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Mathematical modelling and characteristics of the pilot valve applied to a jet-pipe/deflector-jet servovalve

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ABSTRACT

The accurate model of the jet-type valve, as the pilot control stage of a jet-pipe/deflector-jet servovalve, is of great significance to analyze and design a servovalve. However, the flow field in the jet-type valve is too complex to build an accurate mathematical model. In this paper, the collision between the liquid and the jet is supposed as the impact of jet on a moving piston, which makes a complex the fluid mechanical problem become simple. Based on this assumption, a model of the jet-type valve is developed in this paper. Unlike the previous models, the structural parameters, the distance between the jet-nozzle exit and receiving surface, the included angle between two receiver holes as well as the distance between two receiver holes, all can be considered in this model. To test and verify the theoretical model, the pressure and flow characteristic curves of a jet-type valve are given by the methods of flow filed numerical simulation and experiment.As shown by the verification results, the theoretical pressure characteristic curve is very approximate with the experimental data and numerical simulation, while the flow characteristic curves need to be modified and the modified model is valid.

1. Introduction

Hydraulic servo actuators are utilized in aerospace and automotive industrial applications where high power density, high dynamic performance, robustness as well as overload capability are desired [1–3]. For instance, the positioning of aerodynamic control surfaces, precision control of machine tools, marine control equipment [4]. Servovalves, which is the control element of high-performance electrohydraulic servo actuator, plays a significant role in electrohydraulic servo actuator [5]. Their characteristics can greatly affect the performance of electrohydraulic servo actuator [6].

Typically, servovalves are two-stage devices with the pilot control stage and the main stage employing a spool valve. A pilot stage is mainly composed by spool, flapper nozzle and jet-pipe/deflector-jet, whose performance comparisons are shown in Table 1 [7]. The biggest advantage of the jet-pipe/deflector-jet valve over the other valves is less sensitivity to contamination. Beyond that, since there is just a single source of fluid, it has a benign failure mode if it is plugged. For safety reasons, the jet-pipe/deflector-jet valve finds main application in hydraulic control systems working on jet engine and flight control [8,9].

However, owing to the complex flow field in internal flow channel, the mathematical modeling and performance characteristics of the jet-pipe/deflector-jet valve can not be easily predicted as the other valves'. Currently, the optimization and analysis for the jet-pipe/deflector-jet valve are mainly accomplished by experimentation and computational fluid dynamic (CFD) [10–12]. For instance, Allen [9] presented the major parameters that affect pressure recovery. Furthermore, Dushkes and Cahm [9] experimentally measured these pressure recoveries in the receiver holes. To predict the steady state operation of a jet pipe servovalve, Somashekhar et al. [13] put forward the finite element method. Unlike theoretical model, neither the experimentation nor computational fluid dynamic can conveniently analyze and design a jet-type valve. Nevertheless, the theoretical studies on jet-pipe/deflector-jet valve are limited [14–16]. Dhinesh et al. [17] developed a novel piezohydraulic servovalve, and modeled the jet-pipe/deflector-jet valve on the basis of hydraulic resistance theory. Moreover, Zhu and Li [7] adopted this model to analyze performance of deflector-jet servovalve driven by giant magnetostrictive actuator. The hydraulic resistance model cannot reflect the physical mechanism of the jet-pipe/deflector-jet valve. Additionally, the structural parameters are not considered in the model.

As the pilot control element of the servovalve, the accurate model of the jet-type valve is of great significance to for analyzing and designing a servovalve. In order to analyze performance characteristics and design a jet-pipe/deflector-jet servovalve, it is

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Nomenclature

Parameters	*Symbol*
λ_j	Relative distance between the nozzle exit and receiving surface
D_j	Nozzle diameter
D_r	Receiver hole diameter
$2\theta_r$	Included angle between two receiver holes
e	Distance between two receiver holes
θ_t	Nozzle taper angle
C_d	Flow coefficient of receiver hole
C_{dj}	Flow coefficient of nozzle hole
ρ	Oil density
l_j	Distance from nozzle exit to the receiver surface
k_{rj}	Area ratio between the receiver hole and nozzle hole
θ_j	A half of jet expansion angle
v_j	Fluid velocity at the nozzle exit
ψ	Coefficient of flow pattern
R_r	Radius of receiver holes in receiver
C_d	Flow coefficient of the orifice hole
A	Openings area of the orifice hole
Δp	Differential pressure applied on the orifice hole
y	Displacement of the nozzle
p_L	Load pressure
q_L	Load volume flow rate

essential to develop a new model based on the energy transfer processes and the physical mechanism of a jet-pipe/deflector-jet valve.

2. Jet-pipe/deflector-jet valve

As shown in Fig. 1(a), the jet-pipe valve, whose nozzle is at the exit of pipe, creates a varying output pressure by the pipe's deflection. As displayed in Fig. 1(b), the deflector-jet valve, whose pipe is fixed and the nozzle is at the exit of deflector, creates a varying output pressure by the deflector's motion [10]. Even though the two valves possess different structures, their fluid energy transfer processes and operating mechanisms are almost the same, which can be described as Fig. 2. Moreover, they are called as jet-type valve in the following contents.

In a jet-type valve, the pressure energy of the fluid under high pressure is converted into kinetic energy at the nozzle exit. When the high speed fluid shoots into the receiver holes, the fluid kinetic energy is then reconverted as pressure energy to move the spool valve. As shown in Fig. 2(a), the pressure difference between the two receiver holes is zero when the nozzle is centered between the two receiver holes in the receiver. Nonetheless, as the nozzle is moved toward one of the two receiver holes driven by the actuator, the pressure in this receiver hole will be greater than the other one, which thus strokes the spool. Fig. 2(b) shows a schematic of the jet-type valve that illustrates how the pressure difference between the receiver holes varies while the displacement of the nozzle is changed.

3. Model of a jet-type valve

3.1. Theory of turbulent submerged jet

Fig. 3 shows the flow field structure of turbulent submerged free jet stream. The free jet issuing from the nozzle is assumed here to initially have a constant velocity profile. Because of the fluid boundary entrainment, it will experience an increasing cross-sectional area, and the nozzle exit velocity will remain constant within the "potential core" of length L_0. Beyond this point, a normal distribution type of velocity profile will occur and then the centerline velocity will continually decrease with the increasing distance.

The diameter of potential core decreases linearly with the distance from the nozzle exit and the diameter of turbulent mixing zone increases with the distance from the nozzle exit. Obviously, the performance of the amplifier depends on the distance between the nozzle exit and the receiver l_j and this distance significantly affects pressure gain as well as maximum pressure energy recovery [10].

The potential core length L_0 is affected by the multiple parameters including the reynolds number, the diameter of the nozzle and the velocity distribution [18,19]. To develop a less complexity model of a jet-type valve, if the velocity distribution is uniform at cross section of the nozzle, the potential core length L_0 in the jet-type valve is supposed as [20]

$$L_0 \approx 4.19 D_j \tag{1}$$

The diameter of potential core D_{ds} can be obtained from the geometric relationship shown in Fig. 3, it is

$$D_{ds} \approx \frac{L_0 - l_j}{4.19} = \frac{4.19 D_j - l_j}{4.19} = D_j - \frac{l_j}{4.19} \tag{2}$$

Also, the diameter of turbulent mixing zoneD_{bj}can be got from the geometric relationship displayed in Fig. 3, it is given by

$$D_{bj} = D_j + 2 l_j \tan\theta_j \tag{3}$$

If the velocity distribution is uniform at cross section of the nozzle, then q_j equals 12°.

Defining the relative distance from the nozzle to the receiving surface$\lambda_j = l_j / D_j$, the diameter of potential coreD_{ds}can be expressed as

$$D_{ds} = D_j \left(1 - 0.2387\lambda_j\right) \tag{4}$$

The diameter of turbulent mixing zone D_{bj}can be expressed as

$$D_{bj} = D_j \left(1 + 2\lambda_j \tan\theta_j\right) = D_j \left(1 + 0.4251\lambda_j\right) \tag{5}$$

when the fluid from nozzle shoots into a receiver hole, there is a flow stream with diameter of $D_{ej}$and velocity ofv_j, whose momen-

Table 1

Performance comparisons of flapper nozzle, jet-pipe/deflector-jet and spool.

Performance characteristics	Flapper-nozzle	Jet-Pipe/deflector-jet	Spool
Price	Low	Middle	High
Contamination sensitivity	Middle	Low	High
Maximum efficiency at the maximum power	Less than 0.5	More than 0.9	0.667
Linearity	Good	Bad	Middle
Performance at a low pressure	Bad	Good	Middle
Pressure gain, Low gain	Middle	Low	High
Dynamic performance	High	Middle	Low
Controlling force requirements	Small	Middle	Big