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Electrohydraulic servovalves – past, present, and future

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Abstract

In 2016 it is 70 years since the first patent for a two-stage servovalve was filed, and 60 years since the double nozzle-flapper two-stage valve patent was granted. This paper reviews the many alternative servovalve designs that were investigated at that time, focusing on two-stage valves. The development of single-stage valves – otherwise known as direct drive or proportional valves – for industrial rather than aerospace application is also briefly reviewed. Ongoing research into alternative valve technology is then discussed, particularly focussing on piezoelectric actuation and the opportunities afforded by additive manufacturing.

KEYWORDS: Servovalve, Direct drive valve, Nozzle-flapper, Piezoelectric

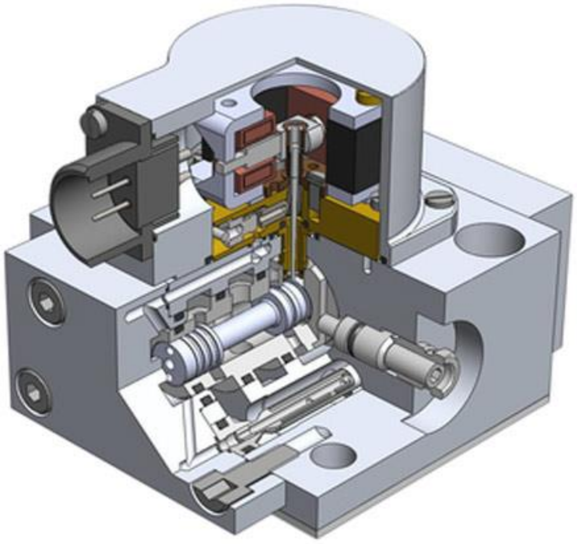
1. Introduction

The servovalve is the key component enabling the creation of closed loop electrohydraulic motion control systems (or 'servomechanisms', the traditional term now largely fallen out of use). 'Servovalve' has come to mean a valve whose main spool is positioned in proportion to the electrical input to the valve, where the spool movement is achieved through internal hydraulic actuation. The spool movement changes the size of metering orifices, thus enabling the valve to control flow; however this flow is dependent on the pressure difference across the orifice unless some form of pressure compensation is used. The most common servovalve design is the two-stage nozzle-flapper valve with mechanical feedback (**Figure 1**). The key parts are:

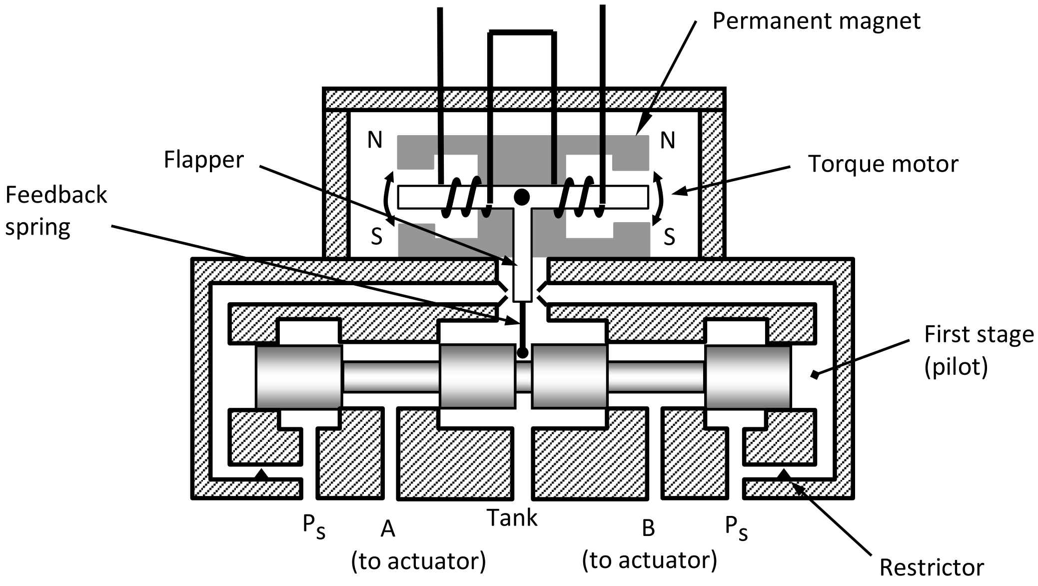
- An electromagnetic torque motor acting as the electrical to mechanical transducer, supported on a flexure tube which gives a friction-free pivot as well isolating the torque motor from the hydraulic fluid (**Figure 2a**).
- A flapper, driven by the torque motor, differentially restricts the flow from a pair of nozzles (**Figure 2b**); the flapper stroke is ~0.1mm. A single nozzle can be used (**Figure 2c**) for modulating pressure on just one end of the spool, but the

unbalanced flow force on the flapper places greater demands on the torque motor.

- The first stage hydraulic circuit forms an H-bridge, where the pair of nozzles are the variable restrictors, generating a pressure difference across the spool when the flapper is off-centre (**Figure 2d**).
- The feedback spring allows the spool to move (stroke ~1mm) until the restoring force on the flapper is in equilibrium with the electromagnetic torque, so the flapper recentralises.

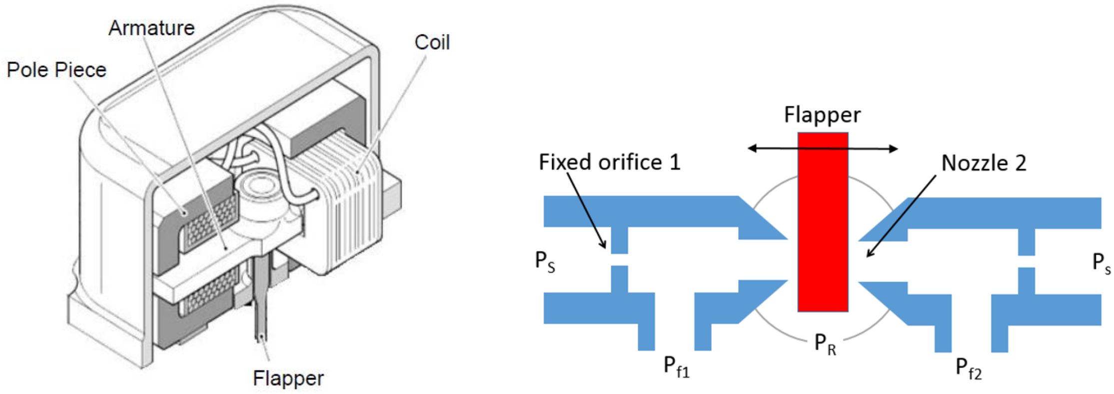


(a) Typical design (courtesy Moog)

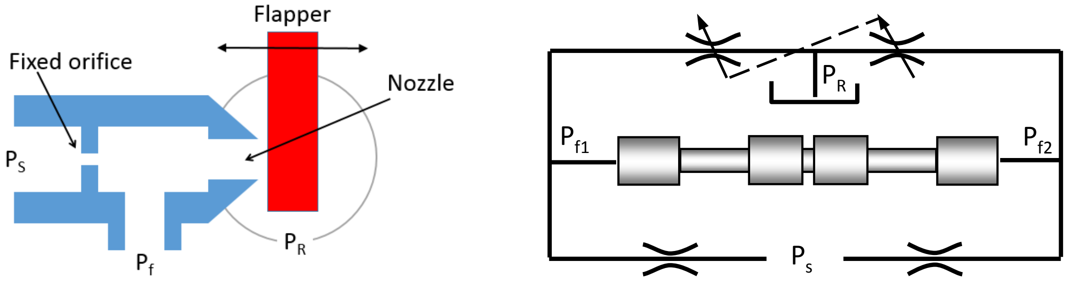


(b) Schematic

Figure 1: A two stage nozzle-flapper servovalve



(a) Torque motor (b) Double nozzle-flapper



(c) Alternative single nozzle-flapper (d) First stage H-bridge circuit

Figure 2: Nozzle-flapper first stage components

The servovalve is a power amplifier as well as an electrical to hydraulic transducer. The electrical input power has an order of magnitude of 0.1W, amplified in the first stage to at least 10W of hydraulic power, and then converted by the main spool to controlling around 10kW of hydraulic output power. So the valve power amplification factor is 10^5. In a three-stage valve, the original spool flow moves a larger spool, with electrical position feedback, giving a further power amplification factor of about 100, and a similar factor again for a four-stage valve.

2. Historical development

Embryonic electrohydraulic servovalves where developed for military applications in the Second World War, such as for automatic fire control (gun aiming) /1,2/. Such servovalves typically consisted of a solenoid driven spool with spring return. These were able to modulate flow, but with poor accuracy and a slow response. Tinsley Industrial Instruments Ltd. (London) patented the first two-stage servovalve /3/ (**Figure 3**). A solenoid (34) moved a sprung first stage spool (47), which drove a rotary main stage (51), whose position was fed back to the first stage by a cam (54), with feedback spring (59) converting position into force.

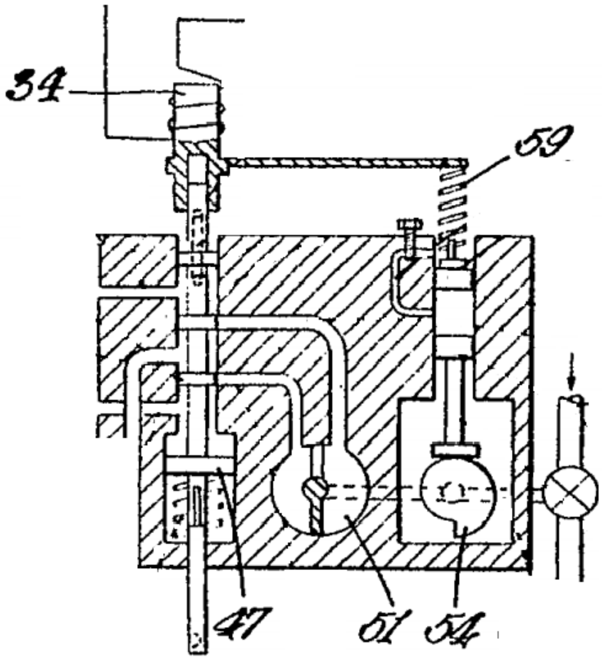


Figure 3: Tinsley 1946 two-stage servovalve, consisting of: solenoid (34); first stage spool (47); main stage (51); feedback cam (54); feedback spring (59)

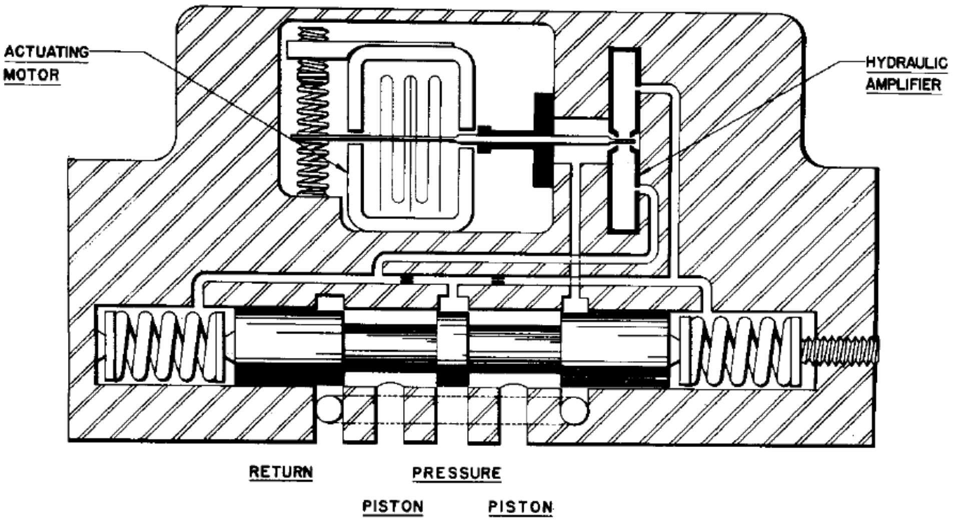
Servovalve development progressed at a tremendous rate through the 1950's, largely driven by the needs of the aerospace industry (particularly missiles). The technical status and available products at that time are well documented in a series of reports commission by the US Air Force /4,5/. In 1955 servovalves were manufactured (or at least prototyped) in the US by Bell, Bendix, Bertea, Cadillac Gage, Drayer Hanson, GE, Hughes, Hydraulic Controls, MIT, Midwestern Geophysical Labs, Honeywell, Moog, North American Aviation, Peacock, Pegasus, Raythoen, Sanders, Sperry, Standard Controls and Westinghouse /4/. It was recognised that single-stage valves with direct electromagnetic actuation of the main metering spool were limited to low flows, due to the small force available from the electromagnetic actuator for overcoming friction, inertial and flow forces. Increasing the size of the electromagnetic actuator to increase force reduces dynamic response due to larger mass and higher coil inductance.

Two stage valves mostly used a nozzle-flapper or a small spool for the first stage, although the jet-pipe first stage was known, but considered to be slower and was confined to industrial rather than aerospace use. The nozzle-flapper, either single or double, had become well established in pneumatic control systems from about 1920 manufactured for example by Foxboro /2/. The second (main) stage spool was sometimes spring-centred, or if unrestrained it was recognised that internal feedback was required to make the main spool position proportional to the electrical input signal. Thus within an actuator position control system the valve acts (to a first approximation) as an integrator – which is desirable – rather than a double integrator – which often leads to instability /1/. Main spool position feedback was either mechanical, via a feedback spring loading the electromagnetic actuator (force feedback) or via translation of the first stage housing (position feedback), or electrical using a main spool position transducer. Hydraulic feedback, comparing load pressure to first stage pressure, was used for pressure control applications.

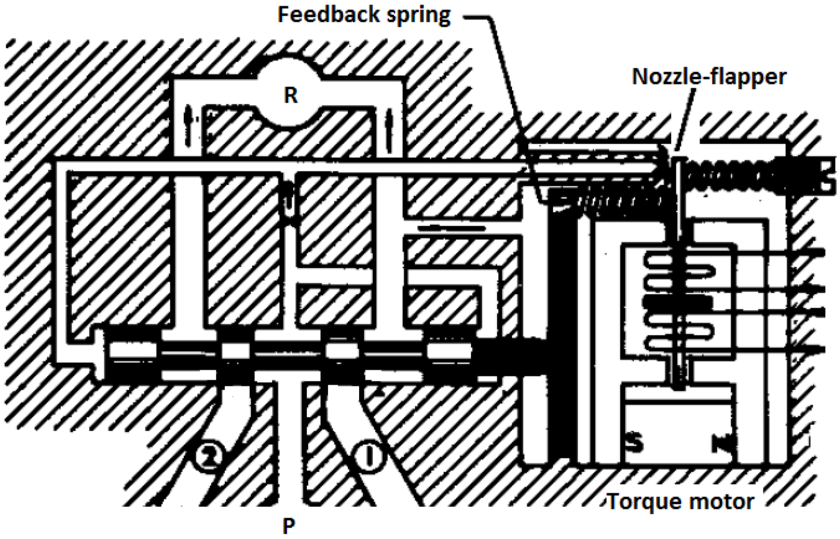
Of 21 designs, the two-stage flow control valves are listed in Table 1, ordered in terms of first stage design and then by main stage feedback. Some are illustrated in **Figures 4 and 5**. In addition to these, integrated valves and cylinders from Hughes and Honeywell, and a plate valve from MIT are described in /4/.

Manufacturer / Type	Electromagnetic driver	First stage	Main stage spool feedback
Bell	torque motor	double nozzle-flapper	no feedback (spring-centred spool)
Moog (Fig. 4a)	torque motor	double nozzle-flapper	no feedback (spring-centred spool)
Cadillac Gage FC-2 (Fig. 4b)	torque motor	single nozzle-flapper	mechanical force feedback
Pegasus (Fig. 4c)	solenoid with spring return	single nozzle-flapper	mechanical position feedback (moving nozzle)
North American	torque motor (PWM)	first stage spool (oscillating)	no feedback (spring-centred spool)
Drayer-Hanson, later made by Lear. (Fig. 5a)	torque motor	first stage spool	mechanical force feedback
Cadillac Gage CG (Fig. 5b)	torque motor (long stroke)	first stage spool	mechanical position feedback (via concentric spools)
Raytheon	antagonistic solenoid pair	first stage spool	mechanical position feedback (via moving bush)
Sanders (Fig. 5c)	torque motor	first stage spool	mechanical position feedback (via moving bush)
Hydraulic Controls	torque motor	first stage spool	electrical position feedback
Bertea	voice coil	first stage spool	electrical position feedback

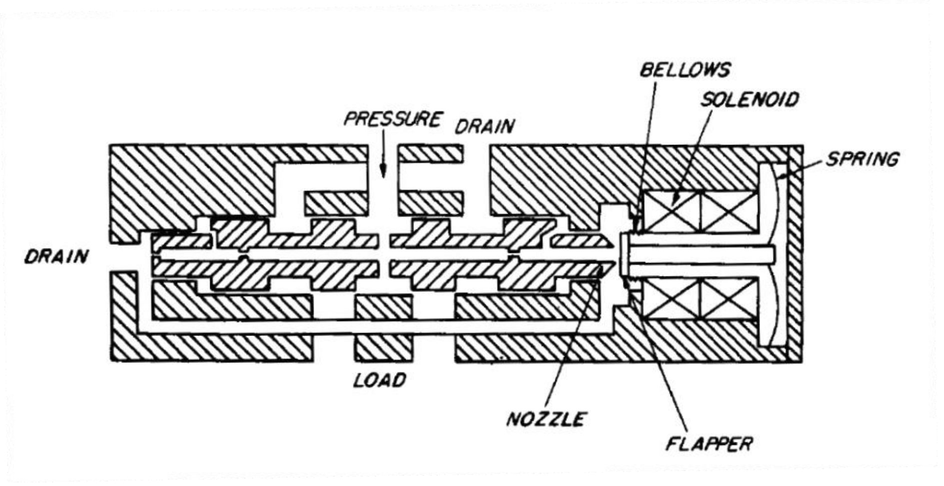
Table 1: Valve designs in 1955 /4/



(a) Moog series 2000 (dry torque motor)

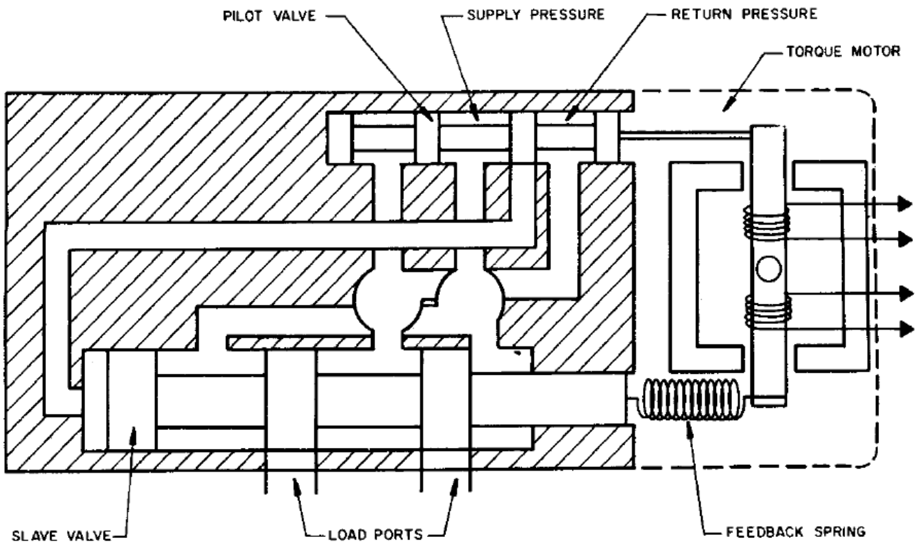


(b) Cadillac Gage FC-2

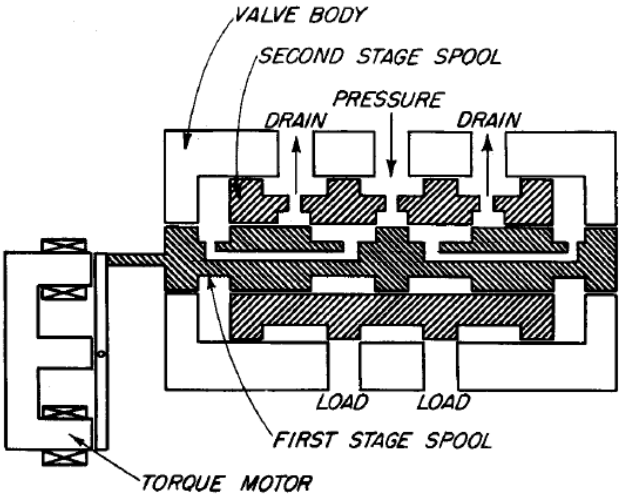


(c) Pegasus 120-B

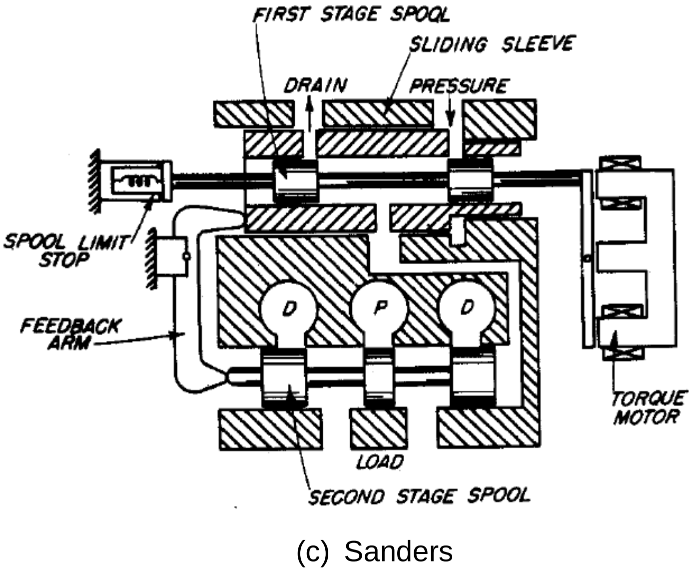
Figure 4: Nozzle-flapper valve designs from 1955 /4/



(a) Lear (previously Drayer-Hanson) /5/



(b) Cadillac Gage CG



(c) Sanders

Figure 5: Valve designs with spool first stage from 1955 /4/

The Hydraulic Controls valve was originally designed at MIT and is described in detail in the seminal book edited by Blackburn, Reethof and Shearer /1/; the book was based on lecture courses given by MIT staff to industrial engineers in the 1950's. This valve showed that electrical spool position feedback could be used very effectively, and popularised the use of torque motors /6/.

The Cadillac Gage FC-2 valve (Figure 4b) is noteworthy as a precursor to the 2-stage valve design that would soon become the *de facto* standard: it combines a torque motor with a nozzle-flapper first stage (albeit in single nozzle form) and mechanical force feedback from the main spool using a feedback spring. This design is also described in a patent filed in 1953 /7/.

The Moog valve (Figure 4a) was originally designed by W.C. (Bill) Moog at the Cornell Aeronautical Laboratory for aircraft and missile control applications /1/. Moog introduced a number of significant practical improvements. Supporting the torque motor on a flexure provided a lightweight frictionless pivot which much reduced valve threshold (input deadband), described in a patent filed in 1950 /8/. When this was granted in 1953, Moog filed another patent, highlighting the deficiencies of this single nozzle design, and proposing the double nozzle-flapper to eliminate sensitivity to supply pressure /9/.

A common fault was due to magnetic particles carried in the oil accumulating in torque motors, but that was solved for the first time in the Series 2000 by isolating the torque motor from the oil /5/. Bell Aerospace file a patent for a similar design the same year /10/.

By 1957, a further 17 new valve designs were available and had also been assessed for the US Air Force /5/, including those manufactured by Boeing, Lear, Dalmo Victor, Robertshaw Fulton, Hydraulic Research, Hagan and National Water. Double nozzle-flapper two-stage valves were starting to dominate. It was noted that nozzle-flapper arrangements were cheaper to manufacture than spool first stages, and all spool first-stages required dither to tackle friction and sometimes overlap.

The following designs had some novel features:

- Sanders SA17D – voice coil / double nozzle-flapper (the flapper actually being a sliding baffle) / mechanical force feedback: all components axially aligned
- Cadillac Gage FC200 – torque motor (dry) / double nozzle-flapper / hydraulic feedback (spool restricts first-stage 'fixed' orifices when it moves)

- Pegasus Model 20 – voice coil or solenoid / double nozzle-double flapper / mechanical position feedback achieved by attaching nozzles to the ends of the spool; effectively a bi-directionally symmetrical version of Figure 4c.

- Hagan – voice coil / first stage spool, spinning to reduce friction / no feedback

Common technical problems reported are null-shift (thought to be mostly due to torque motor magnet temperature sensitivity), nozzle and flapper erosion, torque motor non-linearity if designed to use very small currents, and high frequency instability (squeal). Only Moog and Cadillac Gage are producing commercially available valves in large quantity by this time, although Bendix has many valves under test with end users /5/.

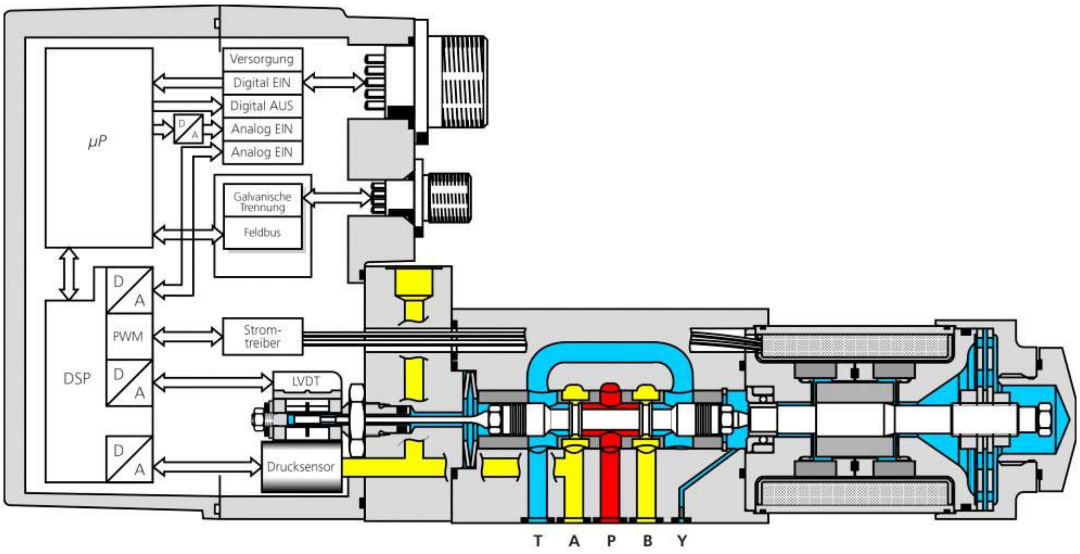
3. Industrial valves

By the end of the 1950's, the two-stage mechanical force feedback servovalve had become established for military and aircraft applications /11/ These included aircraft and missile flight control, radar drives and missile launchers, and also servohydraulic thrust vectoring was starting to be used for space rockets during launch.

Potential industrial application for servohydraulics was also recognised at this time, including for numerical control of machine tools and injection moulding machines, gas and steam turbine controls, steel rolling mills, and precise motion control in the simulation and test industry. Some industrial valves were designed by modifying aerospace valves, for example the '73' series was the first industrial valve from Moog in 1963 /12/. Industrial valves needed to be cheap and low maintenance and began to include:

- Larger bodies for easier machining
- Separate first stage for easier adjustment and repair
- Standardised port patterns
- Better in-built filtering to handle the lower industrial filtration standards

Electrical rather than mechanical spool position feedback allows for higher loop gains improving dynamic response, and also correction for errors due to hysteresis or temperature effects. The inherent safety and compactness of mechanical feedback valves are attractive to aerospace, but industrial valves began to adopt electrical feedback in the 1970's. A landmark was the Bosch plate type servovalve introduced in 1973, with a jet-pipe first stage, a hall-effect position feedback transducer and most importantly on-board electronics to close the loop /12/.



Source: MOOG

Figure 6. Force motor directly driven valve with integrated electronics /13/

	Direct Drive Valve (DDV)			Two-stage Servovalve	
Valve type	Open loop Proportional Valve	Position controlled Proportional Valve	Force motor DDV	Hydraulic pilot, mechanical feedback (MFB)	Hydraulic pilot, electrical feedback(EFB)
Spool actuation	Proportional solenoid, open-loop	Proportional solenoid, closed-loop	Linear force motor (voice coil)	Hydraulic, mechanical feedback	Hydraulic, electrical feedback
Actuation force	<50N	~50N	~200N	~500N	~500N
Static accuracy:					
Hysteresis	5% +	2%	0.2%	2%	0.2%
Dynamic response:					
Step response (100%)	100ms	50ms	15ms	10ms	3ms
90deg phase lag frequency	5Hz	10Hz	50Hz	100Hz	200Hz
Cost	very low	low	medium	high	very high
Size	large	very large	very large	small	medium

Table 2: Example values for typical 4-way valve rated at 40 L/min with 70bar pressure drop (equivalent to 15 L/min at 10 bar valve pressure drop).

Rexroth, Bosch, Vickers and others developed single-stage valves directly positioning the spring-centred spool with a pair of proportional solenoids in open loop, similar to single-stage designs in the early 1950's which had been rejected for aerospace use. Improved accuracy and speed of response was achieved using electrical position feedback for closed loop control. Linear electrical force motors, or voice coil actuators, provide improved linearity compared to proportional solenoids, and limited force output was overcome by replacing Alnico magnets with rare earth magnets in the 1980's. Direct drive valves of this type were developed by Moog (**Figure 6**), and latterly Parker, with dynamic response capabilities similar to two-stage valves.

Table 2 indicates typical valve performance, including valve spool actuation forces. A high valve spool actuation force is required not only to overcome flow forces and accelerate the spool, but also to drive through small contaminant particles which would otherwise jam the valve (chip shear).

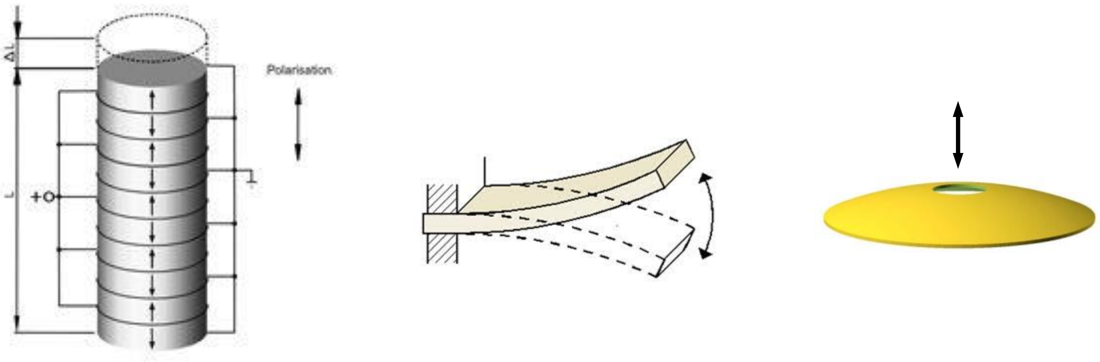
4. Novel valve designs

Alternative valve designs have been explored over many years for increasing the dynamic response, reducing leakage, improving manufacturability or providing other advantages over conventional servovalves (either single or two-stage). Most investigations have involved new ways of actuating the spool, often using active materials.

4.1. Piezoelectric valve actuation

Piezoelectric ceramics deform very rapidly when an electric field is applied but maximum strains are small, in the region of 0.15%. Thus actuation using a stack (**Figure 7a**) realistically requires motion amplification, even for first stage actuation (e.g. flapper movement of around 0.1mm). Rectangular bending actuators (**Figure 7b**) can provide sufficient displacement but fairly small forces. Newly available ring bender actuators (**Figure 7c**) provide sufficient displacement for first stage actuation, and reasonable force levels (~10N – 100N) /14/. Such benders are available with ceramic layers as thin as 20μm, in which case electrode voltages of around 50V provide sufficient field strength. However piezoelectric materials suffer from hysteresis (typically 20%), creep, and stack actuator length is temperature dependent /15/. As the actuator behaves like a capacitor, speed of response is generally constrained by the amplifier current limit.

In the 1955 valve survey /4/, only electromagnetic actuation is shown for the electrical to mechanical conversion, but it states that "piezoelectric crystals have been used on certain experimental models to obtain improved response. However, they have not been



(a) Axial actuator (stack) (b) Rectangular bender (c) Ring bender

Figure 7. Piezoelectric actuation

accepted to date because of high susceptibility to vibration, temperature changes, and electrical noise and because of the difficulty in obtaining sufficiently large displacements from the crystals". A patent for a piezoelectric valve was filed in 1955, covering both a piezo-actuated flapper for a double nozzle-flapper valve, and also delivering fluid using an oscillating piezo-disc i.e. a piezo-pump /16/.

Moving the spool with a stack requires some motion amplification. In a valve described in /17/ this is done with a hydrostatic transformer filled with silicone rubber and a 40:1 piston area ratio. A -90° bandwidth frequency of 270Hz is achieved, and using two opposing actuators at either end of the spool reduces temperature sensitivity (**Figure 8**). Mechanical amplification using a lever is reported in /18/ (**Figure 9**).

Replacing the torque motor in a two-stage valve with a piezoelectric actuator is reported in a number of studies. In /19/ the authors present a servovalve where a flextensional actuator (a stack in a flexing frame providing motion amplification) moves a flapper in a mechanical feedback valve (**Figure 10**). An aerospace servovalve, again with a feedback wire, is presented in /20/. This uses a rectangular piezoelectric bender to move a deflector jet, arguing that the smaller flow forces experienced in a deflector jet (or jet pipe) first stage are more suited to bender use (**Figure 11**). In comparison with a torque motor, it is suggested that a piezoelectric bender may prove easier to manufacture and commission, and give more repeatable performance. In a recent valve prototype, a ring bended is used as the first stage actuator /21,22/ This time the first stage is a miniature spool with some overlap used to minimize first stage leakage flow. Electrical spool position feedback is used (**Figure 12**).

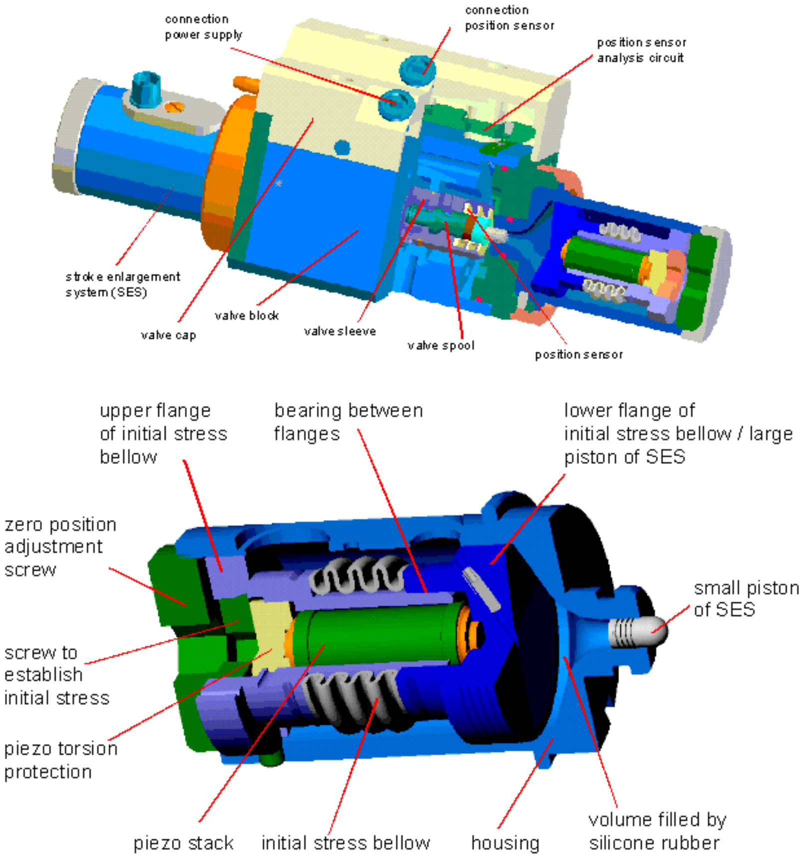


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Figure 8: Spool actuation with hydrostatically amplified piezoelectric stack motion /17/

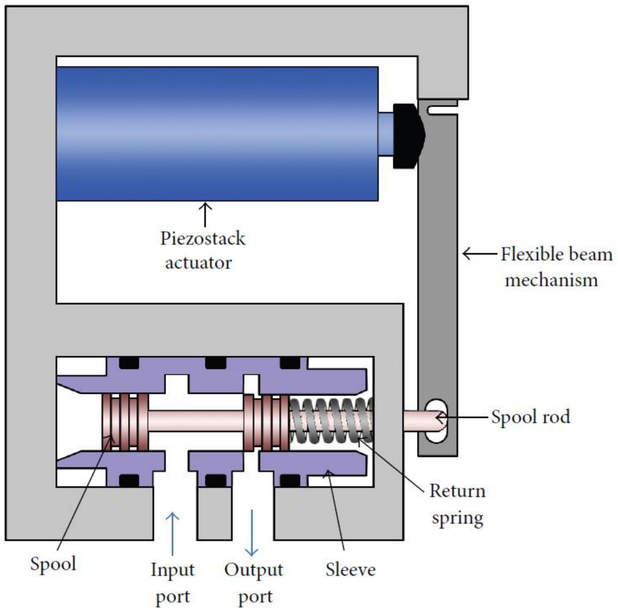


Figure 9: Spool actuation with mechanically amplified piezoelectric stack motion /18/

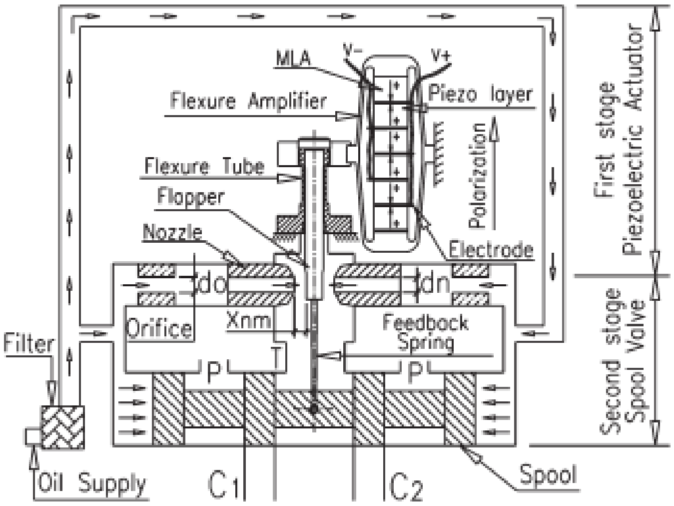


Figure 10: Piezo-stack with flextensional amplification for two-stage valve /19/

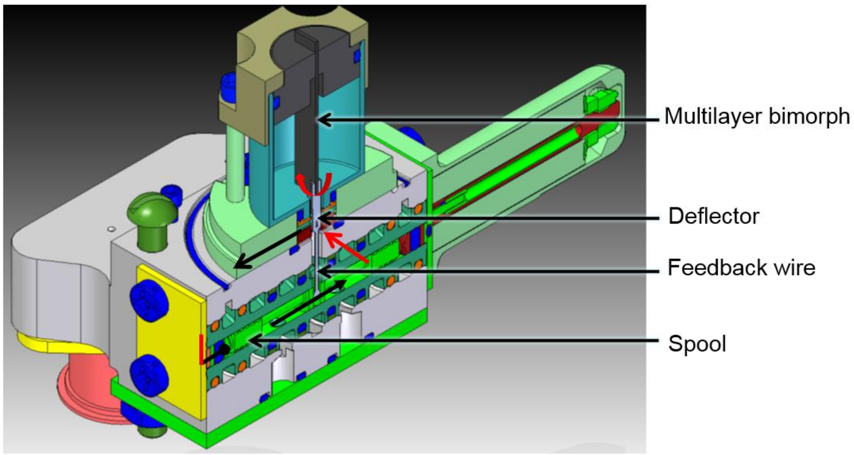


Figure 11: Piezo rectangular bender deflector jet two-stage MFB valve /20/

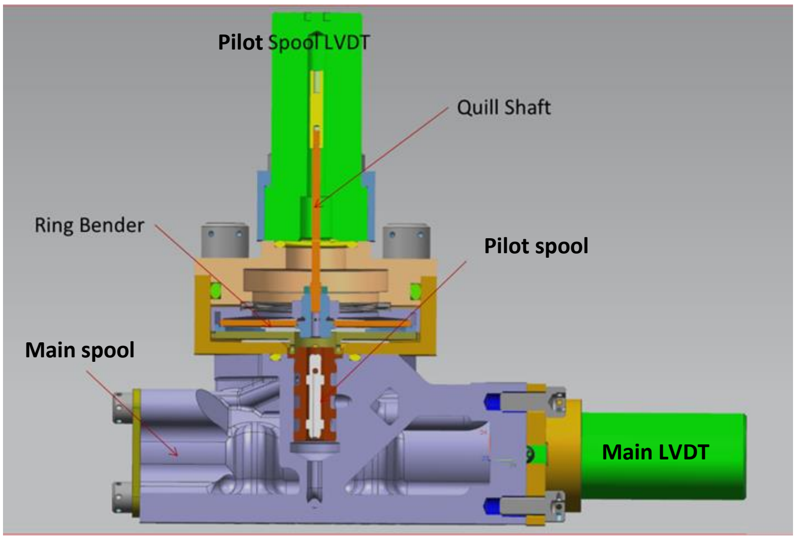


Figure 12: Piezo ring bender actuated pilot spool in two-stage EFB valve /22/

Another piezo-stack actuated first stage concept in described in /23/. As shown in **Figure 13**, all four orifices in the first stage H-bridge are modulated using automotive fuel injectors with 40µm stroke, and a -90° bandwidth of over 1kHz is achieved.

Figure 14 shows a novel concept for increasing the frequency response of a direct-drive valve. The spool bushing sleeve is moved +/-20µm using a stack, complementing the conventional +/-1mm spool movement driven by a linear force motor. Thus fine flow control can be achieved at much higher frequency than the 60Hz bandwidth of the conventional valve /23/

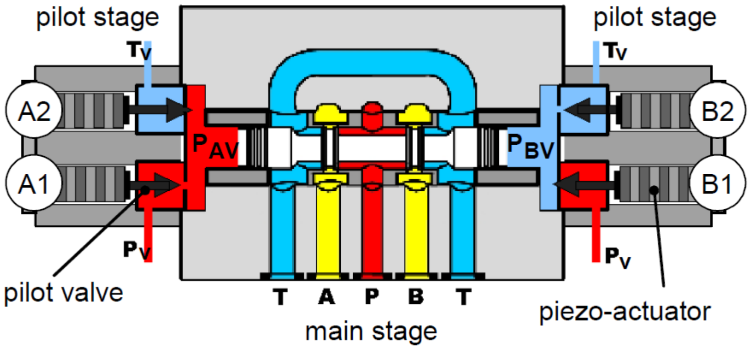
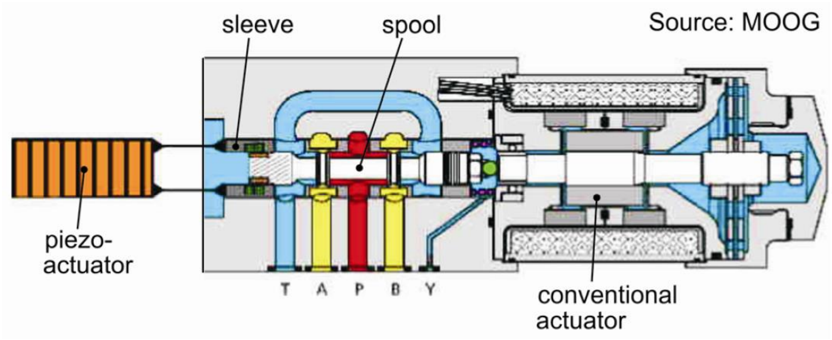


Figure 13: Independent piezo control for first stage H-bridge orifices /23/



Source: MOOG

Figure 14: Dual-actuated valve, combining high frequency and long stroke actuators /23/

4.2. Some other novel designs

Magnetostriction is another material phenomenon which can be used to create a ‘smart‘ actuator. Magnetostrictive spool valve actuation has also been experimented with for many years; recent attempts are reported in /24,25/. The challenges are quite similar to piezoelectric actuation, including limited displacement, hysteresis, and temperature sensitivity.

Alternatives to a spool valve main stage have also been explored. Individual main stage orifice control gives the opportunity for more energy efficient use of hydraulic power. Individual control is achieved through applying electric fields to restrict flow of an Electro-Rheological (ER) fluid in /26/. Another application of a functional fluid is reported in /27/. This time a magnetic fluid is used to improve the performance of a torque motor by increasing its damping; the magnetic fluid fills the air gaps and increases its viscosity in the magnetic field.

4.3 The additive manufacturing advantage

Additive manufacturing (AM) gives a radical new way to manufacture hydraulic components. AM can be used to reduce the weight of a valve body, and importantly give very much greater design freedom because many manufacturing constraints are removed. For the piezovalve of Figure 12, powder bed fusion via laser melting has been adopted to manufacture the body from titanium alloy /21,22/. The research included detailed investigation of resulting fatigue life and other material characteristics. **Figure 15** shows the final valve, and **Figure 16** details the AM valve body. **Figure 17** is an example CT scan showing internal galleries in the body.

5. Conclusions

Many of the basic design ideas in single or two-stage servovalve design had been conceived by the mid-1950's: 60 years ago. The two-stage mechanical feedback servovalve became established through the 1960's for aerospace and then high performance industrial applications. The single stage valve, with proportional solenoid or linear force motor direct spool valve, became established in the 1970's and 80's as a lower cost solution for industrial applications, increasingly with electrical spool position feedback and integrated electronics.

The torque motor driven two-stage valve has been remarkably successful and longlived. Nevertheless, manual assembly and adjustment of torque motors has always proved necessary, which is one motivation for investigating alternative technology, principally harnessing active materials. Also, in a few applications, the potential for faster dynamics that piezoelectric or some other active materials promise is attractive, but this is very much the minority of cases. Despite 60 years of research into alternatives, the torque motor has survived, although the gradual improvements in piezoelectric actuator technology, including drive electronics and hysteresis compensation methods, may eventually provide a viable competitor.

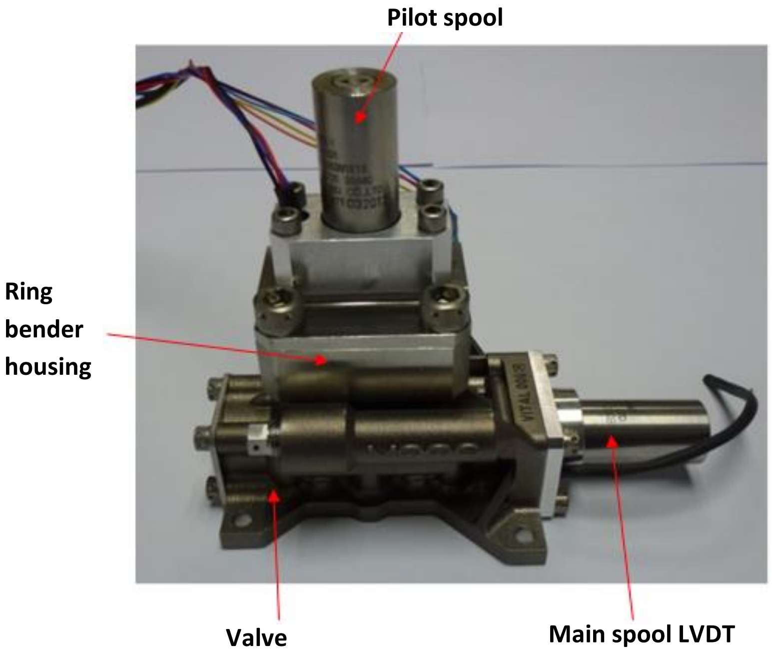


Figure 15. Prototype AM piezovalve /22,23/

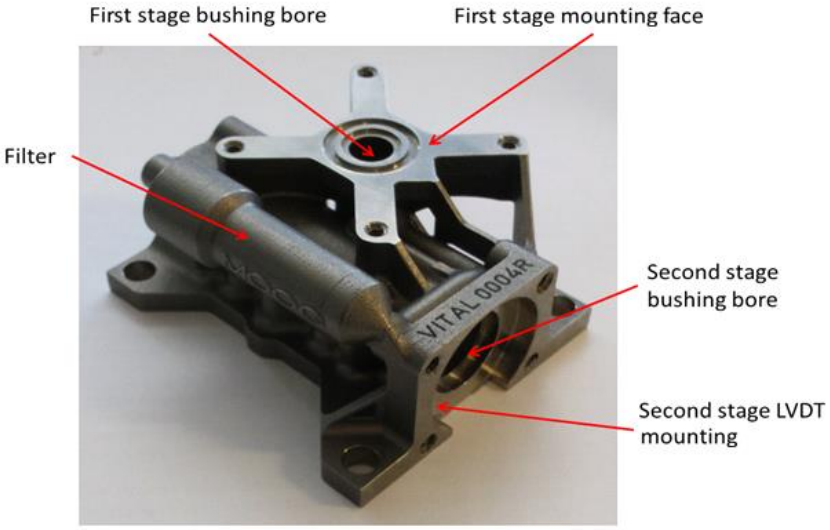


Figure 16: Detail of AM valve body

Figure 17: Three-axis view of CT scan of AM valve body

Additive manufacturing, particularly where manufacturing volumes are not too large (such as in aerospace), removes many manufacturing constraints in valve bodies and other hydraulic components. This will enable a paradigm shift in design ideas which can be physically realised, and the full potential of this manufacturing technology has not yet been recognised.

A futher continuing trend is increased valve intelligence. Integrating self-tuning functions, condition monitoring, and increased communication capability is a trend in industrial valves which will also be adopted in aerospace valves in time.

It should be noted, however, that a shift away from valve-controlled hydraulic systems is occuring. Electrohydrostatic actuation (servopump controlled actuators), or pump-displacement controlled machines are much more energy efficient. Nevertheless the power density and dynamic response of such systems are well below that of traditional valve controlled systems, so the technology trajectory is by no means certain.

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