A LIGHTWEIGHT, LOW LEAKAGE PIEZOELECTRIC SERVOVALVE

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ABSTRACT

We describe a new two-stage aerospace servovalve which has an additively manufactured titanium body, and a small piezoelectrically actuated spool as its first stage, with electrical main stage position feedback. The approach promises to provide low weight, low leakage, and more accurate spool positioning. In addition, it enables increased manufacturing automation thereby reducing cost, increasing repeatability, and generates less waste material. Valve design, operation and measured performance are discussed in this paper.

KEYWORDS

Additive manufacture, servovalve, piezoelectric actuation, electrical feedback valve

I INTRODUCTION

There are around 40 servovalves on a typical single-aisle airliner, being the key control component in both electrohydraulic actuation and fuel control systems. Reducing weight, manufacturing cost, and improving efficiency through reduced leakage are key drivers for new servovalve designs. If acceptable material properties can be obtained, producing servovalve bodies using additive manufacture (AM) could provide significant benefits in weight and manufacturing labour cost, as well as providing additional design freedom. Making complex internal flow galleries which have proven difficult using traditional manufacturing methods is straightforward with AM. It also allows new opportunities for integrating novel sensing and actuation within a valve.

A valve first (or pilot) stage refers to the torque motor and either nozzle-flapper, jet pipe or deflector jet amplifier, and provides the actuation to move the main spool (second stage). Torque motors can be time-consuming and expensive to set-up, requiring significant manual intervention. If not adjusted very precisely the first stage amplifier may not provide stable operation, and there is a continual flow loss (and power loss) through the nozzles or jet. An alternative approach is sought providing a more cost effective, reliable, low leakage alternative which is amenable to automated manufacture.

The specific focus of this paper is a new two-stage servovalve design incorporating piezoelectric actuation and electrical spool position feedback, manufactured using AM. To reduce leakage, a small spool is used for the first stage instead of a conventional nozzle-flapper, jet pipe or deflector jet amplifier.

II VALVE DESIGN

The circuit configuration of the two-stage valve is shown in Figure 1. The valve first stage is a small spool that is directly driven by a piezoelectric ring bender (Figure 2). A ring bender is a flat annular disk that deforms in a concave or convex fashion depending on the polarity of the applied voltage. An example of the bending effect of the actuator can be seen in Figure 3(a). Such an actuator configuration has been chosen since a ring bender actuator exhibits a greater displacement than a stack actuator of the same mass, and an increase in stiffness in comparison to similar size rectangular bender (*Bertin et al*, 2014).

A Noliac CMBR08 multilayer ring bender is used in the valve. This has a 40mm diameter and 1.2mm thickness, a free displacement of ±115μm and a blocking force of ±39N. Figure 3(b) shows the ring bender with its three wire electrical connection. The bender is made up of multiple 67μm thick lead zirconium titanate (PZT) piezoceramic layers. To apply the necessary electric field across the piezoceramic and actuate the device, silver palladium electrodes are located between each layer; see the light lines in Figure 3(c). In order to deflect the ring bender in both directions the electrodes are combined into three groups. One set of electrodes are maintained at a negative voltage (-100V, black wire), one set

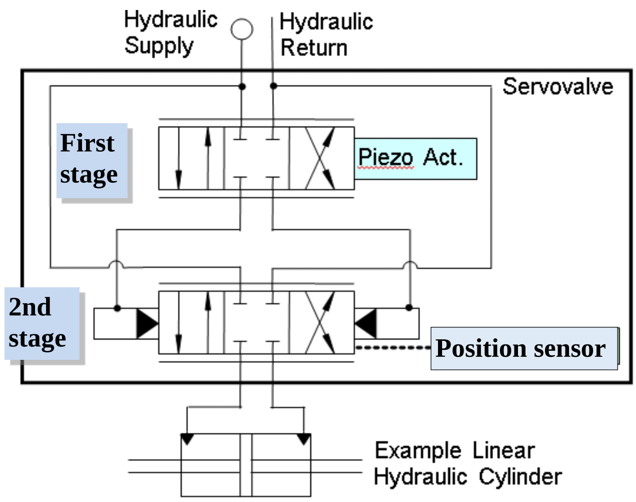

Figure 1. Internal servovalve circuit

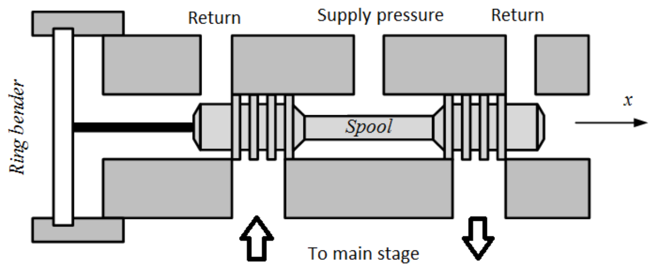

Figure 2. First stage schematic

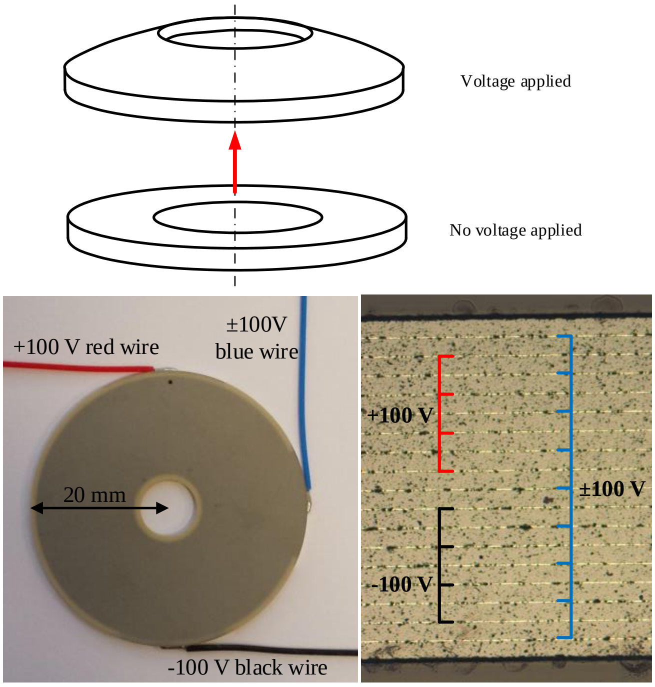

Figure 3. Piezoelecric ring bender: (a) deformation, (b) Noliac CMBR08 with electrical connection, and (c) cross section of actuator (electrode spacing is 67μm)

are maintained at a positive voltage (+100V, red wire), and the voltage is varied on the intervening electrodes (control electrodes, blue wire) between -100V and +100V. Based on an electrode thickness of 67 µm, the magnitude of the maximum electric field is 3kV/mm (200V across 67 µm). This electrode configuration allows deflection of the device in both directions since half of the piezoceramic layers expand in-plane, while the other half contract as the control voltage varies from zero to -100V or 100V. When the control voltage is zero the upper and lower half layers experience the same electric field, resulting in no displacement.

The ring bender is clamped in a flexible mount around its outer edge, and connected by a hub and shaft to the first stage spool. This is incorporated into the two-stage valve as shown in the cross-section of Figure 4. The completed valve is shown in Figure 5. The ring bender, which is submerged in hydraulic fluid, is attached to a linear variable differential transformer (LVDT) position sensor. The main spool position is measured by a second LVDT. The ring bender LVDT is used for monitoring only, whereas the main stage LVDT is used for closed loop control. A proportional-integral spool position controller is used with a 10kHz sample rate. A description and comparison of control methods, including consideration of modelling and compensating piezo-actuator hysteresis, is contained in (Stefanski, 2016).

III ADDITIVE MANUFACTURE

Valve bodies contain intricate fluid galleries. They need to have the strength and stiffness to withstand high hydraulic pressures (e.g. 350bar), and maintain excellent dimensional accuracy despite pressure variations and large changes in temperature (-54°C to +150°C being a typical specification). Clearances around a spool, or tolerances on a metering edge, are of the order of a few microns. Metering edges are adjacent to high velocity fluid (frequently more than 100m/s) and are prone to erosive wear. Currently valve bodies are usually made from aluminium or titanium with a very hard wearing martensitic stainless steel (440C) bushing insert to form the metering edges.

Additive manufacture gives the opportunity to create complex valve bodies which are of much lower weight, only adding material where necessary, and are manufactured cost-effectively with high repeatability and low material waste. The geometry can be optimized to meet the stringent requirements outlined above, without the normal subtractive manufacturing constraints. Available AM processes are reviewed by (Frazier, 2014).

The valve prototype is manufactured from titanium alloy (Ti6Al4V) on a Renishaw AM250 machine which uses a powder bed fusion laser melting process, illustrated in Figure 6. Laser melting is known to be successful with this material, although research is still required to ensure the characteristics and quality are suitable for aerospace applications. In particular, fatigue life is affected by surface finish and microstructure, and the effects of build process parameters

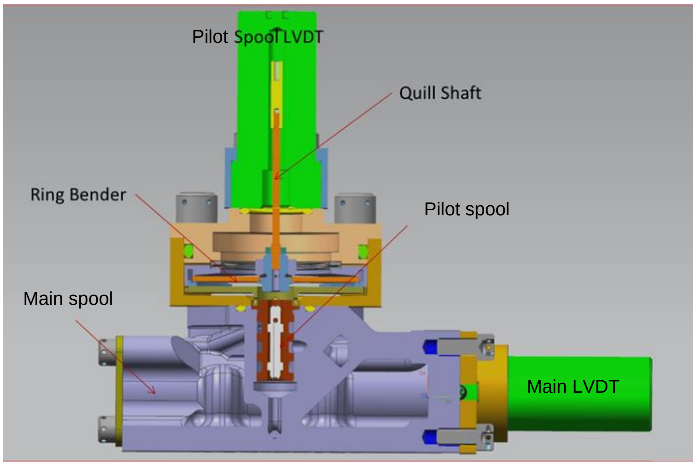

Figure 4. Prototype two-stage valve design

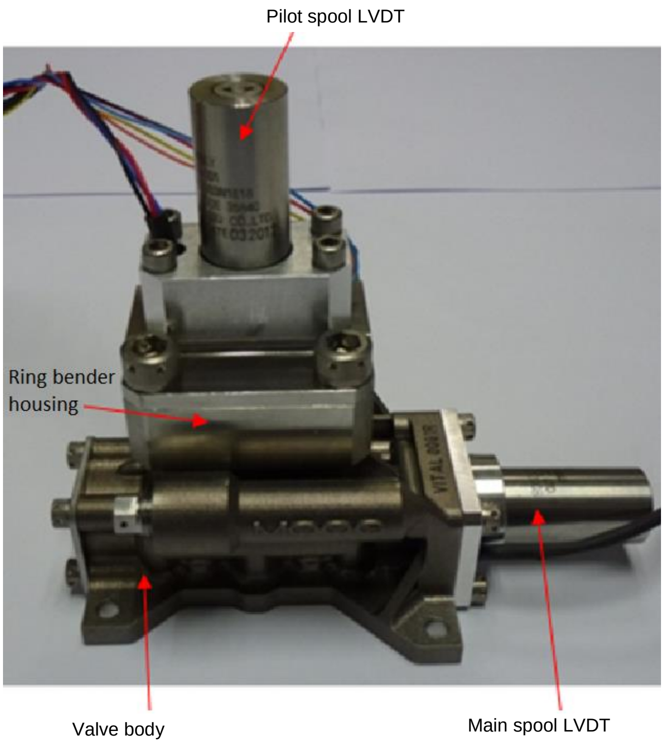

Figure 5. Initial two-stage valve prototype

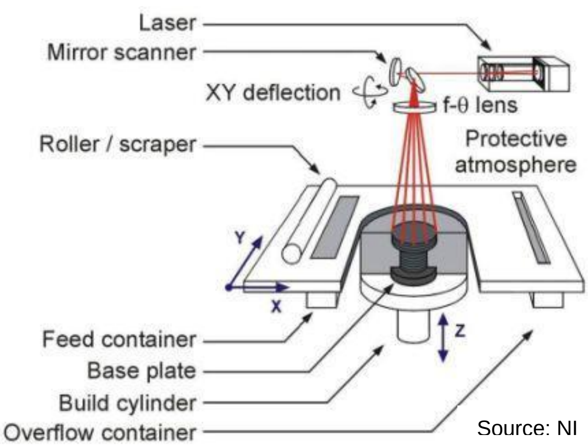

Figure 6. Powder bed laser melting AM process

and heat treatment are just starting to be understood. Certification questions arise with flight actuators and using additive manufacturing for safety critical parts requires new standards to be developed.

As described in more detail in (Guerrier, 2016), for servovalves and other complex hydraulic actuation components, application of AM promises a shorter development cycle, reduced inventory costs for material, better hydraulic efficiency, weight saving, and new repair opportunities.

Figure 7 shows the AM valve body in more detail. A hard stainless steel bushing insert is still required to achieve the required wear properties for the metering edges. Figure 8 illustrates how internal inspection of AM parts can be achieved using CT scanning. A final prototype using the same design concept is shown in Figure 9. This includes integration of first and main stage bodies into the same AM component. The first stage LVDT is omitted in this design, and the closed-loop controller electronics are integrated within the valve body.

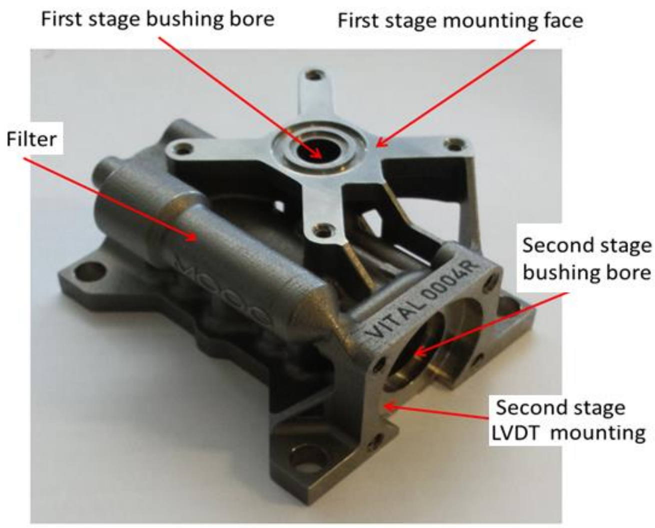

Figure 7. AM body of initial prototype

Figure 8. Three-axis view of CT scan of AM valve body

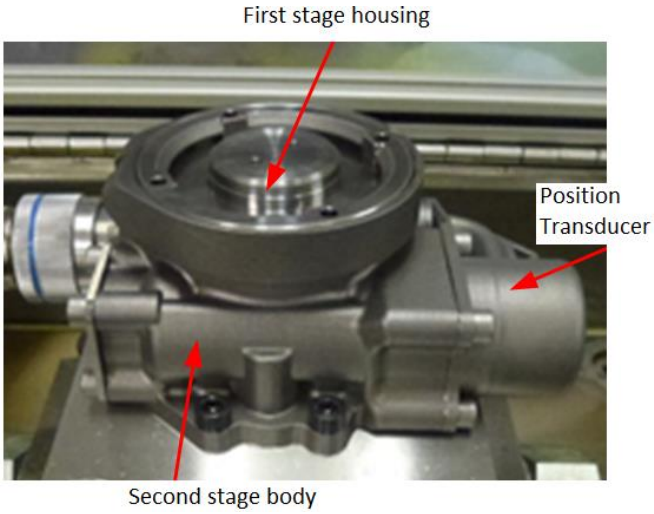

Figure 9. Final prototype

IV MEASURED PERFORMANCE

Both static and dynamic valve performance have been tested. Statically, with 210bar supply pressure and connected cylinder ports, the maximum flow rate is just above 70 L/min, and the leakage flow from pressure to return in the closed (null) position is about 0.1 L/min.

Low frequency full scale cycling of the control signal shows that the ring bender hysteresis is about 20%, which is typical for piezoelectric actuators (Figure 10). However a similar test for the full range of main spool movement shows a linear relationship, as the closed loop controller successfully compensates for the ring bender hysteresis. An earlier piezoelectric servovalve design with mechanical feedback did not have this advantage (Sangiah, 2013)

The dynamic response of the valve spool motion to the ring bender control signal is determined by:

- the power amplifier bandwidth, and its current limit which limits the rate of change of output voltage given that the piezo actuator behaves approximately like a capacitor,
- damping and inertia associated with ring bender and first stage spool motion, and flow forces acting on the spool as the ports open,
- compressibility and flow restriction in the galleries between the first and main stage, along with orifice size in the first stage spool,
- damping and flow forces acting on the main spool, along with its inertia, and the flow and pressure difference from the first stage acting on the main spool end area.

The factors affecting first stage dynamics are analysed in detail in (Persson, 2015), where simulation results are presented.

Figure 11 shows an example main spool position step response at low pressure measured from the initial prototype. The maximum displacement range for the spool is ±0.6mm, so the demanded step size shown is 0 to 25%. The control signal peaks at 5V, and the amplifier output voltage follows this with little delay, peaking at nearly 100V. The ring bender (pilot stage) displaces by a maximum of 45μm, the peak occurring 5ms after the initial step.

Figure 12 is a frequency response measured from the final prototype at full pressure, showing that the dynamic response is similar to conventional valves of the same size.

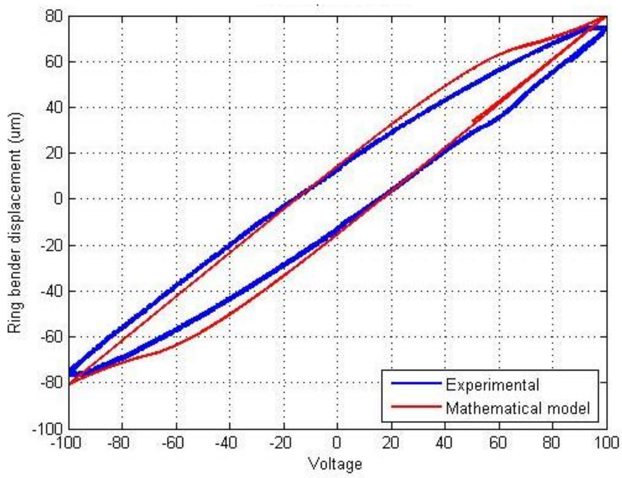

Figure 10. Ring bender (first stage) hysteresis

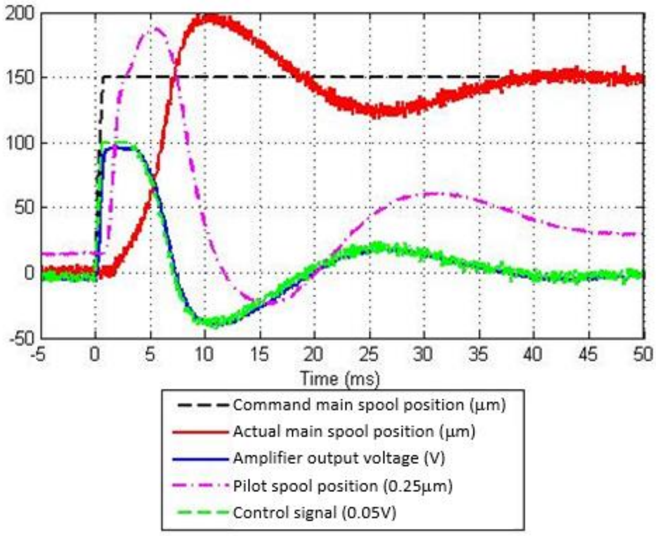

Figure 11. Step response results (100 bar supply)

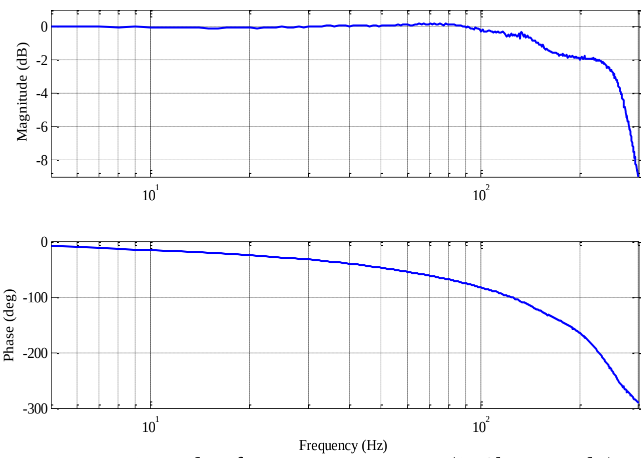

Figure 12. Valve frequency response (210bar supply)

V CONCLUSIONS

A new aerospace servovalve has been prototyped, with a body manufactured by laser melting titanium powder (Ti6Al4V), and a low leakage piezoelectrically actuated first stage. Further development is required before commercialization, but the approach promises to provide:

- low weight and reduced size due to optimized AM structure,
- improved repeatability and reliability through eradication of fine-wire device (torque motor),
- better spool position control compared to conventional mechanical feedback valves: more precise, faster, less sensitive to environmental changes (e.g. temperature), less variability from one valve to another, with provision for ‘intelligent’ health monitoring,
- increased manufacturing automation, improving repeatability and reducing cost,
- manufacturing resource efficiency through less material waste,
- reduced first stage leakage, reducing power loss.

The functional requirements have been met by the design presented in this paper. Durability requirements have also been verified through hydraulic and material fatigue testing, but additional research will be required before certification is possible. The use of electrical feedback is also a new departure for primary flight controls, and the safety case needs to be proven.

Further research is ongoing into digital spool position sensing, and protection and durability of piezoactuators operating in hydraulic fluid. Reducing the size of the piezo amplifier will also need to be addressed. Subtractive machining as a finishing operation for AM parts is necessary, and better integration of additive and subtractive processes is another research thrust.

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ACKNOWLEDGEMENTS

The authors would like to thank Innovate UK, Moog Aircraft Group and Renishaw plc for financial support and guidance during this work. We also acknowledge support of the University of Bath Impact Acceleration Account funded by the UK Engineering and Physical Sciences Research Council.