine size	3,450 × 2,197 × 3,596 mm
Measuring range	1,200 × 1,600 × 600 mm
Operating mode	Automation
Probe series	Fixation and rotation
Measurement resolution	2 μm

Figure 9 Reverse analysis flow diagram (see online version for colours)

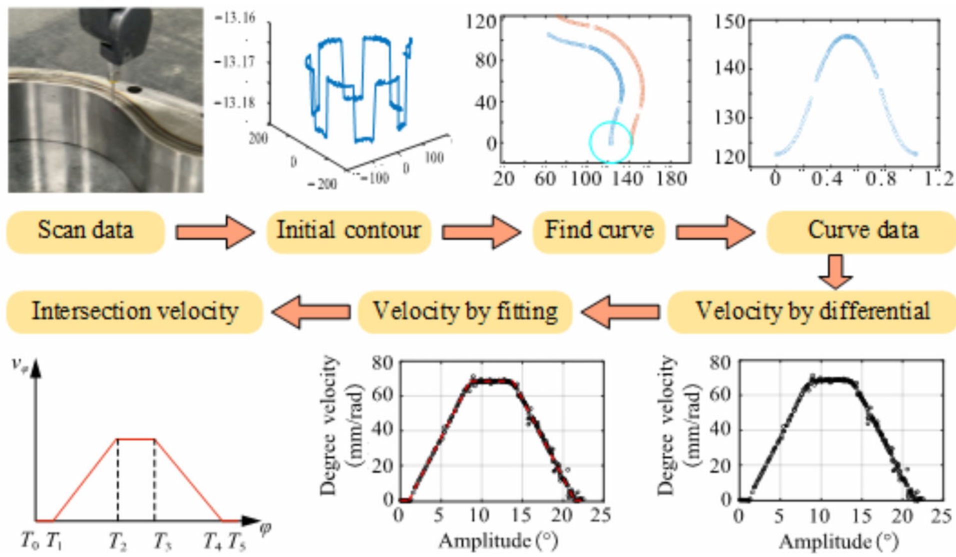


Table 4 Structure parameters and velocity distribution of cam-lobe hydraulic motor

Number	*x*	*z*	*K*	T_0 (°)	T_1 (°)	T_2 (°)	T_3 (°)	T_4 (°)	T_5 (°)	*C*
1	6	10	2.5	0	1.0067	8.4033	13.8690	21.3322	22.5	0.9911
2	6	10	2.5	0	1.0533	8.5513	13.9123	21.577	22.5	0.9783
3	6	10	2.5	0	1.0354	8.5051	13.9015	21.4546	22.5	0.9890
4	6	10	2.5	0	1.0361	8.5618	13.8345	21.4175	22.5	0.9924
5	6	8	2	0	1.0038	14.9652	16.7204	29.4305	30.0	1.0984
6	6	8	2	0	2.0923	13.4774	17.1648	27.8814	30.0	1.0624
7	10	16	4	0	0.9702	10.3465	12.4382	16.9908	18.0	2.0595

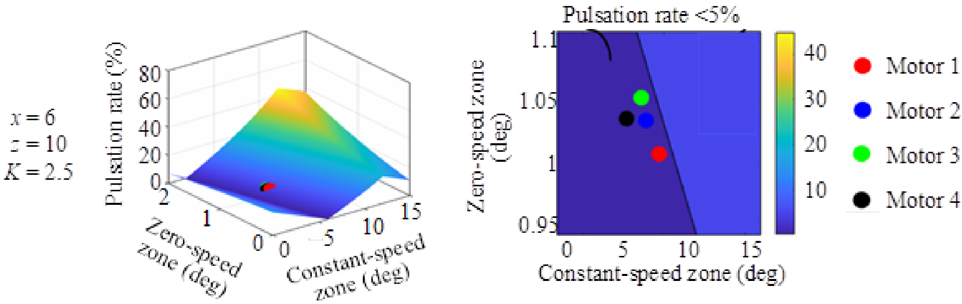
5 Conclusions

This study proposes the low-pulsation design approach of the motion structure for cam-lobe hydraulic motors. The main conclusions are as follows:

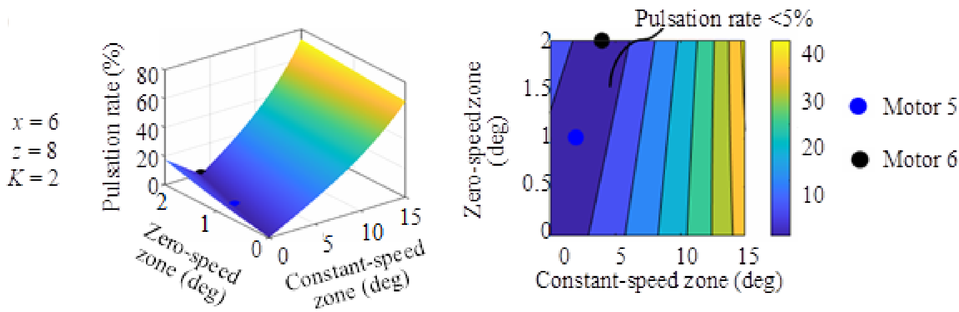
1 When designing the piston number *x* and the action number *z*, the total angle distribution coefficient *K* should not be less than 2 to meet the requirements of low-pulsation design.

2 When the cam ring curve is asymmetric distribution, the asymmetric distribution coefficient *C* is 2 provided that the total angle distribution coefficient should be greater than 3. Additionally, the constant-speed zone should be prioritised for optimisation when adjusting the angle distribution to enhance other performance.

Figure 10 Verification of low pulsation in the constant velocity zone under the zero-speed zone (see online version for colours)



(a)



(b)

Acknowledgements

This work is supported by National Key R&D Program of China under Grant 2021YFB3400501.

References

Ceschini, L., Marconi, A., Martini, C. et al. (2013) 'Tribological behavior of components for radial piston hydraulic motors: bench tests, failure analysis and laboratory dry sliding tests', *Wear*, Vol. 305, Nos. 1–2, p.238247 https://doi.org/10.1016/j.wear.2013.06.012.

Chao, Q., Xu, Z., Shao, Y. et al. (2023) 'Hybrid model-driven and data-driven approach for the health assessment of axial piston pumps', *Int. J. Hydromechatronics*, Vol. 6, No. 1, pp.76–92 https://doi.org/10.1504/IJHM.2023.129123.

Darnet, J. and Bideaux, É. (2022) 'State-of-the-art of variable displacement technologies for radial piston hydraulic machines', *Bath/ASME 2022 Symposium on Fluid Power and Motion Control* https://doi.org/10.1115/FPMC2022-90598.

Dasgupta, K., Mandal, S.K. and Pan, S. (2012) 'Dynamic analysis of a low speed high torque hydrostatic drive using steady-state characteristics', *Mechanism and Machine Theory*, Vol. 52, pp.1–17 https://doi.org/10.1016/j.mechmachtheory.2011.12.004.

Fan, Y., Qiu, L., Li, L. et al. (2022) 'Modeling and simulation analysis of radial piston motor with inner curve based on AMESim', *International Conference on Mechanical Design and Simulation (MDS 2022)*, pp.1372–1377 https://doi.org/10.1117/12.2638759.

Gao, D., Wang, Z. and Zhao, Y. (2012) 'Analysis of stator curve characteristics of low speed high torque water hydraulic motor with radial piston', *Journal of Machine Design*, Vol. 29, No. 9, pp.29–35, p.40 https://doi.org/10.13841/j.cnki.jxsj.2012.09.017.

Huang, F., Huang, F. and Shen, M. (2013) 'Accurate drawing of equal contact stress inner curve for radial-piston hydraulic motor', *Machine Tool and Hydraulics*, Vol. 41, No. 19, pp.148–150 https://doi.org/10.3969/j.issn.1001-3881.2013.19.042.

Kelley, J. and Hagan, M. (2020) 'New fault diagnosis procedure and demonstration on hydraulic servo-motor for single faults', *IEEE/ASME Transactions on Mechatronics*, Vol. 25, No. 3, pp.1499–1509 https://doi.org/10.1109/TMECH.2020.2977857.

Kleckner, R. and Kress, J. (1973) *Step Variable Displacement Hydraulic Motor*, US Patent 3760691A.

Lin, R., Wei, S. and Yuan, X. (2010) 'Low-speed instability analysis for hydraulic motor based on nonlinear dynamics', *Journal of Coal Science and Engineering*, Vol. 16, pp.328–332, China https://doi.org/10.1007/s12404-010-0322-3.

Liu, Y., Deng, Y., Fang, M. et al. (2017) 'Research on the torque characteristics of a seawater hydraulic axial piston motor in deep-sea environment', *Ocean Engineering*, Vol. 146, pp.411–423 https://doi.org/10.1016/j.oceaneng.2017.10.004.

Liu, Y., Gu, L., Yang, B. et al. (2018) 'A new evaluation method on hydraulic system using the instantaneous speed fluctuation of hydraulic motor', *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, Vol. 232, No. 15, pp.2674–2684 https://doi.org/10.1177/0954406217722576.

Nguyen, T., Kurtenbach, S., Hüsing, M. et al. (2019) 'A general framework for motion design of the follower in cam mechanisms by using non-uniform rational B-spline', *Mechanism and Machine Theory*, Vol. 137, pp.374–385 https://doi.org/10.1016/j.mechmachtheory.2019.03.029.

Nguyen, V. and Kim, D. (2007) 'Flexible cam profile synthesis method using smoothing spline curves', *Mechanism and Machine Theory*, Vol. 42, No. 7, pp.825–838 https://doi.org/10.1016/j.mechmachtheory.2006.07.005.

Olsson, H. and Ukonsaari, J. (2003) 'Wear testing and specification of hydraulic fluid in industrial applications', *Tribology International*, Vol. 36, No. 11, pp.835–841 https://doi.org/10.1016/S0301-679X(03)00101-4.

Pettersson, U. and Jacobson, S. (2007) 'Textured surfaces for improved lubrication at high pressure and low sliding speed of roller/piston in hydraulic motors', *Tribology International*, Vol. 40, No. 2, pp.355–359 https://doi.org/10.1016/j.triboint.2005.11.024.

Qiu, H., Lin, C., Li, Z. et al. (2005) 'A universal optimal approach to cam curve design and its applications', *Mechanism and Machine Theory*, Vol. 40, No. 6, pp.669–692 https://doi.org/10.1016/j.mechmachtheory.2004.12.005.

Sjödin, U.I. and Olofsson, U.L-O. (2003) 'Initial sliding wear on piston rings in a radial piston hydraulic motor', *Wear*, Vol. 254, No. 11, pp.1208–1215 https://doi.org/10.1016/S0043-1648(03)00337-5.

Skaare, B., Hörnsten, B. and Nielsen, F.G. (2013) 'Modeling, simulation and control of a wind turbine with a hydraulic transmission system', *Wind Energy*, Vol. 16, No. 8, pp.1256–1276 https://doi.org/10.1002/we.1552.

Tao, J., Wang, H., Liao, H. et al. (2019) 'Mechanical design and numerical simulation of digital-displacement radial piston pump for multi-megawatt wind turbine drivetrain', *Renewable Energy*, Vol. 143, pp.995–1009 https://doi.org/10.1016/j.renene.2019.04.159.

Wang, Z., Xiang, J., Fu, Q. et al. (2022) 'Study on the friction performance of textured surface on water hydraulic motor piston pair', *Tribology Transactions*, Vol. 65, No. 2, pp.308–320 https://doi.org/10.1080/10402004.2022.2027589.

Zhang, C., Tan, H., Fang, Y. et al. (2023) 'Deformation pre-compensated optimization design of cam ring for low pulsation hydraulic motors', *Journal of Zhejiang University – Science A: Applied Physics & Engineering*, Vol. 24, No. 2, pp.130–145 https://doi.org/10.1631/jzus.A2200552.

Zhang, X., Zhang, J., Xu, B. et al. (2021a) 'The effect of slotted hole on minimum oil film thickness of piston in radial piston hydraulic motor', *ASME/BATH 2021 Symposium on Fluid Power and Motion Control* https://doi.org/10.1115/FPMC2021-69937.

Zhang, X., Zhang, J., Zhang, H. et al. (2021b) 'Optimal design of cam ring curve of cam lobe radial-piston motor', *J. Huazhong Univ. of Sci. & Tech. (Natural Science Edition)*, Vol. 49, pp.30–35 https://doi.org/10.13245/j.hust.211005.

Zhang, X., Zhang, J., Cheng, M. et al. (2022a) 'A design constraint for a double-acting telescopic hydraulic cylinder in a hydraulic erecting system', *Journal of Zhejiang University – Science A (Applied Physics & Engineering)*, Vol. 23, No. 1, pp.1–13 https://doi.org/10.1631/jzus.A2100214.

Zhang, Y., Gong, G., Yang, H. et al. (2022b) 'Towards autonomous and optimal excavation of shield machine: a deep reinforcement learning-based approach', *Journal of Zhejiang University – Science A (Applied Physics & Engineering)*, Vol. 23, pp.458–478 https://doi.org/10.1631/jzus.A2100325.

Zhao, C. (2017) 'Life checking calculation and design of stator curve in inner curve hydraulic motor', *Fluid Power Transmission and Control*, Vol. 4, pp.29–32 https://doi.org/1672-8904-(2017)04-0029-004.