New Structure Design for Hydro-viscous Clutch with a Speed Fluctuation Suppression Device

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Abstract: Hydro-viscous clutch (HVC) is a device that relies on multi-oil film shear force to transfer torque, which is especially suitable for fan, water pump and other large rotating machinery speed regulation and energy saving, with stepless speed control, light load starting, flexible braking, overload protection, low cost, convenient maintenance and many other advantages. Aiming at the problem of speed fluctuation caused by the existing HVC working under low pressure condition below 0.5Mpa, a new structure of HVC with speed fluctuation suppression device is proposed, and a speed detecting device is embedded in the driven disk fixed to the output shaft. The speed fluctuation suppression device can effectively reduce the speed fluctuation generated under low-pressure working conditions of the clutch at 0.5Mpa, greatly improving the stability and accuracy of the output of the device.

Keywords: Hydro Viscous Drive; Hydro-Viscous Clutch; Structure Design; Oil Pressure Control Mechanism; Speed Fluctuation Suppression Device; Speed Detection Device

1. Introduction

Hydro-viscous clutch is a crucial transmission device that utilizes the technology of hydro-viscous drive (HVD), which is based on Newton's law of internal friction. It transmits power by leveraging the viscosity of oil and relying on the shear force of the oil film [1]. The hydro-viscous clutch, with its stepless speed control capabilities and stepless speed regulation characteristics, is widely used for speed adjustment in various types of working machines, such as high-power water pumps and fans. The device aims to effectively solve the problem of energy loss caused by pumps, fans, and other working machinery during the operation process. Its energy-saving effect is remarkable, bringing not only important economic benefits to industrial production but also making a positive contribution to environmental protection [2-4].

Output stability and accuracy are undoubtedly the core indicators for measuring the working performance of hydro-viscous clutch. Commonly, hydro-viscous clutch regulates the system oil pressure through the electro-hydraulic proportional relief valve, thereby adjusting the gap between the driving and driven friction plates to achieve the purpose of adjusting the output torque and speed. However, due to issues such as dead zones in the electro-hydraulic proportional relief valve under low-pressure working conditions (below 0.5Mpa), its performance is often unsatisfactory, making it difficult to effectively suppress fluctuations in the clutch's output speed. Worse still, due to the limitations of the internal structure of the conventional hydro-viscous clutch, these speed fluctuations tend to be further amplified, affecting the stability and accuracy of the entire system. For example, when the output speed of hydro-viscous clutch suddenly increases, the speed of its piston cylinder will also increase sharply. This sudden change in speed causes a sudden increase in the centrifugal oil pressure in the piston cylinder, further narrowing the gap between the driving and driven friction plates. This chain reaction leads to a further increase in the output speed, creating a positive feedback loop. Conversely, when the output speed decreases, it can also trigger a similar negative feedback loop [5-10]. Therefore, effectively controlling and managing these speed fluctuations has become one of the critical issues that must be addressed to improve the output stability and accuracy of hydro-viscous clutch.

So far, numerous experts and scholars have proposed various technical solutions to address the speed fluctuation issue in hydro-viscous clutch, but most of these solutions are accompanied by additional energy losses. Given this, it is particularly urgent and necessary to research a technical solution that is lossless or has minimal loss, which will be of great significance in improving the performance of Hydro-viscous clutch and reducing energy consumption.

2. Analysis of the Principle of Hydro-Viscous Drive

In the figure 1 below, the upper plate is parallel to the lower plate. Due to the characteristics of Newtonian fluids and their position in the middle of the two plates, when the upper plate moves parallelly at a speed of v, it can be regarded as a laminar flow condition with parallel movement. The change pattern of fluid molecules between the upper and lower plates exhibits a linear trend. It can be seen that as the oil film thickness δ increases, the movement speed decreases; as the force F and the plate area A increase, the movement speed also increases.

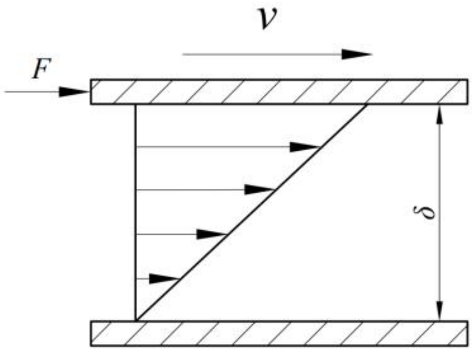

Figure 1. Schematic Diagram of Hydro Viscous Transmission

The calculation and analysis of torque, assuming laminar flow conditions for the plates, yields the shear stress of the oil film between the two flat plates as follows:

$$\tau = \frac{F}{A} = \mu \frac{V}{\delta} \quad (1)$$

τ:Shear stress of oil film, Pa
F:Shear force of oil film, N
μ: Dynamic viscosity, Pa·s
A: Area of the plate, m2
V:Shear velocity of oil film, m/s
δ:Thickness of oil film, m

The torque transmission in hydro-viscous clutch is achieved through the interaction between the driving and driven friction plates. Based on Equation 1.1, the torque transmission capacity of the hydro-viscous clutch can be derived as follows:

$$\begin{aligned} M &= n\int_{R_1}^{R_2} \mu \frac{\left(\omega_1 - \omega_2\right) r}{\delta} 2\pi r^2 dr \\ &= \frac{1}{2} n\pi\mu\left(\omega_1 - \omega_2\right)\frac{1}{\delta}\left(R_2{}^4 - R_1{}^4\right) \end{aligned} \quad (2)$$

μ -Viscosity of transmission oil, Pa • s
δ -Thickness of oil film, m
M-Transmitted torque, N • m
n-Number of oil film plates
ω 1-Angular velocity of the driving friction plate, rad/s
ω 2-Angular velocity of the driven friction plate, rad/s
R2-Outer radius of oil film, m
R1-Inner radius of oil film, m

It is known that the greater the number of friction plates [11-14], the larger the transmitted torque will be. By appropriately selecting the number of friction plates, the transmitted torque can be increased.

There is a direct proportional relationship between the viscosity of the transmission oil and the transmitted torque. It is advisable to select transmission oil with a relatively high viscosity, but it is not recommended to use oil with excessively high viscosity, as this may lead to unnecessary power consumption and excessive resistance in the oil circuit.

3. Design of the New Structure for Hydro-Viscous Clutch

3.1 New Structure of the Main Unit of HVC

As shown in the figure 2, hydro-viscous clutch [15] designed in this paper consists of a transmission mechanism, a control mechanism, a driving shaft cover, a driven shaft cover, and a speed fluctuation suppression device.

3.2 Structural Analysis of HVC

The transmission mechanism comprises a driving shaft, driving friction plates, driven friction plates, a driven drum, a driven disk, a piston, a support disk, and a driven shaft. The control mechanism consists of a piston, elastic elements, and a fixed disk, as well as a speed adjustment mechanism. The speed adjustment mechanism includes an oil tank, a first directional valve, a second directional valve, a first oil duct hose, a second oil duct hose, a third oil duct hose, a speed sensor, a signal amplifier, and a control circuit. The speed fluctuation suppression device comprises a small oil tank, a directional valve a, a directional valve b, a speed-sensitive element, an amplifier, an oil duct hose, and an oil duct disk.

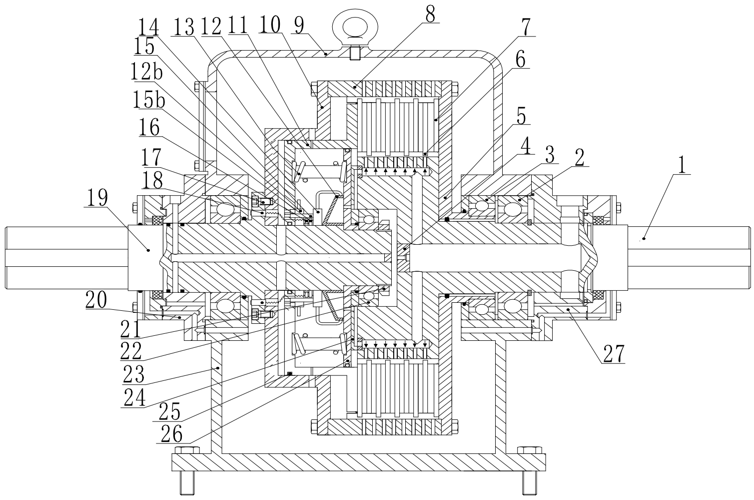

Figure 2. Assembly Diagram of the Main Unit of Hydro-Viscous Clutch
1-Driving shaft; 2-Bearing 1; 3-Bearing 2; 4-Screw plug; 5-Support disk; 6-driving friction plate; 7-driven friction plate; 8-driven drum; 9-Upper case; 10-driven disk; 11-Piston; 12-Small oil tank; 12b-Directional valve b; 13-Spring; 14-Directional valve a; 15-Oil duct hose; 15b-Controller; 16-Signal amplifier; 17-Screw; 18-Speed sensor; 19-Driven shaft; 20-Driven shaft cover; 21-Lock nut; 22-Bearing 3; 23-Lower case; 24-Oil duct disk; 25-Seal ring; 26-Spring-loaded disk; 27-Driving shaft cover.

3.3 Working Principle Analysis of HVC

The control mechanism comprises only one piston cylinder. The driving friction plate is installed on the driven shaft, while the driven friction plate is mounted on the driven drum, which is fixedly connected to the driven disk, and the driven disk is fixedly connected to the driven shaft. The driving shaft cover is equipped with radial oil passages, enabling the external lubricating oil supply system to connect with the radial oil passages of the driving shaft cover. Similarly, the driven shaft cover also features radial oil passages, allowing the external control oil supply system to connect with its radial oil passages. The driving shaft is designed with a first radial oil passage, a second radial oil passage, an axial oil passage, and an oil distribution passage. The lubricating oil first enters the first radial oil passage of the driving shaft, flows into the axial oil passage, and then into the second radial oil passage. The driven shaft is equipped with a first radial oil passage, a second radial oil passage, and an axial oil passage. The control oil enters the first radial oil passage of the driven shaft, flows into the axial oil passage, then into the second radial oil passage, and finally into the piston cylinder.

Furthermore, the piston cylinder consists of the driven disk , the piston, the spring-loaded disk, and the preload spring. The driven disk is fixedly connected to the driven shaft, and a piston cylinder body is formed between the driven disk and the spring-loaded disk. The piston cylinder body is divided into a working oil chamber and a spring displacement chamber by the piston. Specifically, the working oil chamber is formed by the driven disk and the piston, while the spring displacement chamber is formed by the piston and the spring-loaded disk. The spring is located within the spring displacement chamber, with one end fixedly connected to the piston and the other end fixedly connected to the spring-loaded disk. In the driven friction plate assembly, the driven friction plate adjacent to the end face of the piston is fixedly connected to the piston.

Furthermore, the speed fluctuation suppression device described in this paper comprises a small oil tank, directional valve a, directional valve b, a speed-sensitive element, an amplifier, an oil duct hose, and an oil duct disk.

The small oil tank is located within the spring displacement chamber and is fixedly connected to the spring-loaded disk. The speed-sensitive element is connected to the signal amplifier through wires, the signal amplifier is connected to the controller through wires, and the controller is connected to both directional valve a and directional valve b through wires. The opening and closing of the directional valves are controlled by the speed-sensitive element through the signal amplifier and the controller. The oil from the small oil tank comes from the lubricating oil circuit and flows through the directional valves to the oil duct hose, thus connecting with the piston cylinder.

The unique design of the trapezoidal conical small oil tank enables the oil to flow smoothly out from the narrow edge of the trapezoid and towards the directional valves. This shaped tank utilizes centrifugal force to eject the oil, and the narrow end creates a higher outflow pressure, facilitating the discharge of oil. The working oil chamber has a larger contact area with the cylinder body compared to ordinary liquid viscous clutches, resulting in lower working pressure, with a maximum oil pressure of 0.5Mpa. This design not only helps reduce oil system leakage but more importantly facilitates oil replenishment for the speed fluctuation suppression device. It allows direct detection of output speed, enabling a closed-loop control mechanism and ensuring precise control [16]. Speed measurement through the driven disk involves a simple circuit that is not easily interfered with, and the internal oil drainage and replenishment system does not require the addition of external devices.

4. Design of the Oil Pressure Control Mechanism Structure

4.1 Schematic Diagram of the Oil Pressure Control Mechanism Structure

The schematic diagram of the oil pressure control mechanism structure is shown in the figure 3, which is mainly consists of lubrication oil circuit and control oil circuit[17].

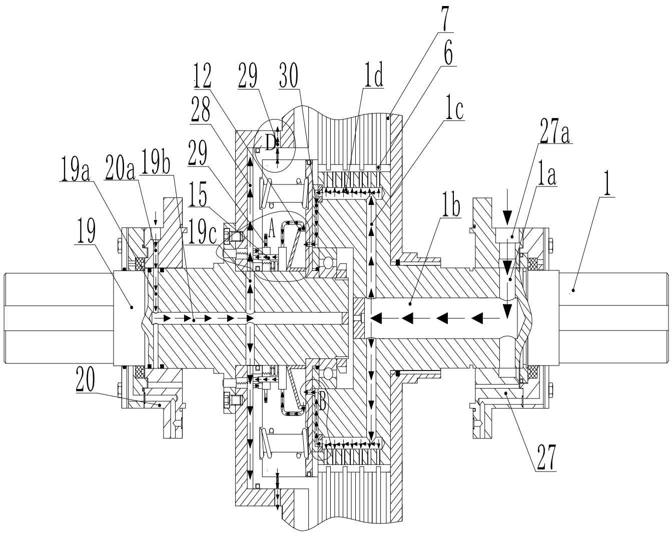

Figure 3. Schematic Diagram of the Oil Pressure Control Mechanism Structure

1-Driving shaft; 1a-First radial oil Passage of the driving shaft; 1b-Axial oil passage of the driving shaft; 1c-Second radial oil passage of the driving shaft; 1d-Oil diverter passage of the driving shaft; 6-driving friction plate; 7-driven friction plate; 15-Oil duct hose; 19-Driven shaft; 19a-First radial oil passage of the driven shaft; 19b-Axial oil passage of the driven shaft; 19c-Second radial oil passage of the driven shaft; 20 -Driven shaft cover; 20a-Radial oil passage of the driven shaft cover; 27-Driving shaft cover; 27a-Radial oil passage of the driving shaft cover; 28-Working oil chamber; 29-Oil discharge circuit; 30-Oil passage leading to the small oil tank.

4.2 Analysis of the Working Principle for the Oil Circuit

The working principle of the lubrication oil circuit is as follows: The external lubrication oil system introduces lubricating oil through the radial oil passage 27a of the driving shaft cover 27. This lubricating oil first flows into the first radial oil passage 1a of the driving shaft, and then enters the axial oil passage 1b of the driving shaft. Subsequently, the lubricating oil flows through the second radial oil passage 1c of the driving shaft into the oil divider passage 1d. Finally, the lubricating oil is evenly distributed between the driving friction plate 6 and the driven friction plate 7 through small holes on the second radial oil passage 1c. This design ensures adequate and uniform lubrication, thereby improving the operational stability and service life of the clutch. The control oil circuit includes the control oil inlet circuit, the control oil discharge circuit, and the control oil refill circuit. The principle of the control oil inlet circuit is as follows: The external control oil system introduces control oil through the radial oil passage 20a of the driven shaft cover 20. This control oil first flows into the first radial oil passage 19a of the driven shaft, and then enters the axial oil passage 19b of the driven shaft. Subsequently, the control oil flows through the second radial oil passage 19c of the driven shaft into the working oil chamber 28. This oil circuit design ensures the precise flow and distribution of control oil, thereby achieving effective control of hydro-viscous clutch. The principle of the control oil discharge circuit is: When the output speed exceeds the preset speed, the oil in the working oil chamber 28 is discharged to reduce the working oil pressure, thereby increasing the gap between the drive and driven friction plates and decreasing the output speed, ultimately maintaining a stable output speed. The control element 15b controls the directional valve (b) 12b to open, allowing the oil in the working oil chamber 28 to enter the piston through the axial oil discharge passage 29 on the piston and then be discharged from the box 9 through the radial oil discharge passage 29 on the piston. The principle of the control oil refill circuit is: When the output speed is less than the preset speed, the oil in the working oil chamber 28 is refilled to increase the working oil pressure, thereby reducing the gap between the drive and driven friction plates and increasing the output speed, ultimately maintaining a stable output speed. The oil in the oil divider passage 1d of the driving shaft 1 flows into the small oil tank 12 through the oil passage 30 leading to the small oil tank. The directional valve 14 controls the oil in the small oil tank 12 to flow to the working oil chamber 28 through the oil duct hose 15.

5. Structural Design of the Speed Adjustment Mechanism

5.1 Schematic Diagram of the Speed Adjustment Mechanism Structure

As shown in the figure 4 and figure 5, the control circuit is primarily composed of a microprocessor, an analog-to-digital converter, two digital-to-analog converters, and two signal amplifiers.

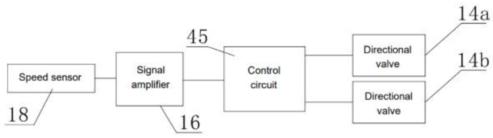

Figure 4. Schematic Diagram of the Connection of the Speed Adjustment Mechanism

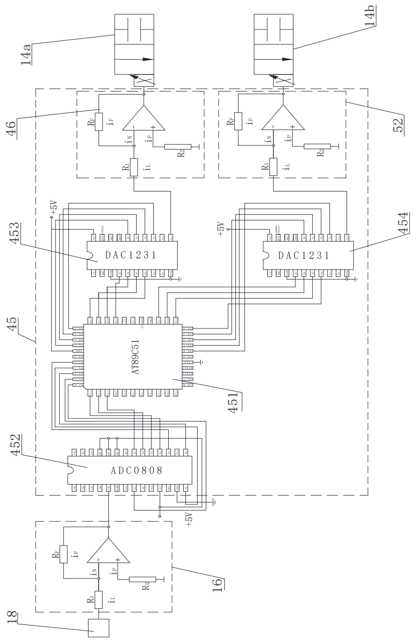

Figure 5. Schematic Diagram of the Circuit Connection of the Speed Adjustment Mechanism

16-Signal amplifier; 18-Speed sensor; Control circuit 45; Directional valve 14a; Directional valve 14b; 46-Signal amplifier; 52-Signal amplifier; 451-Microprocessor; 452-Analog-to-digital converter; 453-Digital-to-analog converter; 454-Digital-to-analog converter.

5.2 Analysis Analysis for the Control Circuit

The analog-to-digital converter and the two digital-to-analog converters are all connected to the microprocessor, responsible for converting analog signals to digital signals and vice versa, ensuring accurate transmission of information. The analog-to-digital converter is also connected to a signal amplifier for amplifying signals, thus enhancing their strength and stability. The second signal amplifier is connected between the first digital-to-analog converter and the first directional valve. Its function is to further adjust and optimize the signal output from the digital-to-analog converter, ensuring precise control of the first directional valve's operation. Similarly, the third signal amplifier is connected between the second digital-to-analog converter and the second directional valve, performing a similar function to ensure precise control of the second directional valve.

This structure enables the clutch to detect abrupt changes in the driven shaft's rotational speed (also known as the output speed) in real-time using a speed sensor. Consequently, it emits corresponding control electrical signals to regulate the directional valves and achieve automatic oil replenishment or discharge. This addresses the issue of output speed fluctuations under control oil pressures below 0.5Mpa, thereby enhancing the output stability and accuracy of the speed-regulating clutch.

6. Speed Fluctuation Suppression Device

When the output speed exceeds the preset speed and generates a fluctuation, the change in speed triggers the speed-sensitive element 18 to produce an electrical signal. This signal is then amplified by the signal amplifier 16 and transmitted to the controller 15b. The controller determines the magnitude of the speed mutation. If the speed change is gradual, it indicates that the clutch is under speed regulation response conditions, and no electrical signal is required. However, if the speed change is abrupt, it signifies an abnormal change in the clutch's output speed. In this case, an electrical signal is needed to control the directional valve 12b to open, allowing the oil in the working chamber to be discharged through the oil discharge circuit 29, thus reducing the output speed fluctuation. Conversely, when the output speed falls below the preset speed and generates a fluctuation, the resulting speed mutation triggers the speed-sensitive element 18 to produce an electrical signal. This signal is then amplified by the signal amplifier 16 and transmitted to the controller. The controller issues a command to activate the directional valve 14, which opens and allows oil from the small fuel tank 12 to flow into the working chamber 28 of the piston cylinder. This increases the oil pressure in the working chamber 28 to a predetermined level, effectively reducing the speed fluctuation.

7. Conclusion

1)A speed regulation mechanism has been designed that successfully achieves real-time detection of the driven shaft's rotational speed (i.e., the output speed) by introducing a critical component-the speed sensor. When a sudden change in speed is detected, the sensor promptly emits corresponding control electrical signals to regulate the operation of the directional valves, enabling automatic oil replenishment or discharge. This addresses the issue of output speed fluctuations that arise when the control oil pressure is below 0.5Mpa, significantly enhancing the output stability and accuracy of the hydro viscous clutch.

2)The inclusion of an oil tank within the speed regulation mechanism significantly improves the response speed for oil replenishment, positively impacting the stability of the output speed. The oil tank ensures that when lubricant supplementation is needed, the speed regulation mechanism can quickly obtain the required oil volume, thereby promptly restoring and maintaining a stable speed output. This optimization not only enhances the system's response performance but also improves overall operational stability and reliability.

3)The placement of an oil channel disk between the fixed disk and the driving shaft significantly enhances system performance while optimizing cost structure. The oil channel disk precisely guides and controls the flow of lubricating oil, ensuring its efficient and accurate delivery to the speed regulation mechanism, thus significantly improving the response speed for oil replenishment. This improvement enables the system to respond quickly when lubricant supplementation is required, effectively maintaining a stable output speed and enhancing overall operational efficiency. Additionally, the design of the oil channel disk effectively reduces lubricant waste. By precisely controlling the flow and use of lubricating oil, resources can be maximized and costs can be saved.

4)The adoption of a driven disk speed measurement scheme simplifies the circuit design and effectively reduces the risk of interference. This speed measurement method not only improves measurement accuracy but also enhances system stability. Concurrently, the introduction of an internal oil discharge and replenishment system establishes a closed-loop control mechanism, ensuring precise control of the output speed.

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