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Power characteristics of a variable hydraulic transformer

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Abstract The flow control of hydraulic transformers is a great challenge. To meet this challenge, a new kind of hydraulic transformer, variable hydraulic transformer (VHT), is proposed in this work. This paper focuses on the power characteristics of the newly proposed VHT, including instantaneous power, average power, power pulsation, and efficiency. In the analyses, the concepts of efficiency, input power, output power, starting angle, and ceasing angle are defined or redefined. To investigate the power characteristics, their models are derived by considering the governing factors such as the control angle of the swash plate and the structure of the port plate. This work highlights that the load flow can be adjusted by adjusting the control angle of the swash plate, and the power characteristics at the *B*-port produce a remarkable change. In addition, the VHT has a starting angle and a ceasing angle, and these two angles can be adjusted by the influencing factors. The results reveal that the power pulsation and the jump points of the instantaneous power are the primary causes of a less smooth work. Then, it is shown that the control angle of the port plate, the control angle of the swash plate, and the pressures at the ports are the three key elements for a stable operation. The results also reveal that the adjustment of the influencing factors can improve the efficiency.

1. Introduction

In the field of aircraft, power transmission and control are of vital importance.[1] The hydraulic system is the means of transmission and energy control on a plane or a missile. It is often used for the undercarriage, the steering engine, the fuel system, and the test bed on an aircraft. Relative to electrical transmission and mechanical transmission, the advantages of hydraulic transmission consist of big output force, light weight, little inertia, conveniently adjusted speed, and easy control, so it has a broad prospect in the field of aerospace, watercraft, engineering machinery, construction machinery, machine tool equipment, etc. With the advancement of hydraulics, the electro-hydrostatic actuator is developed to meet its reliability. In the current condition that our world is appealing to energy saving, according to its own innate advantages, hydraulics has been developed with a new technique, the common pressure rail (CPR) system. The CPR system, like the structure of a

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power grid,[2] can recuperate energy to improve the system efficiency and enhance the controllability of actuators, so that all loads are controlled individually. The CPR system can also decrease the weight and the cost of the system (the weight is an important parameter of an aircraft.).[3] In spite of that, the application of the CPR system is limited by the following two restrictions:

(1) The CPR system can only recuperate the energy of rotating loads.
(2) The CPR system can only recuperate the energy of a load whose pressure is higher than the supply pressure.

These restrictions can be solved by a hydraulic transformer that can change a fixed actuator to a variable one through transforming the supply pressure to any load pressure.[4,5] Moreover, a hydraulic transformer can transform a low-load pressure to a high-load one and recuperate the energy of the loads into a high-pressure accumulator. Thus, the CPR system can recuperate more energy.[6] The hydraulic transformer has served as a core component, but its performance restricts the energy-saving efficiency of the CPR system to a larger extent.[7] With the increasing needs for energy saving and emission reduction in the world, the study of hydraulic transformers is progressing rapidly. A conventional hydraulic transformer is a combination of a motor unit and a pump unit, so it has high cost, heavy weight, great bulk, and low efficiency. As a result, it cannot effectively improve the system efficiency.[8] Currently, one prototype of the hydraulic transformer mainly researched in many countries is a new hydraulic transformer that was presented by Innas in 1997, called the Innas hydraulic transformer (IHT). The IHT integrated a motoring unit and a pumping unit into one unit, and utilized three ports in one port plate to achieve the functions of the motor and the pump (the A-port acting as a motor, the B-port acting as a pump, and the T-port compensating for the flow at the A-port or B-port). Therefore, it is credited with properties such as simple structure, reduced bulk and weight, reduced friction and leakage, raised efficiency, reduced rotational inertia of the control part, and then enhanced controllability.[9,10] The IHT has a bright prospect in the field of engineering machinery, vehicle, aerospace, ship, test-bed, etc.

The narrow range of the output pressure was the main problem in the early development of the IHT, which has now been worked out.[11] Then, in order to improve the IHT's performance, a floating cup hydraulic transformer has been developed.[12,13] Later, many kinds of controlling ways of positioning the port plate have appeared to define the output pressure.[14] Like the noise in a pump or a motor, the noise reduction in the IHT is under study.[15–17] Recently, many achievements have been made in the research of the IHT's applications, specifically in the aspect of pressure control.[18–21] However, little has been reported on the flow control of the IHT.[22–24] There is a one-to-one correspondence between the load pressure and the control angle of the port plate in the IHT.[25] The swash plate of the IHT is fixed, so there is a one-to-one correspondence between the load flow and the load pressure. Hence, the load flow cannot be adjusted at the value of the load pressure. When the port plat is fixed, the load pressure is fixed. Therefore, varying the control angle of the swash plate can only adjust the load flow. To meet the requirements that the load flow rate varies with the change of the load pressure, a new type of hydraulic transformer needs to be developed. Unlike the IHT, the variable hydraulic transformer (VHT) we present has a variable swash plate.[26] The VHT can adjust the load flow through varying the control angle of the swash plate and also the load pressure through varying the control angle of the port plate. The VHT can shift from a pressure transducer to a power transducer to meet the requirements. So far, no public literature has been found on the study of the instantaneous power, the average power, and the power pulsation of a hydraulic transformer. In some previous works, the effect of the pressure at the B-port was ignored in the evaluation of the efficiency of a hydraulic transformer. Some researchers considered the pressure in the input power when $\delta < 60°$ and also the pressure in the output power when $\delta > 60°$.[11] Since the VHT is the latest innovation of hydraulic transformers, no corresponding analysis has been found in the literatures. In this work, the efficiency of a hydraulic transformer is redefined, and the instantaneous power, average power, and power pulsation are investigated. Some factors that influence the power characteristics of the VHT are analyzed. The power is the main factor that affects the stable operation of the VHT. Therefore, this work contributes the principle of power control for the stable operation of the VHT.

2. Foundation for modeling the power characteristics

A VHT is manufactured based on a variable pump or motor. In this paper, the VHT is manufactured based on a swash plate axial piston pump or motor. The VHT adjusts the displacements individually at the T-port, B-port, and A-port by varying the control angle of the port plate, and changes the pressure characteristics by adjusting the flow rate ratio at the ports. The VHT adjusts displacements uniformly at the ports by varying the control angle of the swash plate, and changes the flow characteristics by adjusting the flow rate without changing the flow rate ratio at the ports.

The right of Fig. 1 is a view, whose projection direction is from the swash plate to the port plate. One piston moves in parallel with the rotational axis of the cylinder barrel (axis OO') which is a linear coordinate system (O is the origin, and OO' is in the positive direction).

Where TDC is top dead center of the piston movement; BDC is bottom dead center of the piston movement; $\omega = \frac{2\pi n}{60}$ rad/s is angular speed of the cylinder barrel; n = 1000 r/min is rotational speed of the cylinder barrel; ϕ is angular displacement of the piston, with the positive direction being counterclockwise, (°); $R = \frac{D}{2} = 35.5$ is radius of the

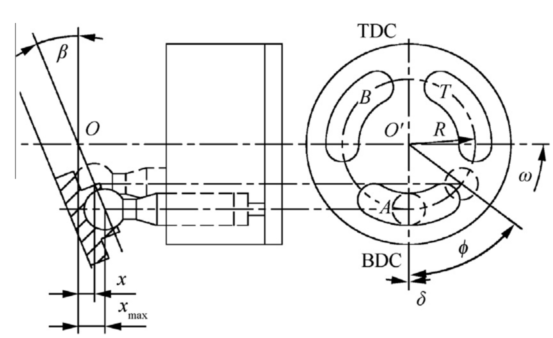

Fig. 1 Structural schematics of VHT.