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Direct drive servo valve based on magnetostrictive actuator: Multi-coupled modeling and its compound control strategy

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ABSTRACT

In this paper, a multi-coupled model of a direct drive servo valve driven by giant magnetostrictive actuator (GMM-DDV) is established with its constitute hysteresis studied based on Jiles–Atherton model. In order to enhance its tracking performance, a compound control strategy is proposed: a feedforward controller based on the inverse of the hysteresis is employed, a semi-adaptive PID controller optimized by PSO is accompanied with the feedforward controller to deal with the disturbance of the system. The numerical simulation is realized by a joint environment of AMESim and Simulink; the special experimentation system is setup combined a master computer and a control processer based on DSP, the effectiveness of the proposed model and control strategy is valid.

1. Introduction

Electro-hydraulic actuation servo systems in high frequency domain are implemented extensively in modern industry stretches from high-speed aerospace aircrafts [1–3]; to active suspension structures for intelligent vehicles and automatics [4,5]. The electro-hydraulic servo valve (EHSV), bridging the electrical and fluid signal in the system, is regarded as the crux to improve the dynamic performance of the whole system. The most commonly applied EHSVs are nozzle flapper valves as well as jet pipe valves. Despite certain advantages of the above traditional structures, there is still a considerable chasm between their poor dynamic responds, attributed to the inherent lag, and the expectation of swift actuation system.

Direct drive servo valve (DDV) is a novel structure to enhance the dynamic property of EHSV, with the spool motivated directly by a linear or torque motor, the respond of EHSV is accelerated. With remarkable dynamic performance and resistance to oil contamination, DDV has attracted extensive attentions of researchers world widely [6–10]. However, ascribed to the single stage structure of DDV, its dynamic performance is dominated by the frequency respond of its electro-mechanical driver.

In this case, giant magnetostrictive actuator (GMA), with notable frequency respond and considerable stroke [11,12], is employed in this paper serving as the driver of DDV. A hydraulic amplifier, based on flexible piston, is employed to enlarge the stroke of GMA and meet the requirement of sliding valve. However, ascribed to the constitute hysteresis and multi-coupled operating fields [13], the proposed GMM-DDV suffers a severe nonlinearity and tracks poorly with the reference signal in open loop. in order to suppressing the impacts of its nonlinearity, an explicit model is required.

However, in most of the former literatures concerning the dynamic modeling of EHSV based on smart materials, only simplified linear models are covered: Wang Xinhua developed hydraulic servo valve based on GMA and employed a linear relation between exciting field and magnetostriction [14]; Zhang Yibo setups a linearized model of GMA based overflow valve and employs a displacement amplification structure to enlarge the displacement of actuator. Since his works concerns primarily on the static case, the amplification mechanism is regarded as a proportional constant in mathematic model [15]; Zhang Chengming fabricated a self-cooling valve which uses a tube GMM rod as the actuator, he setup a coupled model for the embedded GMA: the governing equation between H and flux density B is described by a semi-linear piezomagnetic equation without consideration of hysteresis, in addition, the model focus on the dynamics of the GMA alone and the model of hydraulic components are not covered [16]; Karunanidhi proposed and fabricated two flapper–nozzle type EHSV based on GMA, he

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Nomenclature

A_r	Section area of GMM rod m^2
A_{F1}	Equivalent area of big film m^2
A_{F2}	Equivalent area of small film m^2
AMP	Amplification ratio of the amplifier
c_r	Damping of GMM rod
c_z	Equivalent damping of GMA and hydraulic amplifier
c	Reversible parameter of GMM
C_d	Flow coefficient of sliding valve
C_v	Velocity coefficient of sliding valve
E_r	Elastic module of GMM rod Pa
E_h	Equivalent elastic module of oil in hydraulic amplifier Pa
$e(k)$	Tested tracking error in point K m
F_{HA}	Force exerted on hydraulic amplifier N
F_{TS}	Force generated by transfer shaft
F_{EL}	Force generated by return board N
F_{VF}	Viscous friction force N
F_{st}	Static hydrodynamic force N
F_{tr}	Dynamic hydrodynamic force N
F_{DDV}	Force exerted on sliding valve N
H	Magnetic field strength A/m
H_e	Equivalent field strength within GMM rod A/m
I	Exciting current of GMA A
k	Pinning parameter of GMM A/m
k_{F1}	Equivalent stiffness of big film N/m
k_{F2}	Equivalent stiffness of small film N/m
k_z	Equivalent stiffness of GMA and hydraulic amplifier N/m
k_{st}	Equivalent static hydrodynamic coefficient N/m;
k_{tr}	Equivalent dynamic hydrodynamic coefficient Ns/m
k_{EL}	Equivalent stiffness elastic return board N
k_{VF}	Viscous friction coefficient of sliding valve Ns/m
l_r	Length of GMM rod m
M	Magnetization of GMM A/m
M_s	Saturation magnetization of GMM A/m
M_{an}	Anhysteresis magnetization of GMM A/m
M_{irr}	Irreversible magnetization of GMM A/m
M_{rev}	Reversible magnetization of GMM A/m
m_{TS}	Mass of transferring shaft in GMA kg
m_{F1}	Mass of big film kg
m_{F2}	Mass of small film kg
m_z	Equivalent mass of GMA and hydraulic amplifier
m_{spool}	Mass of the spool kg
n	Turns of the exciting coil
Para	Physical meaning Unit
V	Volume of sealed chamber of hydraulic amplifier m^3
W	Area gradient of sliding valve m
x_r	Deformation of GMM rod/output displacement of GMA m
a	Shape parameter of GMM A/m
δ	Modification parameters
λ_s	Saturation strain of GMM
λ	Magnetostriction of GMM rod
ϵ	Total strain of GMM rod
σ	Stress of GMM rod
ΔP	Pressure drop of sliding valve Pa
θ	Jet angle of sliding valve $^\circ$
L	Damping length of sliding valve m
ρ_h	Density of hydraulic oil of sliding valve kg/m3
Δq	Oil pressure variation of sealed chamber Pa
ΔV	Volume pushed by big piston L

setup a model between input current I and the square of magnetization M^2, in his model the influence of hydrodynamic force is not counted [17]. Sonam Yun develops a pneumatic valve based on PZT and in his model, the output force of PZT is regarded as a linear relationship [18]. Guglielmo Magri developed a gas combi boiler diverting valve using shape memory alloy (SMA), the constitute model of SMA actuator is setup based on the test strain-stress diagram [19]. Megnin developed a SMA based micro fluid valve, the modeling of SMA dynamic is based on fitting the test curves [20].

Dynamic control strategies for servo valve based on smart material mainly concern the PZT cases, the GMA cases are rare except for some simulation works [15,21]. The control strategies in these works are mainly the classical or modified PID controllers. For PID controllers, there are mainly two ways in tuning its parameters, the first method is online tuning, which means the parameters could be altered according to the working condition in real time, and the control parameters is calculated within closeloop, this method enjoys a more flexible structure and helps to suppress the perturbation of the system, however, since the iteration process is conducted within the close loop, it takes a longer time to calculate and send out the control input to the servo valve, which will degrade the tracking performance when the driving frequency is high: Zhou Miaolei has proposed a Fuzzy-PID controller accompanied with a Preisach model for a novel PZT-DDV, the tracking error of the controller is .0.74% in 5 Hz [22,23]; Cao Feng proposed two intellectual PID controllers based on neural network to control a PZT based EHSV, the tested tacking error beneath 0.5 μm under a driving frequency of 2 Hz [24].

Another PID tuning method is offline tuning, the PID controller is tuned in advance. This method helps to form a more concise structure of the controller and performs better in the high frequency tracking control. However, the controller cannot be adjusted according to the working condition and eventually degrades the anti-disturbance performance. Karam has proposed a GA optimized PID controller offline, through simulation and experimentation, this controller performs better than a compensator as well as a classical PID controller in step tests [25]; E Shiju proposed a PID controller for PZT-EHSV and the control parameters are tuned in advance by trial and error, the response time after control is reduced to 3 ms.

The objective of this paper concerns the establishment of a multi-coupled model of a novel electro hydraulic servo valve based on GMM actuator and a corresponding controller to enhance its tracking performance in high frequency.

In this work, a multi-coupled model for GMM-DDV is proposed to cover not only the dynamics of GMA but also the dynamics of a novel hydraulic amplification mechanism as well as the sliding valve. The hysteresis in magnetization procedure is calculated based on J-A model, compared with the Presaich model. This model provides a physical scope of the hysteresis behavior of GMA. The dynamic performance of hydraulic amplifier is modeled by a series of transfer functions; in this way, the dynamic of the amplifier in high frequency could be detailed. The fluid dynamics is coupled in the model as the static and transient hydrodynamic force, therefore the dynamics of sliding valve is also coupled in the overall model.

A compound control strategy is proposed based on the multi-coupled model of GMM-DDV, the constitute hysteresis is compensated by a feedforward inverse using J–A model and the a close loop controller is employed to suppress the disturbance in system, Consider the characteristics of both online and offline PID controllers, in this work, we developed a semi-adaptive PSO-PID controller to balance the demand of tracking performance and anti-disturbance capacity in GMM-DDV control.