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Theoretical study of flow ripple for an aviation axial-piston pump with damping holes in the valve plate

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Abstract Based on the structure of a certain type of aviation axial-piston pump's valve plate which adopts a pre-pressurization fluid path (consisting a damping hole, a buffer chamber, and an orifice) to reduce flow ripple, a single-piston model of the aviation axial-piston pump is presented. This single-piston model comprehensively considers fluid compressibility, orifice restriction effect, fluid resistance in the capillary tube, and the leakage flow. Besides, the instantaneous discharge areas used in the single-piston model have been calculated in detail. Based on the single-piston model, a multi-piston pump model has been established according to the simple hydraulic circuit. The single- and multi-piston pump models have been realized by the S-function in Matlab/Simulink. The developed multi-piston pump model has been validated by being compared with the numerical result by computational fluid dynamic (CFD). The effects of the pre-pressurization fluid path on the flow ripple and the instantaneous pressure in the piston chamber have been studied and optimized design recommendations for the aviation axial-piston pump have been given out.

1. Introduction

Axial-piston pumps are widely used in aircraft hydraulic systems for supplying hydraulic power to flight actuators because they have high output pressure, high efficiency, and high reliability. However, axial-piston pumps will generate large flow ripple because of their inherent structures and working principles. Flow ripple can induce pressure fluctuation and piping vibration, which are very harmful to aircraft hydraulic systems.[1] According to statistics, almost half of the reported failures of hydraulic systems on aircrafts were due to the fracture of hydraulic pipes.[2] Consequently, the flow ripple of aviation axial-piston pumps is the root cause of hydraulic pipes' fracture. The key component that controls the dynamics of a pump is the valve plate,[3] and the most common measure used to reduce flow ripple is setting up a pressure relief groove or damping hole on the face of the valve plate prior to the opening of a discharge kidney slot reducing severity of the cylinder reverse flow.[4,5] The effect of the pressure relief groove or damping hole on the flow ripple of an axial-piston pump has been a research hotspot.

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Nomenclature

Parameters	Definition
A_h	Section area of the damping hole (m^2)
A_o	Cross section area of the orifice (m^2)
A_p	Cross section area of piston (m^2)
A_v	Discharge orifice area of the throttle valve (m^2)
A_{kd}	Discharge area of the ith piston kidney port in communication with the discharge port (m^2)
A_{kh}	Discharge area of the ith piston kidney port in communication with the damping hole (m^2)
C_d	Discharge coefficient of piston kidney port
C_h	Discharge coefficient of damping hole
C_o	Discharge coefficient of the orifice
C_v	Discharge coefficient of the throttle valve
d_d	Diameter of the piston leakage hole (m)
d_h	Diameter of the damping hole (m)
d_o	Diameter of the orifice (m)
d_p	Piston diameter (m)
dV	Volume change of the piston chamber (m^3)
E	Fluid bulk modulus (Pa)
K_{ih}	Inertia effect factor of the fluid in damping hole
l_k	Length of linearized kidney port (m)
l_p	Total length of the piston (m)
l_{cp}	Instantaneous overlap length of the piston and the cylinder block (m)
l_{h1}, l_{h2}	Lengths of the damping hole (m)
l_{cp0}	Initial overlap length of the piston and the cylinder block when the piston is at TDC (m)
n	Rotation speed of pump (r/min)
P_c	Pressure inside the pump shell chamber (Pa)
P_d	Pressure in discharge port (Pa)
P_T	Pressure of the oil tank (Pa)
P_{bc}	Pressure in buffer chamber (Pa)
P_{pi}	Instantaneous pressure in the ith piston chamber (Pa)
Q_d	Inverse flow rate from discharge port to piston chamber (m^3/s)
Q_g	Geometry flow rate of single piston (m^3/s)
Q_h	Inverse flow rate from damping hole to piston chamber (m^3/s)
Q_l	Leakage flow rate of single piston (m^3/s)
Q_o	Flow rate through the orifice (m^3/s)
Q_p	Total discharge flow rate of axial-piston pump (m^3/s)
Q_v	Flow rate through the throttle valve (m^3/s)
Q_{lv}	Leakage flow rate through the gap between the valve plate and the cylinder block (m^3/s)
Q_{pi}	Discharge flow rate of individual piston to discharge port (m^3/s)
Q_{lci}	Leakage flow rate through the gap between the piston and the cylinder block (m^3/s)
Q_{lsi}	Leakage flow rate through the gap between the swash plate and the slipper (m^3/s)
R	Piston distribution radius (m)
R_1	Inside radius of the inside valve plate seal ring (m)
R_2	Outside radius of the inside valve plate seal ring (m)
R_3	Inside radius of the outside valve plate seal ring (m)
R_4	Outside radius of the outside valve plate seal ring (m)
R_s	Outer radius of the slipper (m)
r_h	Radius of the damping hole (m)
r_k	Width radius of kidney port and discharge port (m)
r_s	Inner radius of the slipper (m)
t	Time (s)
V_0	Initial volume of piston chamber when piston is at TDC (m^3)
V_h	Volume of the damping hole (m^3)
V_{bc}	Volume of the buffer chamber (m^3)
V_{dc}	Discharge chamber control volume (m^3)
V_{pc}	Instantaneous volume of the piston chamber (m^3)
Z	Number of pistons
α_1, α_2, α_3, α_4	Angular segmentation points of calculating A_{kh} (°)
β_1, β_2, β_3, β_4, β_5	Angular segmentation points of calculating A_{kd} (°)
γ	Angle of the swash plate (°)
θ_1, θ_2, θ_3, θ_4, θ_5	Angles used in calculation of the discharge area (°)
φ	Position angle of piston (°)
ω	Angular velocity of pump (rad/s)
ρ	Fluid density (kg/m^3)
μ	Kinetic viscosity of the fluid (m^2/s)
δ_p	Oil film thickness between the piston and the cylinder block (m)
δ_s	Clearance between the slipper and the swash plate (m)
δ_v	Clearance between the valve plate and the cylinder block (m)
Γ_h	Integral area function used to describe the fluid inertia (m^{-1})

Within the last forty years, significant research on cylinder pressure transient and flow ripple of axial-piston pumps has appeared in the literatures. However, almost all the literatures focused on axial-piston pumps with silencing grooves in valve plates. Helgestad et al[6] gave out a method for calculating cylinder pressure in axial-piston hydraulic pumps with or without silencing grooves considering fluid compressibility, cylinder leakage, and orifice restriction effect. Edge and Darling[7,8] put forward an improved theoretical model for cylinder pressure taking fluid inertia in silencing grooves into consideration. Base on the theory of Edge and Darling, Harrison and Edge[9] calculated the total delivery flow ripple of an axial-piston pump with ripple-reduction mechanism by summation of each cylinder flow whose phase difference was considered, but cylinder leakage was neglected in their study. Based on the idealized pump flow model, Manring[10] investigated the actual flow ripple of an axial-piston swash-plate type hydrostatic pump with silencing grooves in its valve plate by considering pump leakage and fluid compressibility. Design aspects of valve plates of slot geometries and their effects on pump volumetric