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Effects of materials on the tribological properties and the noise of gerotor pump used in active vibration damping system

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Abstract
An automobile active vibration damping system is mainly consists of a pump-controlled cylinder system with highly responsive, small volume and lightweight, the performance of the friction pair of the hydraulic pump puts forward high requirements. A compact and lightweight gerotor pump was designed, and the characteristics of the friction pair and the noise of the rotor and valve plate materials were investigated in this study. Tribological experiments were conducted on different materials with and without surface microtexture distribution pair. Results show that the steady-state average friction coefficients of Poly-Ether-Ether-Ketone (PEEK) without and with microtexture surface are 0.059 and 0.044, respectively, and the friction coefficient reduces by 25.4%. Lead bronze without and with microtexture surface are 0.137 and 0.103, the friction coefficient reduces by approximately 24.8%. Inner and outer rotor noise experiments show that different materials have different effects on reducing the noise at different speeds. The gerotor pump noise ranges from high to low in the order: 9Cr18/9Cr18>9Cr18/PEEK>PEEK/PEEK. The active vibration damping system gerotor pump using PEEK can reduce the noise, compared with the inner and outer rotors using 9Cr18, the noise of gerotor pump only inner rotor uses PEEK is reduced by 2.78% and 0.78% at 1000 rpm and 5000 rpm, both of rotors uses PEEK can reduce the noise 4.5% and 2.57% at the rotation speed is 1000 rpm and 5000 rpm. The flow characteristics of the gerotor pump with PEEK rotors are studied at the end of the article, as the rotation speed increases, the volumetric efficiency of the pump decreases. Therefore, the selection and surface treatment of these materials are suitable for the active vibration damping system gerotor pump.

Keywords : Active vibration damping system, Gerotor pump, Surface microtexture, Friction and wear characteristics, Noise

1. Introduction

With the rapid development of intelligent hydraulic equipment, the performance requirements of hydraulic components, such as active vibration damping system for mobile machinery have gradually increased. This system must have fast response, sustainable operation, small size and lightweight, and these factors have become the inevitable trend of future development. Some scholars have studied the characteristics of automotive vibration damping systems (Kim and Lee, 2011; Vu et al., 2016; Witters and Swever, 2010; Wang and Hou, 2019), but few studies have been conducted on active vibration damping systems. Ma et al. (Ma et al., 2013) studied a new electric wheel with active control of suspension for in-wheel motor, and researched its dynamic characteristics. Another structure active vibration damping system uses a closed pump-controlled cylinder system, where the pump rotating speed is approximately 5000 rpm, the working pressure is approximately 2.5 MPa, and is frequently in a start-stop condition. We proposed an active vibration

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damping system power unit to meet these requirements, as shown in Fig. 1. This power unit is mainly composed of a high speed gerotor pump and a motor. This pump is mainly composed of an inner rotor, an outer rotor and two valve plates. The friction characteristic between the inner and outer rotors of the gerotor pump and the valve plate is very important for the power unit of the active vibration damping system, The tribological characteristics of the inner rotor, outer rotor and valve plate of the gerotor pump must be studied.

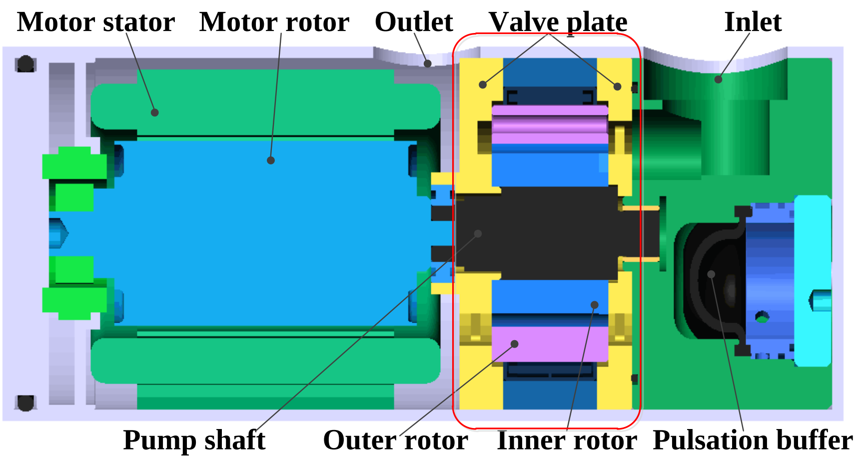

Fig. 1 Active vibration damping system power unit

A gerotor pump is frequently used in the lubrication oil system of internal combustion engines and hydraulic system power devices (Buono et al., 2016; Daniela et al., 2017; Giovanni and Andrea, 2016). The relative slip speed of gerotor pump is small because of its compact structure and the difference between the inner and outer rotors is only one tooth, compared with the traditional external gear pump flow characteristics, its output flow pulsation is small and can provide stable power (Chai et al., 2020), making it extremely suitable for active vibration damping systems, and other medium and low-pressure intelligent hydraulic equipment (Stryczek et al., 2014a). KWON et al. (KWON et al., 2008) analyzed the contact stress of the inner and outer rotors of the gerotor pump. In this study, we focused on the suitable materials for the inner rotor, outer rotor and valve plate of the gerotor pump and investigated their tribological performance to obtain a light and reliable high-speed gerotor pump.

Some scholars have investigated hydraulic pumps with different structures under different working environments, such as engineering plastics. These plastics are used in the construction of fluid power elements and systems and provide considerable benefits, such as mass, vibration and noise reductions and improved tribological properties. Poly-ether-ether-ketone (PEEK) is a special polymer material with excellent comprehensive properties and can replace traditional materials, such as metals and ceramics, in many special fields. This plastic is considered a high-performance engineering plastic because of its high-temperature resistance, self-lubrication, wear resistance and fatigue resistance. It is mainly used in aerospace, automotive industry, electrical and electronic and medical equipment, the PEEK is more expensive than commonly used metal materials, however, the PEEK is the better choice when weight and mechanical properties are both required, in mass production, the injection molding process can be used to save its manufacturing cost. For active vibration damping systems, the hydraulic power unit gerotor pump frequently starts/stops and forward /reverse, the inertia of metal rotors is large at high speed. The light weight of PEEK can reduce the rotational inertia of the rotor of the gerotor pump and improve the response speed of the power unit. In the study of the characteristics of PEEK materials, Mohammed et al. (Mohammed and Fareed, 2016) used a simple dip coating on the PEEK surface to reduce its wear and friction coefficient. The results showed that nanocomposite coating is extremely effective in improving the tribological properties of PEEK with 3% ultra-high-molecular-weight polyethylene coating reinforced with 0.2% of carbon nanotubes, showing an extremely low friction coefficient of 0.09 and a wear life of more than 25,000 cycles at a normal load of 9 N and a sliding speed of 0.5 m/s. Koike et al. (Koike et al., 2011) found that the bearings achieve relatively long lives of more than 1.0×10^6 cycles and a unique self-lubrication feature that removes the raceway of microdepressions, deposits and smearing under the action of medium load. Leveuf et al. (Leveuf et al., 2018) explored the characterisation of fatigue lifetime of a short carbon fibre-reinforced PEEK matrix thermoplastic composite using a heat build-up protocol, accurately predicted the fatigue curves using an energetic criterion, and determined the influence of material variation on the fatigue properties.

In the application of new materials for hydraulic pumps friction and wear characteristics, Wu et al. (Wu et al., 2016a) studied the tribological characteristics of high-velocity oxy-fuel spraying WC-10Co-4Cr coating combined with sintered Si3N4 under natural silt-laden and filtered water from sea and river. The results indicated that the WC-10Co-4Cr/ Si3N4 tribopair has wide applicability to different natural waters. Wu et al. (Wu et al., 2016b) also investigated the synergistic effects of corrosion and abrasion of cemented carbide coating under natural silt-laden waters. Wei et al. (Wei et al., 2019) explored the feasibility of AISI 630 steel applied to slipper/swashplate pair of a water hydraulic pump, systematically conducted a frictional corrosion experiment simulating slipper/swashplate pair operation under three different lubricating conditions, and evaluated the influence of lubricating medium and solution aging on corrosion wear of AISI 630 steel and indirect corrosion wear of its dual PEEK surface through scanning electron microscopy. Zhang et al. (Zhang et al., 2015) assessed the tribological behaviour of 30% carbon fibre-reinforced PEEK and 30% carbon fibre/PTFE/graphite-reinforced PEEK sliding against AISI630 steel under seawater lubrication through experimental tests with a ring-on-ring contacted test apparatus. The results revealed that 30% carbon fibre/PTFE/graphite-reinforced PEEK has a lower friction coefficient and better wear resistance than 30% carbon fibre-reinforced PEEK. These research results are based on different water medium environments, and the application of light engineering plastics in oil media-related research should be conducted. Some scholars have conducted research on noise using these engineering plastics. These scholars have studied the friction and wear characteristics of new materials in hydraulic pumps.

Some scholars have also studied the influence of new materials on the noise and temperature of hydraulic pumps. Wu et al. (Wu et al., 2017) explored the effects of materials on the pump noise through experiments and theoretical simulations. The results showed that the pump noise with different port valve seat materials ranges from high to low in the order: 316L>NYLON>PEEK>PTFE. Leonid and Pavel (Leonid and Pavel, 2016) studied a gear micropump with alternate rotors of a polymer composite material: PEEK, PPSGF40, polyformaldehyde (POM)-C and PA6. The results indicated that PPS and PEEK are advantageous in manufacturing polymer rotors to reduce pump noise. Babikir et al. (Babikir et al., 2019) proposed an alternative method to predict the noise of a submersible axial piston pump for different valve seat materials and indicated that the pump noise is small when the valve materials are PEEK and PTFE, the results indicated that different engineering materials will have a significant effect on the noise of hydraulic pumps. In this study, the noise of different pairs of materials for the inner and outer rotors of the gerotor pump was investigated. J. Stryczek et al. (Stryczek et al., 2014b) designed and manufactured a POM gerotor pump and found that an excessive increase in oil temperature and rotational speed results in increased POM gear temperature, thereby reducing POM gear strength. Justyna and Jaroslaw (Justyna and Jaroslaw, 2014; Justyna and Jaroslaw, 2018) explored the construction and experimental research results of gerotor pump with gears comprising POM and PPS. The results showed that the pump with gears comprising plastic can operate at high speeds (up to 4000 rpm) at working fluid temperature of 25–50°C and 4 MPa working pressure at the pump outlet.

Numerous studies have focused on understanding the influence of surface properties (roughness, grooves, discrete micro-textures) on the performance of hydrodynamically lubricated contacts (Gropper et al., 2016; Liang et al., 2020; Chen et al., 2019; Ma et al., 2019; Zhang et al., 2018; Hua et al., 2018; Wang, 2020). The research results show that reasonable surface treatment method can effectively improve the characteristics of friction pair. The active vibration damping system is a closed pump control cylinder system, and the power unit need good heat dissipation performance. The valve plate uses lead bronze because of the excellent heat dissipation performance of copper to meet the high–speed requirements.

In this study, we focused on lightweight materials with good wear resistance and applied them to high-speed gerotor pumps for active vibration damping systems. We used laser technology to design the surface microtexture on the PEEK, lead bronze and 9Cr18 specimens, conducted a friction and wear test on a friction test machine, and compared them with the friction and wear test of smooth surface specimens.

2. Gerotor pump rotor and valve plate materials performance experiment

2.1 Experimental principle

Tribological experiments on active vibration damping system gerotor pump distribution pair were conducted on an MM-W1B type vertical friction and wear testing machine produced by Jinan Shidai Shijin Testing Group Co., Ltd., China, as shown in Fig. 2a. Its working principle is shown in Fig. 2b, and this test system is mainly composed of a driving system, loading system and test information collection system. The driving system consists of a frequency conversion

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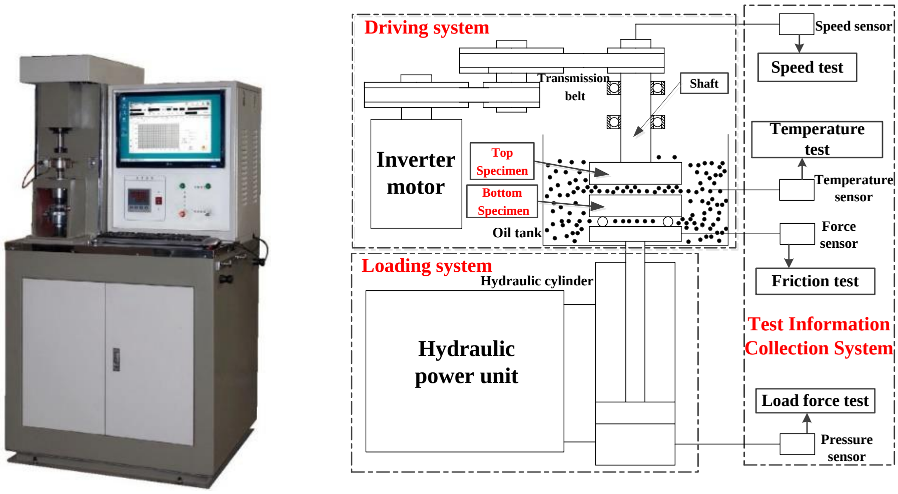
motor and speed increasing device. The top and bottom specimens are placed at the end of the transmission shaft, the specimen is immersed in hydraulic oil, and the speed of the friction pair is adjusted by adjusting the speed of the inverter motor when performing the friction test. The loading system has a hydraulic power unit to control hydraulic cylinder output force, and the loading force of the friction pair can be dynamically adjusted. The test information collection system collects the speed, temperature, load force and pressure of the loading system during the test.

Before testing, the top and bottom specimens must be thoroughly cleaned with aviation kerosene, and hydraulic oil is used for cleaning to ensure the accuracy of the test in a dust-free environment. The weights of PEEK, 9Cr18 and lead bronze specimens should be measured with a balance before and after the test to obtain their abrasions.



(a) (b)

Fig. 2 (a) MM-W1B type vertical friction and wear testing machine (b) Test system working principle.

2.2 Specimen material properties

The carbon fibre-reinforced PEEK is used as the inner/outer rotor material of the gerotor pump, 9Cr18 stainless steel is used as the inner/outer rotor, and lead bronze is used as the valve plate material in this study to meet the high-speed and wear resistance requirements and reduce the active vibration damping system weight and noise under high-speed conditions. The properties of the carbon fibre-reinforced PEEK, 9Cr18 stainless steel and lead bronze are shown in Tables 1, 2 and 3.

Table 1 The properties of the carbon fiber reinforced PEEK

Material name	Carbon fiber reinforced PEEK
Density (g/cm^3)	1.4
Tensile strength (MPa)	260
Compression strength (MPa)	300
Bending strength (MPa)	380
Heat distortion temperature(℃)	315
Hardness (HD)	88

Table 2 The properties of the 9Cr18

Material name	9Cr18
Heat treatment process	QPQ salt bath nitriding
Density (g/cm^3)	7.75
Hardness (HV0.05)	1290±100

Table 3 The properties of the Lead bronze

Material name	Lead bronze
Tensile strength (MPa)	590
Elongation	≥7%
Hardness (HRB)	≥HRB83

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2.3 Specimen structure features

Under high-speed operating conditions, the load-bearing characteristics of the oil distribution film of the active vibration damping system gerotor pump directly affects its reliability. Hua Xijun (Hua et al., 2018) and Wang Meiling (Wang, 2020) research results show that microtexture surface can reduce the friction coefficient effectively, therefore, a group of friction pair specimens adopts surface texture technology in this study to improve the load-bearing characteristics of the oil film of the friction pair. Surface texture technology refers to the use of physical or chemical methods to process regularly distributed micro-pits on the friction pair surface. As a technical means to improve the tribological performance, it can store lubricating oil to increase the bearing capacity of the oil film on the friction pair surface, avoid dry friction on the friction pair surface, and store solid abrasive particles to reduce secondary friction and wear caused by abrasive particles. Fig. 3 shows the hemispherical surface microtexture in this study.

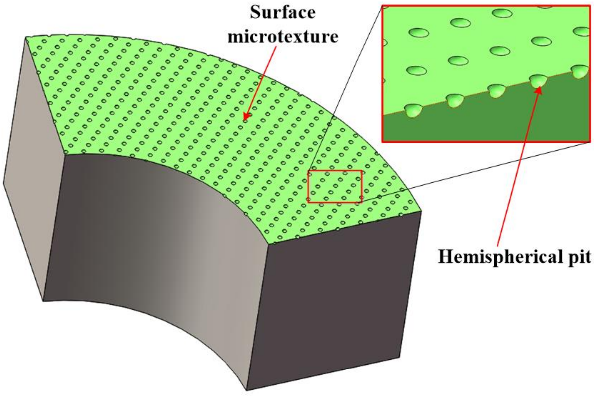

Fig. 3 Hemispherical surface microtexture

With the development of processing technology, laser processing technology has gradually been applied. Laser processing technology can be used to process micro-texture on the surface of metallic and non-metallic materials (Hua et al., 2018; Wang, 2020; Johnny Dufils et al., 2017). Therefore, we use laser processing technology to process micro-textures on the surface of the material. Fig. 4 shows the HY-TS20A laser marking machine. The equipment mainly includes pulse laser, computer control system, optical path, laser scanning system and fixture. The software can directly set the pulse laser frequency, scanning speed, laser spot processing interval, scanning times and array range.

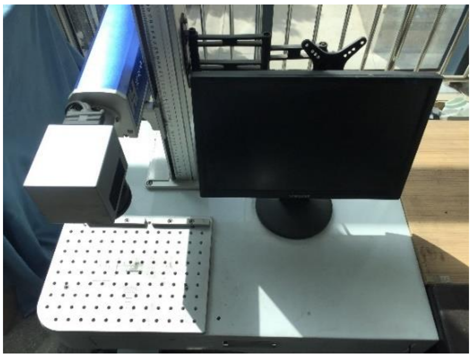

Fig. 4 HY-TS20A laser marking machine

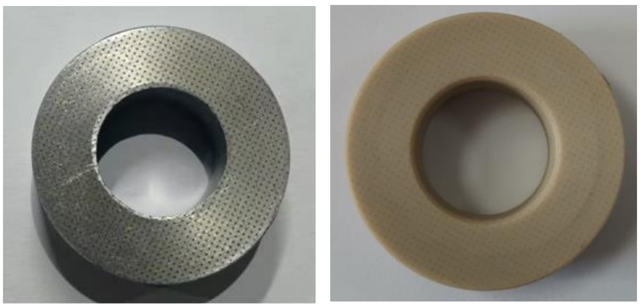

Fig. 5 Laser-processed 9Cr18（left）and PEEK (right) specimens

The HY-TS20A laser marking machine power is set to 20 W, and the pulse frequency is set to 30 kHz. The number of scans is changed to obtain micro-textures with different diameters and depths. The laser spot diameter is 5–7 µm, and the laser spot processing pitch is 0.4 mm. The number of 9Cr18 stainless steel scans is 20 times, and the PEEK is scanned for 15 times because it has a low melting point and should not be excessively scanned,the regular distribution of micro-texture can be processed by laser, but the shape of the micro-texture holes processed by laser is inconsistent (Johnny et al., 2017; Hua et al., 2018). Alloy copper is unconducive to laser processing because its reflectivity is as high as 97%. Thus, the copper surface needs to be treated with reflection (blackened with a marker), the copper scan number is 30 times, and the surface is cleaned with alcohol after processing. Fig. 5 shows the laser-processed 9Cr18 and PEEK（The pure PEEK can show the surface texture more clearly.）specimens. The microtexture is regularly distributed on the friction pair surface. The test specimens need to be deburred and cleaned with an ultrasonic cleaner to remove the slag in the micropits. After completing all the operations, a 3D profilometer was used to measure the changes in the surface of the friction pair pair surface.

3. Results and discussion of the tribological properties of different materials and structures

The inner rotor and outer rotor materials use PEEK or 9Cr18, and the valve plate material uses lead bronze in accordance with the operating conditions of the active vibration damping system gerotor pump and the *pv* value of the material to meet the requirements. Thus, the upper specimens of the friction and wear test use 9Cr18, and the bottom specimens use PEEK and lead bronze to obtain the friction and wear characteristics between the inner and outer rotors and the friction and wear characteristics of the rotor with the valve plate. The tribological properties include friction coefficients and wear rates in this study.

3.1 Friction coefficients of materials

Fig. 6 shows the test friction coefficient curve of PEEK without micro-texture as a bottom specimen. At the beginning of the test, the friction coefficient of PEEK slightly increases, probably because the uneven wear particles on the surface increase the friction coefficient at the beginning of the friction experiment. After approximately 400 s, the friction coefficient shows a gradual downward trend, and the subsequent friction coefficient gradually stabilises at around 0.06. Fig. 7 shows the test friction coefficient curve of PEEK with micro-texture as a bottom specimen, and its experimental scheme is the same as the method in Fig. 6, except that the bottom specimen uses PEEK with micro-texture. The results show that the friction coefficient of PEEK with micro-texture is low, the initial stage of the experiment is different from the results in Fig. 7, and the friction coefficient of PEEK slightly decreases at the beginning.

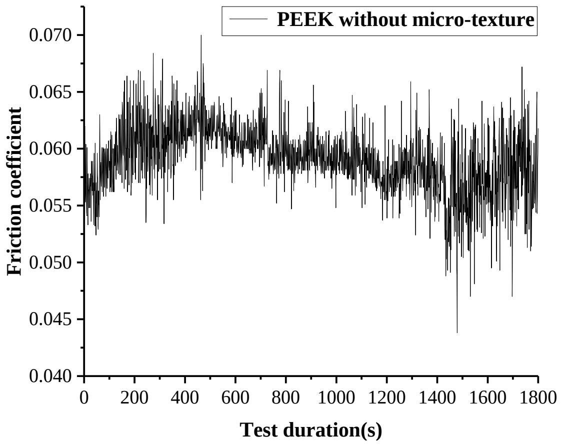

Fig. 6 PEEK without micro-texture friction coefficient

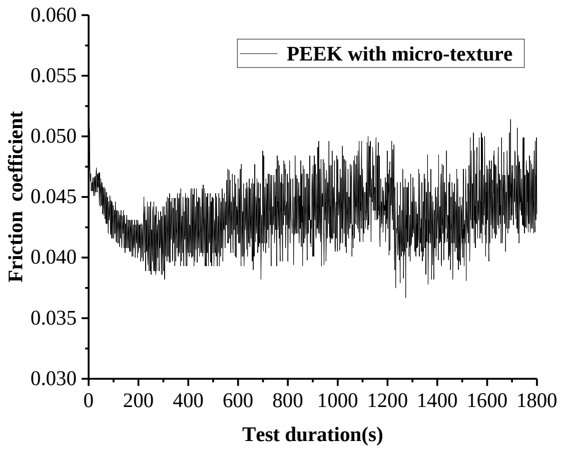

Fig. 7 PEEK with micro-texture friction coefficient

Fig. 8 shows the test friction coefficient curve of lead bronze without micro-texture as a bottom specimen. The friction coefficient is slightly large because of the uneven surface of the friction pair. As the test time progresses, the friction coefficient gradually approaches a stable range. Fig. 9 shows the test friction coefficient curve of lead bronze with micro-texture as a bottom specimen, and its experimental scheme is the same as the method in Fig. 7, except that the bottom specimen uses lead bronze with micro-texture. The results show that the friction coefficient of lead bronze without micro-texture is low and small fluctuation.

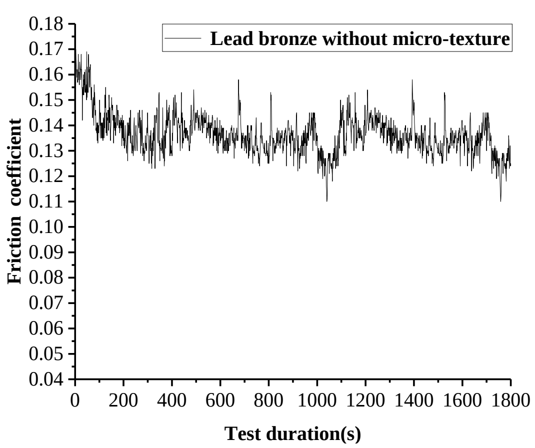

Fig. 8 Lead bronze without micro-texture friction coefficient

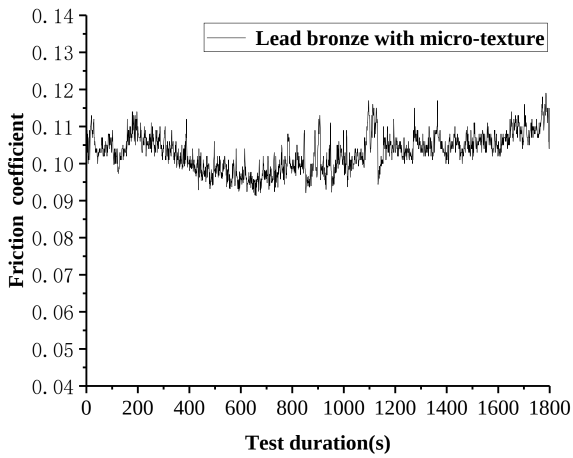

Fig. 9 Lead bronze with micro-texture friction coefficient

The steady-state average friction coefficients of different surface structures and materials are shown in Fig. 8. The friction coefficients of the two materials with 9Cr18 are significantly different, and the friction coefficient of PEEK is significantly smaller than that of lead bronze. Abscissas 1 and 2 in Fig. 9 indicate the specimens without and with microtexture surface, respectively. The steady-state average friction coefficient of PEEK without microtexture surface is 0.059. The steady-state average friction coefficient of PEEK with microtexture is 0.044, and the friction coefficient reduces by approximately 25.4%. The steady-state average friction coefficient of lead bronze without microtexture surface is 0.137. The steady-state average friction coefficient of lead bronze with microtexture surface is 0.103, and the friction coefficient reduces by approximately 24.8%. The experimental results of two materials using microtexture surface show that reasonable microtexture surface is beneficial to reduce the friction coefficient.

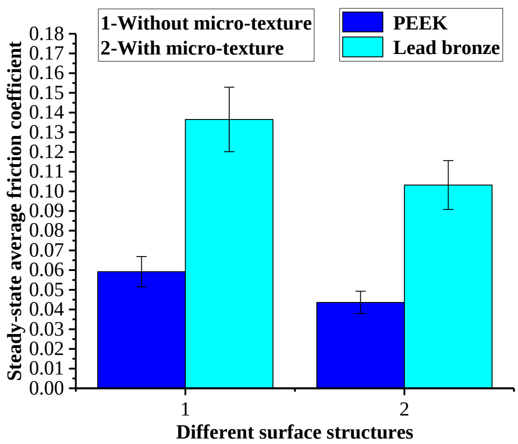

Fig. 10 Steady-state average friction coefficient with different surface structures and materials

3.2 Wear rates of materials

Fig. 11 shows the time wear rates after 30 minutes of the experiment under 200 N load. The wear rates of the two materials with or without microtexture surface were compared. The wear rates of PEEK specimens without and with microtexture are different from lead bronze. The wear rates of PEEK specimens without and with microtexture are 2.3×10^{-9} and 0.58×10^{-9}, respectively, and the wear rates decrease by 74.78%, surface microtexture can effectively reduces wear rates for PEEK. Fig. 10 also shows the wear rates of lead bronze. The wear rates of lead bronze without and with microtexture surface are 2.92×10^{-9} and 4.9×10^{-9}. The wear rate increases by 67.81%, surface microtexture increased wear rates for lead bronze. Although the microtexture surface technology reduces the friction coefficient, the wear rate of lead bronze increases.

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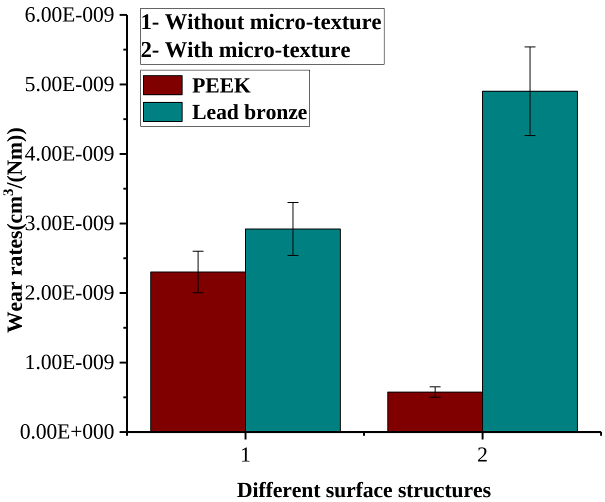

Fig. 11 Wear rates with different surface structures and materials

The valve plate uses lead bronze material to increase its heat dissipation performance because the active vibration damping system is a closed system and considering the heat dissipation performance of the friction pair. The end face clearance of the rotor of the gerotor pump is fixed, if the wear rates of the valve plate is too large, the volumetric efficiency of the gerotor pump has dropped significantly. At the same time, the friction performance of gerotor pump must be sacrificed to some extent to improve its life. Fig. 12 shows the lead bronze with microtexture specimen surface wear state measured by 3D surface profilometer after 1 hour test, there are obvious signs of wear on the surface of the specimen, the surface microtexture is worn away. Therefore, we used a smooth surface for the gerotor pump valve plate rather than the microtexture surface technology, the key is to design a suitable fit clearance.

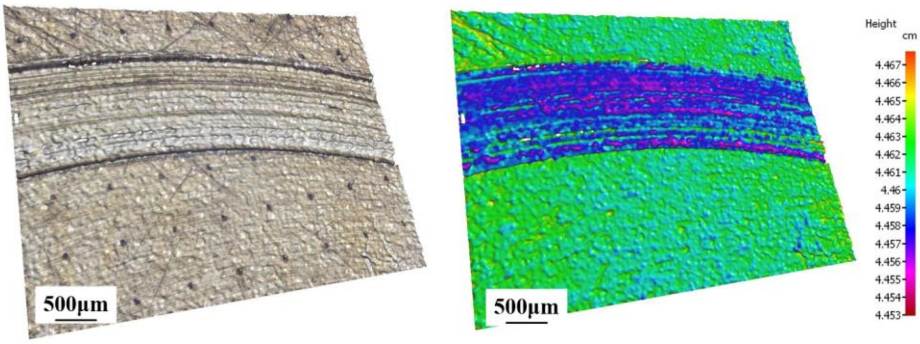

Fig. 12 The lead bronze specimen surface wear state

3.3 Noise experiment of different paired materials of inner and outer rotor

Two paired materials are used for the inner and outer rotors to study the noise characteristics of the gerotor pump. The active vibration damping system high-speed gerotor pump test bench is designed, as shown in Fig. 13. The test pump is driven by a three-phase asynchronous motor (TE6000-7.5HP835-190102), its maximum speed can reach 7000 rpm, and the motor speed is regulated with a frequency converter (ABB-ACS550-01-015A-4). The noise level of the gerotor pump is tested at different speeds with a noise measuring instrument.

Fig.14 shows the hydraulic circuit schematic of the active vibration damping system gerotor pump. The test system can be tested under two working conditions: One is that the charge pump is not working to test the pressure and flow characteristics of the gerotor pump when it is self-priming, and the other is that the charge pump is working, which simulates the working conditions of the active vibration damping system and test the flow characteristics of the gerotor pump.

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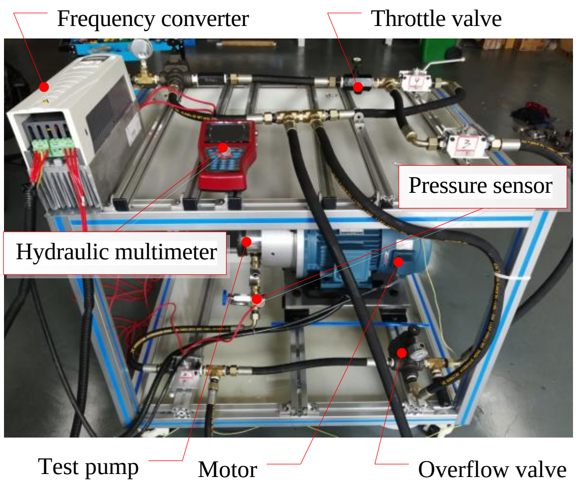
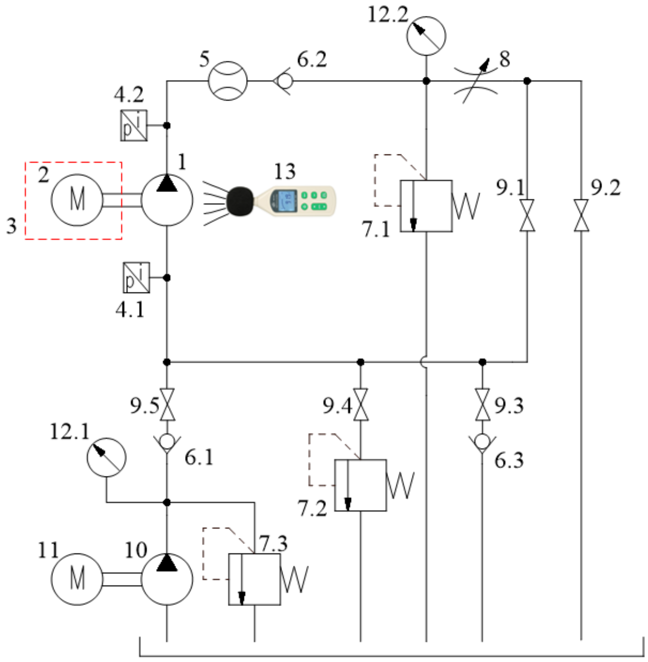


Fig. 13 Active vibration damping system gerotor pump test bench



1. Gerotor pump 2. Inverter motor 3. Motor cover 4. Pressure sensor 5. Flowmeter 6. Check valve 7. Relief valve 8.Tthrottle valve 9. Shut-off valve 10. Charge pump 11. Electric motor 12. Pressure gauge 13. Noise measuring instrument

Fig. 14 Active vibration damping system gerotor pump schematic of test system

We designed and manufactured 8/9 tooth gerotor pumps with different materials in accordance with the displacement requirements of the active vibration damping system gerotor pump. Because of the low melting point of PEEK, effective and regular surface texture is difficult to manufacture, therefore, the surface of the inner and outer rotors of the gerotor pump does not use surface texture technology. Fig. 15 shows the different combinations of inner and outer rotors, and Fig. 15(a) shows that the inner rotor uses PEEK and the outer rotor uses 9Cr18. The rotors in Fig. 15(b) use 9Cr18, and the rotors in Fig. 15(c) use PEEK. Fig. 16 shows the valve plates made of lead bronze.

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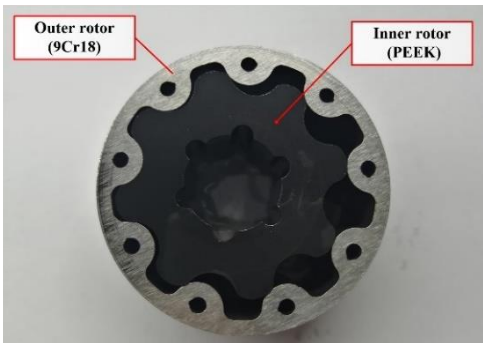
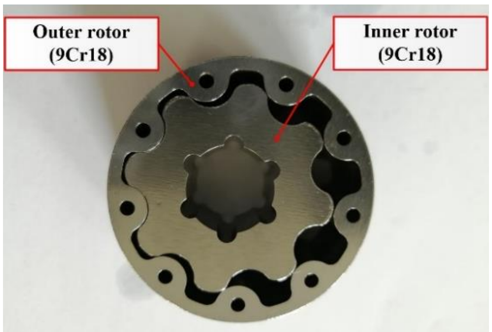
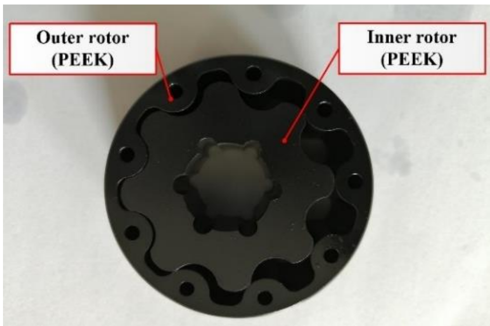


(a) PEEK for inner rotor and 9Cr18 for outer rotor



(b) 9Cr18 for inner rotor and outer rotor



(c) PEEK for inner rotor and outer rotor

Fig. 15 Different combinations of inner and outer rotor

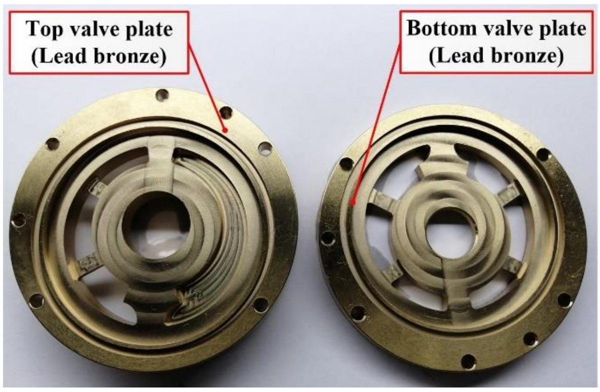


Fig. 16 Valve plates made of lead bronze

The noise experiment is conducted on the active vibration damping system gerotor pump test bench. In order to test the noise of the pump more accurately and reduce the influence of the external environment on the measurement result, a motor cover with sponge is coverd on the motor, and use a hand-held noise measuring instrument at a position 0.5

meters away from the gerotor pump..

In order to study the noise under the three combinations of inner and outer rotor materials shown in Fig. 15, During the experiment, the three combined forms of inner and outer rotors were installed in the active vibration damping system gerotor pump. Adjust the throttle valve opening size in Fig. 13 to make the outlet pressure of the gerotor pump to 2.5MPa, and record the noise corresponding to the three combinations of inner and outer rotors at 1000 rpm, 1500 rpm, 2500 rpm, 3500 rpm, 4500 rpm, and 5500 rpm.

The average noise experimental results are shown in Table 4, it can be known from the experimental results that the noise of the three combinations is different at different speeds, the inner rotor uses PEEK, and the outer rotor uses 9Cr18 in the first case. Two rotors use PEEK in the second case, and two rotors use 9Cr18 in the third case. When the gerotor pump rotation speed is 1000 rpm, the noise of the pump under the three combinations of inner and outer rotors is less than 80 dB(A).

Table 4 Average noise of different materials of inner and outer rotors at different speeds

Materials / Speed (rpm) / Noise (dB(A))	1000	1500	2500	3500	4500	5500
PEEK/9Cr18	73.4	82.7	82.1	84.7	85.2	88.7
PEEK/PEEK	72.1	81.4	83.2	84.2	84.9	87.1
9Cr18/9Cr18	75.5	84.3	84.6	85.8	87.8	89.4

Fig. 17 shows the noise of different materials of inner and outer rotors at different speeds. The relation between noise and speed is nonlinear, the results show that the pump noise, including fluid and mechanical noises, increases with the increase in speed of each material. The hydraulic pump has insufficient oil absorption with the increase in speed, and the noise of the gerotor pump significantly increases when the speed exceeds 1500 rpm.

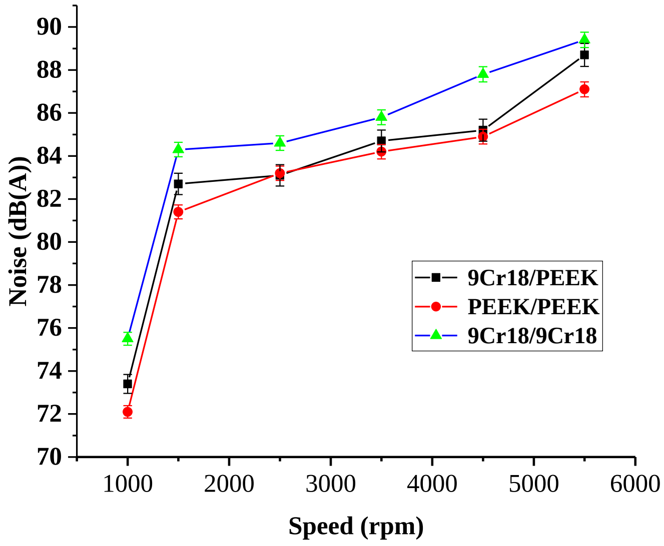


Fig. 17 Experimental noise of the pump varies with speed

Fig. 18 shows the noise reduction percentage of the gerotor pump when the inner rotor of the gerotor pump is made of PEEK material and the inner and outer rotors are both made of PEEK. Compared with the inner and outer rotors using 9Cr18, when the gerotor pump rotation speed is 1000 rpm, the noise of gerotor pump only inner rotor uses PEEK is reduced by 2.78%, and both rotors use PEEK to reduce the noise of the pump by 4.5%. The inner and outer rotors use PEEK, which can effectively reduce the noise of the active vibration damping system. As the rotational speed of the gerotor pump increases, the noise of the pump gradually increases. When the rotational speed of the pump reaches 5500 rpm, the noise of gerotor pump only inner rotor use PEEK is reduced by 0.78%, and both rotors use PEEK to reduce the noise of the pump by about 2.57%， under the high-speed working conditions, the self-priming performance of the gerotor pump becomes worse, the cavitation noise accounts for a larger proportion than the mechanical noise, and the noise reduction effect is not obvious when the inner and outer rotors are made of different materials.

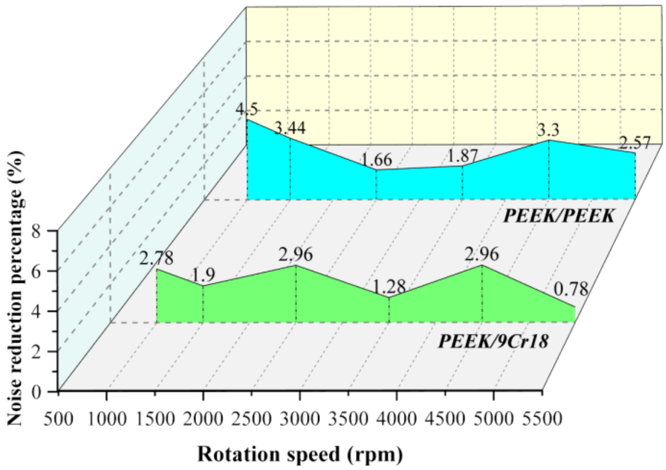


Fig. 18 The influence of using PEEK material on the noise of gerotor pump

The experimental results indicate that the noise is affected by rotor materials. Different materials have different effects on reducing the noise at different speeds. The noise of the gerotor pump is the largest when the two rotors use 9Cr18. The gerotor pump noise ranges from high to low in the order: 9Cr18/9Cr18>9Cr18/PEEK>PEEK/PEEK. The results show that the active vibration damping system gerotor pump using PEEK can reduce the noise.

Fig. 19 The wear of PEEK inner and outer rotors after the test

Fig. 19 shows the wear of PEEK inner and outer rotors after six hours test, the wear of the inner and outer rotor surfaces is different, that the surface of the inner rotor had only slight rotation marks and there was almost no wear, and there is also no wear on the meshing surfaces of the inner and outer rotors, but the wear on the outer edge of the outer rotor surface is greater than that of the inner rotor. The main reason is the radius of the outer rotor is greater than the addendum circle of the inner rotor. When the gerotor pump is at high speed, the outer rotor has a large linear velocity, which results in serious wear on the outer edge of the outer rotor surface.

The test results show that the inner rotor of the gerotor pump of the active vibration damping system can be made of PEEK material, but the outer rotor is not suitable. From the comprehensive consideration of wear resistance and noise reduction, the outer rotor adopts 9Cr18 material.

3.4 Flow characteristics of the gerotor pump

Using PEEK for the inner rotor and 9Cr18 for the outer rotor is a better combination method. Active vibration damping system gerotor pump inner and outer rotors use this combination not only in terms of wear resistance, but also can reduce the inertia of the pump forward and reverse rotation and the noise of the system. The inner and outer rotors are installed in the gerotor pump, and test its flow characteristics on the gerotor pump test system. Fig. 20 shows the output flow of the gerotor pump at different speeds. The blue point represents the theoretical flow of the pump, and the red is the actual test flow.

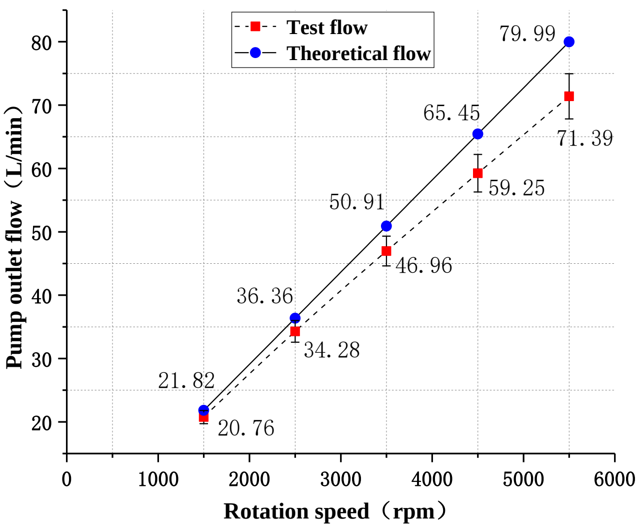


Fig. 20 The output flow of the gerotor pump

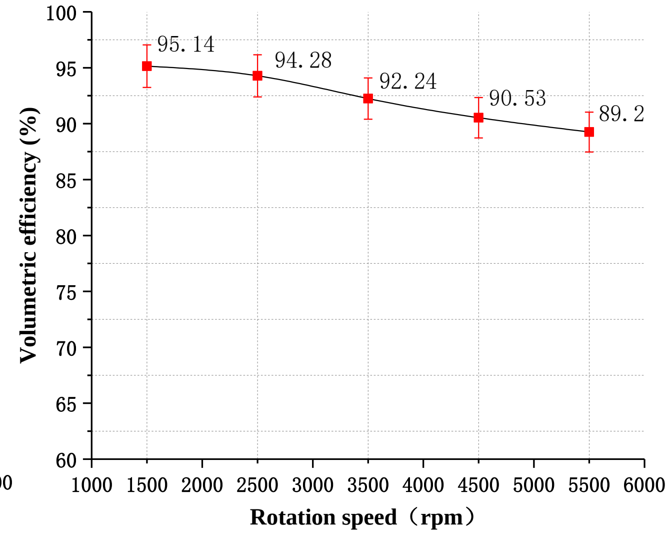


Fig. 21 Volumetric efficiency of the gerotor pump

Fig. 21 shows the volumetric efficiency of the gerotor pump at different speeds. When the rotation speed is 1500 rpm, the volumetric efficiency of the pump is up to 95.14%. As the rotational speed of the gerotor pump increases, its volumetric efficiency gradually decreases, this is mainly due to the increase in pump speed, which makes the gerotor pump insufficient oil absorption and leads to a decrease in volumetric efficiency. This result is also corresponding to the results of the noise experiment. As the speed increases, the cavitation noise caused by insufficient pump suction will also increase.

4. Conclusions

In this study, a compact and lightweight active vibration damping system gerotor pump was proposed, and the characteristics of the friction pair and the noise of the rotor and valve plate materials were investigated.

Tribological experiments of different materials with and without microtexture surface distribution pair were conducted. The top specimens use 9Cr18 material with microtexture, and the bottom specimens use PEEK and lead bronze. The results show that the steady-state average friction coefficients of PEEK without and with microtexture surface are 0.059 and 0.044, respectively, and the friction coefficient reduces by 25.4%. The wear rates of PEEK specimen with microtexture surface decrease by 74.78%. Thus, the PEEK rotors with microtexture surface is good for improving the lubrication characteristics of the active vibration damping system gerotor pump. The steady-state average friction coefficients of lead bronze without and with microtexture surface are 0.137 and 0.103, respectively, and the friction coefficient reduces by approximately 24.8%. The wear rates of lead bronze show the opposite result, and the wear rats of lead bronze with microtexture surface increase by approximately 67.81% compared with that of lead bronze without microtexture surface. Thus, the valve plate of the gerotor pump made of lead bronze without microtexture surface is comprehensively considered.

The noises generated by the gerotor pump at different speeds are studied, and the experiment of material combinations of inner and outer rotor noise experiment is conducted on the active vibration damping system gerotor pump test bench. The results show that different materials have different effects on reducing the noise at different speeds. The noise increases with the increase in speed, and the gerotor pump noise ranges from high to low in the order: 9Cr18/9Cr18>9Cr18/PEEK>PEEK/PEEK. The results show that the active vibration damping system gerotor pump

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using PEEK can reduce the noise, compared with the inner and outer rotors using 9Cr18, the noise of gerotor pump only inner rotor uses PEEK is reduced by 2.78% and 0.78% at 1000 rpm and 5000 rpm, both of rotors uses PEEK can reduce the noise 4.5% and 2.57% at the rotation speed is 1000 rpm and 5000 rpm.. Therefore, the selection and surface treatment of these materials are suitable for the active vibration damping system gerotor pump.

The flow characteristic of the gerotor pump experiment shows that with the increase of speed, the insufficient oil absorption leads to decrease of the pump volumetric efficiency. The noise generated by insufficient oil absorption is also one of the reasons for the high noise of the high-speed gerotor pump.

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Author Contributions

Wenbin Cao and Yinshui Liu designed most of the experiments. Wenbin Cao and Guixiang Bai performed most experiments. Jie Dong and Qingzhen Dong gave some constructive suggestions about surface texture structure of friction pair. Yinshui Liu also gave some constructive suggestions about how to write this manuscript.

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