



Non-linear control of a hydraulic piezo-valve using a generalised Prandtl–Ishlinskii hysteresis model

Frederik Stefanski^{a,*}, Bartosz Minorowicz^a, Johan Persson^b, Andrew Plummer^b, Chris Bowen^b

^a Faculty of Mechanical Engineering and Management, Institute of Mechanical Technology, Poznan University of Technology, Piotrowo Street 3, Poznan 60-965, Poland

^b Centre for Power Transmission and motion Control, Department of Mechanical Engineering, University of Bath, Bath, BA2 7AY, UK

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ABSTRACT

The potential to actuate proportional flow control valves using piezoelectric ceramics or other smart materials has been investigated for a number of years. Although performance advantages compared to electromagnetic actuation have been demonstrated, a major obstacle has proven to be ferroelectric hysteresis, which is typically 20% for a piezoelectric actuator. In this paper, a detailed study of valve control methods incorporating hysteresis compensation is made for the first time. Experimental results are obtained from a novel spool valve actuated by a multi-layer piezoelectric ring bender. A generalised Prandtl–Ishlinskii model, fitted to experimental training data from the prototype valve, is used to model hysteresis empirically. This form of model is analytically invertible and is used to compensate for hysteresis in the prototype valve both open loop, and in several configurations of closed loop real time control system. The closed loop control configurations use PID (Proportional Integral Derivative) control with either the inverse hysteresis model in the forward path or in a command feedforward path. Performance is compared to both open and closed loop control without hysteresis compensation via step and frequency response results. Results show a significant improvement in accuracy and dynamic performance using hysteresis compensation in open loop, but where valve position feedback is available for closed loop control the improvements are smaller, and so conventional PID control may well be sufficient. It is concluded that the ability to combine state-of-the-art multi-layer piezoelectric bending actuators with either sophisticated hysteresis compensation or closed loop control provides a route for the creation of a new generation of high performance piezoelectric valves.

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1. Introduction

Actuation using smart materials, such as piezoelectric ceramics and shape memory alloys, is an alternative to classical designs where movement is achieved by an electromagnetic force. Solenoids and torque motors are conventionally used in electrohydraulics to control flow and pressure. However, in the last two decades a number of new concepts which use smart

* Corresponding author.

E-mail addresses: frederik.stefanski@gmail.com (F. Stefanski), bartosz.minorowicz@put.poznan.pl (B. Minorowicz), L.J.Persson@bath.ac.uk (J. Persson), A.R.Plummer@bath.ac.uk (A. Plummer), C.R.Bowen@bath.ac.uk (C. Bowen).

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materials have been described in literature [1,2]. The main aim of the application of smart materials has been to improve performance in terms of speed of response or accuracy, or to reduce mass or power consumption. In this paper, we describe a small spool valve actuated by a piezoelectric ring bender. The motivation for designing a piezoelectric actuated valve [3] is to avoid the complexity of electromagnetic actuation, reduce the cost of manual set up and the consequent lack of repeatability and reliability associated with electromagnetic actuators such as torque motors.

Valve actuation using smart materials has been the subject of a number of previous studies. Linder et al. [4] described a servovalve with a spool directly driven by a piezoelectric stack actuator. However, the approach required mechanical amplification in order to obtain sufficient spool displacement. A similar concept is presented in [5], and the authors undertook performance tests at high temperatures. Changbin et al. [6] used a spool that was directly driven by a piezoelectric stack actuator; the major hysteresis loop was measured and phenomenological hysteresis models were discussed, but the final controller did not include hysteresis compensation. A whole family of valves using piezoelectric elements was developed in RWTH Aachen [7,8]. These papers were focused on the description of the different valve designs using piezoelectric actuation and investigation of their basic performance.

Research into smart materials for hydraulic valves most frequently concern two-stage servovalves. A conventional servovalve has an electromagnetic torque motor providing first-stage actuation, and either a flapper-nozzle, jet pipe or deflector jet as the first hydraulic stage to create a pressure difference across the ends of the main spool. This pressure difference is used to control spool position, which determines the port orifices sizes and hence the main-stage flowrate. The conventional torque motor and first-stage is a complex design including machining processes with tight tolerances, manual assembly, and requiring a very accurate calibration process [9]. In [10] the authors indicate the benefits of utilising piezoelectric actuators compared with torque motors; these include the ability to achieve significant mass reduction, smaller size, a simpler mechanical design and zero power requirement for constant spool position. An increase of torque motor performance is also possible by application magnetic fluids in the air gaps [11]. Piezoceramic materials are one example of a smart material to provide actuation and are characterised by a high dynamic response but small maximum strains, in the region of 0.15%. Therefore, a challenge is to create sufficient displacement for first stage actuation since typically there is a need for a displacement in the region of ± 0.1 mm. One of the drawbacks of utilising piezoelectric actuation includes the need for complex amplifier electronics and operation at a higher voltage compared to a torque motor. In addition piezoelectric materials suffer from hysteresis, creep and a temperature dependence [12,13], primarily as a consequence of domain motion in the ferroelectric materials employed. A number of piezoelectric actuator designs for valve applications are based on bender actuators [14–16]. Sedziak et al. [14] investigated a servovalve with barometric feedback where the ferroelectric hysteresis of the piezoelectric had a significant influence on the valve flow characteristics. In [17] the authors presented a servovalve where a piezoelectric stack actuator moved a flapper assembly and the displacement of the piezoelectric stack was mechanically amplified. The influence of ferroelectric hysteresis can also be observed in the response of the flow rate versus input voltage. These valves are distinguished by control based on spool or actuator position feedback provided by electrical position transducers. Conversely, [18] presents an aerospace servovalve where a mechanical feedback wire is retained between the spool and piezoelectric bender, which is currently an industry requirement for safety-critical flight controls.

Many smart actuator materials exhibit hysteresis, which prevents accurate and precise open loop control and hinders tuning of closed loop controllers. To better describe this phenomenon, mathematical models of hysteresis have been developed [19], which relate the input and output of the system; rather than being physics-based. An early model was developed by Preisach to describe magnetisation effects in ferromagnetic materials [20]. Krasnosel'skii and Pokrovskii proposed a modification of this model [21]. These models use a sum of discrete elements called *operators* or *hysterons*, therefore the quality of the model depends on the number of elements used. In this field a group of Prandtl–Ishlinskii models (classical, modified and generalised) which combines a simple structure and analytical invertability have been developed; the approach provides an easy application for real time hysteresis compensation. The application of a hysteresis model in a piezoelectric servovalve control system has been reported [22], in which a precise fuzzy control algorithm with Preisach hysteresis model in a feedforward loop was proposed to provide better valve performance than PID (proportional integral derivative) control. Nevertheless, the results presented in [22] do not show the accuracy of Preisach model in following hysteresis behaviour. The authors used this model as a feedforward compensator, but it is also possible to perform direct compensation by using the inverse Preisach model. Unlike the Prandtl–Ishlinskii analytical inversion, inversion of the Preisach model is more complicated and its requires numerical operations [23,24]. Furthermore, the presented results are only limited to tracing results of a low frequency (5 Hz) sine wave and do not investigate the performance of this control approach for a dynamic response or at a wider frequency bandwidth. When using smart materials for actuating positioning systems in other applications described in literature [25,26], controllers with hysteresis compensation have shown to provide better performance.

Conventional servovalves also exhibit hysteresis because of magnetisation effects in the armature and parts of the core. The technical literature defines hysteresis in flow control servovalves as the difference in the electric current applied to the torque motor coils to generate the same output flow in a test cycle from a negative to a positive rated current. The hysteresis value is presented as a percentage of rated current, and is typically less than 3% [27]. However, in smart actuator materials the hysteresis can be much larger, and presents a very significant obstacle to accurate control. Despite many examples of piezoelectric and other smart material valves being proposed, hysteresis compensation has been rarely investigated to date. Thus the main contribution of this paper is to undertake a detailed investigation of different control strategies to improve

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