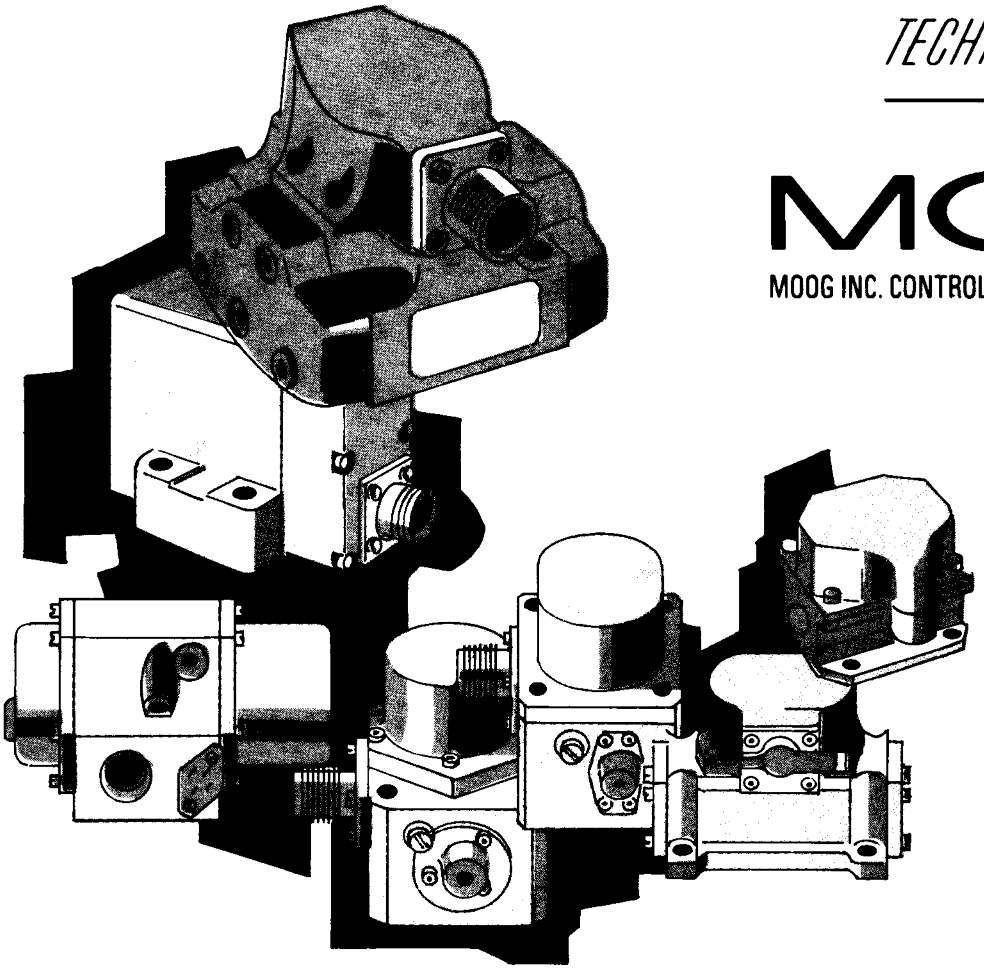
TECHNICAL BULLETIN 141

MOOG®

MOOG INC. CONTROLS DIVISION, EAST AURORA, N.Y. 14052



A BRIEF HISTORY OF **ELECTROHYDRAULIC** SERVOMECHANISMS

R. H. MASKREY
W. J. THAYER

This article appeared in the
ASME Journal of Dynamic Systems
Measurement and Control, June 1978

Fluid power control, that is the transmission and control of energy by means of a pressurized fluid, is an old and well recognized discipline. The growth of fluid power has accelerated with our desires to control ever increasing quantities of power and mass with higher speeds and greater precision. More specifically, where precise motion control is desired and space and weight are limited, the convenience of high power-to-weight ratio makes hydraulic servomechanisms the ideal control elements.

The demand to achieve more accurate and faster control at high power levels, especially in the areas of machine tools, primary flight controls, and automatic fire control produced an ideal marriage of hydraulic servomechanisms with electronic signal processing. Information could be transduced, generated, and processed more easily in the electronic medium than as pure mechanical or fluid signals, while the delivery of power at high speeds could be accomplished best by the hydraulic servo. This marriage of electronics and hydraulics into electrohydraulic servomechanisms created both a solution to an existing class of control problems and a demand for a whole new strain of components. The evolution of these components is really a story of increasingly demanding applications each of which caused the creation of better, or more efficient, or more reliable, or faster devices. To satisfy this demand, new manufacturing methods had to be conceived and original testing techniques developed.

The key element in this family of mechanisms is the electrohydraulic servovalve. With power gains on the order of 10^4 to 10^6, the servovalve is a very effective forward loop "amplifier" as well as an electrical to hydraulic transducer. It is the development of the servovalve, then, that has paced and will continue to pace the growth of electrohydraulics.

GENEALOGY

Electrohydraulic servomechanisms trace their roots back through a variety of disciplines. The earliest contributor is the fundamental work in hydraulics from the early Greek and Roman civilizations. During the Industrial Revolution a number of eminently practical inventions led to the development of a variety of hydromechanical devices which increased the influence of hydraulics. A second branch of the family tree is the field of process controls, where pneumatic devices for signal transmission were developed, refined and eventually used in power control applications and in hydraulics. Meanwhile, the advances in machining technology were leading to the use of close fitted parts, tighter dimensional controls and better structural materials which created an environment for high pressure hydraulic systems. The demand for high pressures was accelerated during World War I, especially by manufacturers of naval equipment, and ultimately led to a whole industry manufacturing high pressure fluid power components. The spreading acceptability of this medium helped to fuel the demand for more sophisticated electrohydraulic control.

A third branch of the family tree grows from the relatively recent field of electromechanical devices. Large motors and solenoids used as prime movers, spawned a field of electromechanical servomechanisms, where miniature versions, (AC or DC servomotors and relays) were used as control devices. This provided three benefits: first, it led to miniaturization of the motors (better magnets and materials); second, it provided a reason for expanding the amount of knowledge in the field of closed loop controls; and third, it led to the development of a family of electromechanical transducers. The first development led directly to the servovalve, while the latter two enhanced the climate and created the demand for better closed loop control.

The latest contributor to the family is the field of electronics. While the vacuum tube amplifier was the device that made the field of electrohydraulic control possible, it has been the advancement in solid state electronics, allowing a significant reduction in size and power consumption, that has made it practical. In addition to the contribution to drive electronics, solid state technology has provided new and innovative measuring devices, novel transducers that open up new fields of control, and expanded means of handling signal information so that more complex control problems can be solved.

EARLY HISTORY

The earliest contributors to fluid power probably do not have their deeds recorded, however the earliest meaningful contributor to our subject must surely be Ktesbios [1],[1] an Alexandrian living during the period 285 to 247 B.C. Living in a time and place well known for its outstanding scientific achievements, Ktesbios is credited with the invention of what must have been the first hydraulic servomechanism. Among his many inventions was the water clock, which was used to keep time over a long period, typically months.

Time was recorded by measuring the level of water in a vessel with the rate of flow into the vessel held constant. Ktesbios solved this problem of constant flow by controlling the water level (hence pressure) in an upstream vessel which fed the timing vessel through a fixed orifice. The water level was controlled by a float which opened and closed, proportionally, a variable orifice feeding the upstream vessel. By any rigorous definition this is a servomechanism which is still in use today, although not in water clocks. In fact, the demise of the water clock was presaged in the 14th century by the mechanical clock, and the float valve for hydraulic control appears to have gone with it for the next four centuries.

Float valves were next used in England around 1750 for controlling liquid level in domestic water supplies and in steam boilers. During this time, the 18th century, designs for steam boilers proliferated in England, in Russia, and eventually throughout the rest of Europe. This period, of course, was the Industrial Revolution and it made its mark felt on hydraulic servos. As the boiler inventions grew, so did the control schemes. Many varieties of flow valves were patented, as well as a new device to control steam pressure. By 1800 these were called regulators, a term that became more common to all feedback devices, and some that were not.

The Industrial Revolution created in its wake a flood of gadgets and inventions that today are essential ingredients of all electrohydraulic systems. Bramah's hydraulic press in 1796, for example, required the invention of a cup packing by Henry Maudslay to make it work. This is the forerunner of our seal technology. Those presses, consisting of a hand pump and a cylinder, gained popularity in the manufacturing industries of England and doubtlessly led to the use of steam driven pumps and the eventual transmission of power through hydraulic lines. During the late 1800's, many English towns had central high pressure hydraulic systems for power distribution. Although this scheme was eclipsed by the more efficient use of electric power distribution, it did lead to the invention of the variable stroke hydraulic pump and the accumulator.

During the 19th century, countless feedback devices were invented, but only those that had applicability to prime movers such as hydraulic governors found acceptance. Hence, the technology of servomechanisms was limited to mechanical and hydromechanical devices up through the start of the 20th century. Then came the application of electrical solutions to control problems, and an acquiescence to a more theoretical treatment. Because of this diversification, the "Age of Enlightenment" came to servomechanisms in the '1920's, 30's, and 40's with the involvement of people like Kupfmuller, Nyquist, Oldenburger, Black, and Bode.

The early 1900's saw several significant developments, including the use of oil as the fluid medium, the use of electric actuation on directional control valves, and the development of pumping elements. Mechanical feedback servos appeared as vehicle power steering units in the late 1920's even though they were not popularly applied to automobiles until the late 1940's.

During the period prior to World War II, several significant events occurred. In the process control field, pneumatics were being used for computation, control and signal transmission. This work required mechanical/pneumatic transducers, and created a need for valves. Askania Regulator Company and Askania-Werke, Germany, developed and patented a valve using the jet pipe principle, in which fluid pressure is converted into momentum of a jet. The jet is directed between two receivers where the momentum is recovered as a pressure or flow. Similarly, Foxboro developed the nozzle-flapper valve which uses the cylindrical curtain orifice area formed by a flat plate moving toward a sharp edged nozzle. These two devices, Figs. 1 and 2, would play important roles in the future development of the servovalve.

Siemens of Germany developed a dual-input valve that accepted mechanical inputs through a spring and electrical inputs through a moving coil, permanent magnet motor. While relatively primitive by today's standards, this valve was used in a closed position loop, and became a forerunner of valves used in aircraft automatic flight controls.

---

[1] Numbers in brackets designate References at end of paper.

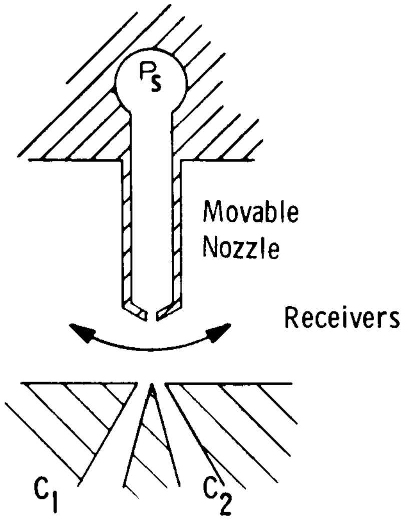


FIGURE 1 — Jet Pipe Valve

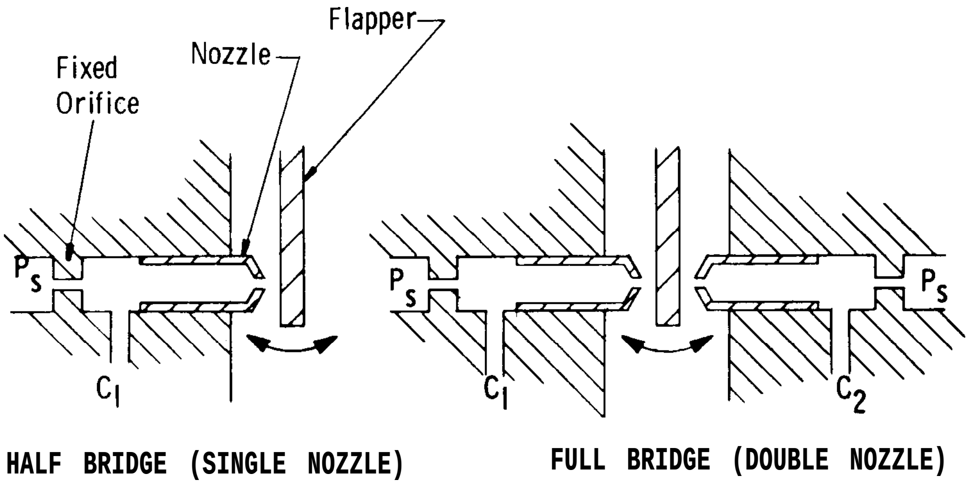


FIGURE 2 Flapper-nozzle Valve

Several attempts at closed loop electrohydraulic control were made, of which the Tiebel [2] patent illustrated in Fig. 3 gives a typical example. Here mechanical motion signals from a rate gyro are summed with motions generated by a DC motor that, in turn, electrically sums signals from an attitude gyro with inner loop feedback of cylinder position. The resulting error signal moves a four-way sliding spool providing correcting flow to the cylinder.

POST WAR DEVELOPMENTS

Electrohydraulic servomechanisms made an important jump as a result of World War II, for several reasons:

- The pace of hardware development (materials, fluids, electronics etc.) was accelerated by the heavy R & D efforts.
- Automatic control theory was developed and proven. It was documented and became universally accepted.
- A whole class of knowledgeable people who found automatic control challenging were turned loose in the post war commercial and aircraft environments.

Some of the post war developments in electrohydraulic components are dramatic, but most are evolutionary, involving improvements over existing limitations. The best way to understand these developments then is chronologically. The history of electrohydraulics during this period is really a history of the servovalve, its evolution and growth. By the end of the War, a servovalve was principally a sliding spool moving inside a sleeve which served to meter hydraulic flow. The spool was moved by a direct acting motor, usually a DC solenoid. Proportional control was achieved by causing the solenoid to act against a spring and varying the motor current to cause a change in position, hence valve flow.

In 1946 Tinsley [3] of England patented the first two-stage valve. It used a direct acting solenoid to drive a spool for the first stage, which then drove the second spool stage with differential pressures. This was an early attempt to overcome the low force levels in single-stage valves and provide better hysteresis with less environmental sensitivity.

Shortly afterwards, this was improved upon by Raytheon and Bell Aircraft [4] who developed two-stage valves that implemented feedback from the second stage by causing the first-stage bushing to follow the second stage motion (direct mechanical follow up).

About the same time, the Dynamic Analysis and Controls Laboratory at MIT [5] added two improvements to the two-stage valve. The first was the use of a true torque motor (a permanent magnet, variable reluctance actuator), instead of a solenoid, which results in a significant power savings and an improvement in linearity. Second was the use of a spool position transducer to electrically feed back second-stage position. The use of electrical feedback in a high gain loop helped to reduce the effect of high friction levels at the first-stage spool, and thereby improve the

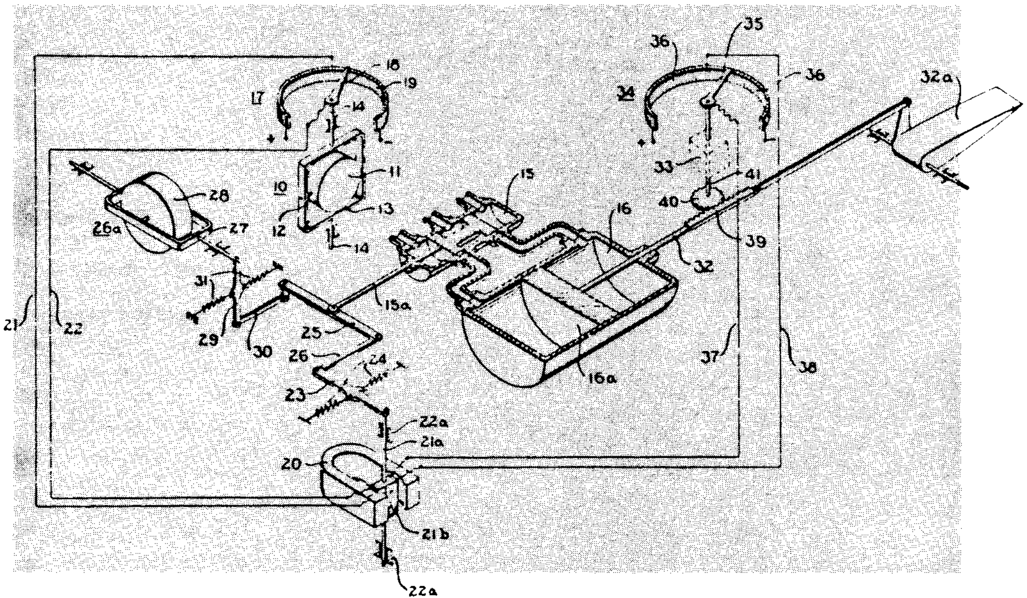


FIGURE 3 — Tiebel Patent

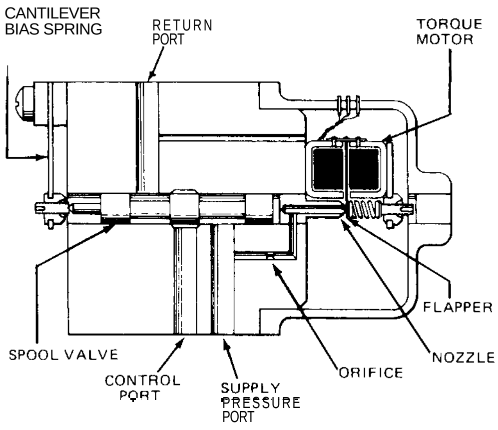


FIGURE 4 — Single-nozzle Two-stage Servovalve (1950)

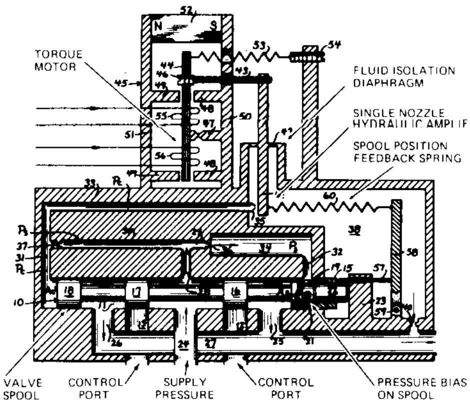


FIGURE 5 — Mechanical Feedback Two-stage Servovalve (1955)

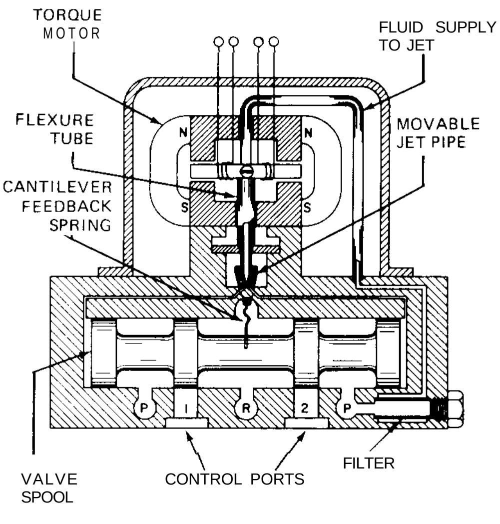


FIGURE 6 — Jet Pipe Servovalve (1957)

valve static characteristics. This friction effect is known as valve threshold.

In 1950 W. C. Moog, Jr. [6] developed the first two-stage servovalve using a frictionless pilot stage (Fig. 4). A flapper and nozzle variable orifice was used in conjunction with a fixed orifice to drive a second-stage spool in a three-way mode. The flapper-nozzle valve was driven by a torque motor, and spool position was achieved by a spring acting directly on the spool. The advantages of this construction were an appreciable reduction in valve threshold, and a high dynamic response because of the lower mass of the first-stage parts. Frequency response on the order of 90° at 100 Hz was possible allowing for the use of servovalves in high gain positron servos.

The use of mechanical force feedback in a two-stage valve was pioneered T. H. Carson [7] in 1953 (Fig. 5). A tension spring was used to generate force (torque) on the torque motor proportional to the spool position, thus closing a mechanical loop around the spool position. By combining the frictionless first stage with mechanical feedback from the second stage, he was able to improve threshold, improve dynamic response because of lower first-stage displacements, and reduce temperature and pressure caused spool position anomalies because of increased first stage gain allowed by feedback.

An improvement in environmental sensitivity was achieved by Moog [8] in 1953 with the introduction of a symmetrical, double-nozzle orifice bridge. This reduced environmentally caused null offsets. About the same time reliability was improved by Wolpin [9] who introduced a means of isolating the torque motor from the fluid.

In 1957 R. Atchley [10] devised a two-stage servovalve with a first stage based on the Askania jet pipe valve. This valve (Fig. 6) provided a single oil inlet path Instead of the dual path in flapper-nozzle valves, thus providing a measure of reliability for a particular failure mode.

Throughout this period a number of specialty devices were developed to speak to peculiar needs. Some of these include: servovalves with dynamically shaped pressure feedback for stabilization of resonant loads; redundant servovalves that detect their own failures and isolate them automatically; servovalves with positive pressure feedback to compensate statically for structural compliance; servo-actuators which vote between multiple inputs for redundancy; and three-stage servovalves for higher flow capacity.

MARKET GROWTH, AEROSPACE

Because of the evolution in hardware, the application of electrohydraulic servos has grown from a rather small, sophisticated market to a much larger, lower cost and less complex market which exists today.

The market origins were in the military, where electrohydraulics were originally used for radar drives, guidance platform drives, and controls for missile launchers. The high cost of early electrohydraulic servos, both in initial investment and reliability, was seen as a necessity for the performance achieved. Electrohydraulics were the exclusive purview of the military for the following reasons:

- Military budgets could afford the development costs.
- Improved performance was often the dominant goal of military equipment, and performance compromises were unacceptable.
- The staff required to do the analytical and design work in this technology was found mostly at military prime contractors, whether industrial or research oriented.
- The use of hydraulic power was common in many military vehicles.

Because of the successful early applications and the resulting pressure for better hardware, the list grew to include flight controls for missiles and radar antenna positioners. In aircraft, electrohydraulics were used for things like stability augmentation in flight control systems (where limited authority automatic control was added to the manual flight controls) and in dynamically tuning magnetron cavities for radar generation and anti-jamming protection. Helicopters became an early proving ground for electrohydraulic servos because of their critical need for stability augmentation.

The advent of the space age, especially with the magnitude of activity in the late 50's and 60's, brought a new field with conditions similar to those just mentioned, plus the need to position very large masses at high speed together with an unprecedented demand for reliability. The primary use of electrohydraulics was in flight control. Control was achieved by vectoring the basic thrust of the vehicle, whether moving the nozzle of a liquid or solid rocket engine or the entire motor on some solid rockets, or by directing the exhaust stream either with liquid secondary injection orthogonal to the stream or by positioning vanes in the stream itself. Electrohydraulic servoactuators have been used for guidance and control by one of the above schemes in almost every space launch vehicle. Beyond the launch vehicle itself, however, little need exists because of the low power and low dynamic requirements of orbiting vehicles.

The space program, in addition to broadening the base of the available market, brought a demand for more reliable hardware in all areas: electrical, mechanical and hydraulic. This led to the development of more reliable components as well as new techniques for achieving reliable performance, and new methods for inspection and quality control of manufacturing, all of which have led to better hardware and greater acceptance of the control medium. Some of the most complex examples of redundant flight controls are evident in the space shuttle orbiter and launch vehicle. Four channels of information and control are summed hydraulically with appropriate sensing and shutdown logic in each flight surface power actuator.

Meanwhile, a whole new generation of high performance aircraft was evolving, accompanied by new demands and new problems for fluid power control. With the increase in size, speed, and cost of commercial transport aircraft came the necessity to fly under adverse weather conditions (Category 3 landings), hence the need for more reliable flight control systems. The solution involved high power, high authority flight controls in redundant groups of three, such that a single failure could not cause failure of the system. The SST added a new dimension to the problem because of its changing aerodynamic stability with speed and loading. The supersonic transport required an automatic flight control system (stability augmentation) that was operating full time, and resulted in development of four-channel "voted" servomechanisms. In spite of its demise, the Boeing SST has an impact on the development of flight control servos. The current generation of military aircraft has been designed to take advantage of this thinking. By designing an aircraft with marginal stability, it can be made much more maneuverable and produce less drag, thereby using less fuel. However, it must then have a full time automatic flight control, which means redundant electrohydraulic servoactuators.

INDUSTRIAL

About the same time, the late 1950's, the industrial marketplace was creating a demand for electrohydraulic servos. One of the first major users was the machine tool Industry. Numerical control and computer control of milling machines was just beginning, and electrohydraulics were used in most of the early machine table positioning servos. These were typically hydraulic servomotors, used to turn lead screws, directly replacing the human operator. As NC control expanded to Include riveting machines, punch presses, nibblers, tube benders etc., so did the need for electrohydraulic servos.

The machine tool market, while not demanding in the same way as military and space applications, brought a whole host of new and different requirements to the fluid power industry. The pressures of cost and reliability brought about new manufacturing techniques and standardization. Hydraulics were viewed as messy and excessively sensitive to dirty environments, and this led to the concept, or problem, of mass education of the users of hydraulic equipment. This in itself did much to spread the marketability and acceptance of electrohydraulics.

More sophisticated industrial applications were a direct result of the military influence, principally in the testing field. An early combination of both was the use of electrohydraulic servos in flight simulators. Electrohydraulics are used for motion control of six degree of freedom aircraft simulators and for generating stick reaction forces for the pilot. The need for large dynamic forces in structural testing aircraft flight surfaces, missile components, and environmental testing of avionics equipment led to the development of high response, high force testing devices. Dynamic test equipment has since grown into an industry of its own where, today, everything from automobiles to shipping cartons are tested on electrohydraulic shakers.

Non military industrial applications have sprung up in a wide variety of areas in the past three decades. Some of these are worthy of note because of the contribution to control technology; some, just because of their uniqueness. Industrial automation; that is, the mechanization of specialized manufacturing processes or the control of these processes by a stored program, was a logical outgrowth of the NC efforts. The number and types of these control systems are almost limitless, but a few are a particular note. Prominent among these are controls for industrial robots. Robots came of age about 15 years ago, bringing a new dimension of automation to many industries. While early robots required very little unique from electrohydraulics other than economy, recent developments (especially in the area of precision assembly robots which have the ability to follow contours and incorporate tactile feedback) do begin to press limits of technology.

A second area is in processing of plastic. This is a relatively young industry, thus tends to move faster with respect to new processing techniques. Because of the high forces needed, hydraulics were a natural for early injection molding and blow molding machines. The wider use of engineering plastics, and the higher cost of raw material, have led to a demand for servocontrol in both injection and blow molding in order to improve part quality with a minimum amount of material. A related field, die casting, has also demanded precision control over what was previously a relatively brute force process, and hence turned to electrohydraulics. Injection molding and die casting have accelerated the development of higher flow servovalves.

A unique application of electrohydraulics is in the Vibroseis[2] field. This is a means of oil exploration where the geological signature of the ground is taken by simultaneously vibrating the ground in two or three locations at various frequencies and measuring the reflected energy. These exciters tend to be very high frequency, high power devices, and have resulted in higher flow, higher response servovalves to meet the need.

Turbine controls, both gas and steam, are large users of electrohydraulic servos and have made demands on system components that have resulted in better reliability.

A natural consequence of the industrial application of fluid power servo control, was the automation of mobile equipment. While fluid power is relatively common in agricultural and construction equipment, electrohydraulic servocontrols are not. One of the first uses for electrohydraulic servocontrol was for road grading and paving and railroad bed maintenance where loops are closed around level sensors and position transducers following guide wires to generate motions of large road grading or paving machines, or curb pavers.

More recently, the use of electrohydraulic servocontrolled hydrostatic transmissions has opened up whole arenas of possibility for automatic control. While the use of hydrostatic transmissions is

---

[2] Trademark of Continental Oil Company.

not new, the development of low cost pumps and motors specifically for transmission uses, and compatible servomechanisms to precisely control swashplate position, creates a new dimension in fluid power control. A variable displacement pump/motor combination is highly efficient in comparison to a servovalve (which is a throttling element), so servocontrol of a pump/motor provides fluid power control at power levels well above that achieved with servovalves, but at some sacrifice in performance. Specifically, dynamic response suffers due to compliance of the entrapped fluid between the pump and motor, and static positioning accuracy is poor due to the characteristically high coulomb friction of rotary hydraulic motors.

Hydrostatic servos have been used as open loop control elements in heavy construction equipment and agricultural vehicles. By closing a feedback loop around the transmission, various parameters such as speed, horsepower, or torque can be controlled. This allows use of hydrostatic servos in machine tool spindle drives, cranes and hoists, tracked vehicle steering systems and power take-offs.

TODAY

In order to appreciate where electrohydraulics is today, it helps to summarize the technology as it exists. Typically, there are two dominant performance parameters that can be used to classify most electrohydraulic servos. One of these is size, that is power or flow rate, and the second is dynamic response. For convenience we can represent power as the primary power required to the control device, and represent dynamic response by the dynamic performance of the control element. Fig. 7 shows a graph where the ordinant is power level and the abscissa is frequency. In order to appreciate size, the ordinant is also calibrated with the load flow available at 1000 psi. Note that these axes are logarithmic.

There are three dominant regions to this graph. The major region represents the range of power.response where electrohydraulics are generally used. At lower power levels and lower frequencies, other means are usually more satisfactory, such as direct electromechanical control, or electropneumatic, and in many cases non proportional control. The region of high power and high frequency represents requirements beyond the present level of technology. Within the major region of normal electrohydraulic control, several zones can be indicated where various forms of control are dominant.

Note that this region encompasses about three decades of frequency and power. The low power, high frequency demands are typically satisfied by single-stage servovalves and represent instrument type servos. The high power, low frequency demands are often those where remote control is a more important criteria than performance, and these are often satisfied with hydrostatic drives. Technically, the requirements above 2 in^3/sec (cis), or $\frac{1}{2}$ gpm, are satisfied with two-stage servovalves, and above 50 gpm with three-stage servovalves. The single-stage valves are, of course, the highest response, while three-stage valves are slower, and hydrostatics the slowest.

It is interesting to plot commercially available servovalves on this graph. A specific valve should be able to satisfy a requirement below and to its left, however it may be larger and more complex than necessary. As a result, there are many sizes and configurations of available servovalves that fill the shaded region.

Of more interest, though, is to designate the areas of typical applications. This is done in Fig. 8 for some typical commercial applications and in Fig. 9 for corresponding aerospace applications. The application labels are not meant to be restrictive, but rather to indicate characteristic areas. For example, there are watchmaking machine tools that use low flow servovalves with 500 Hz natural frequency, and there are large spindle drives in the 50 horsepower category that use hydrostatic drives. Yet, the majority of machine tool servovalves fall around 100 Hz and 5 to 20gpm.

AREAS FOR GROWTH

While it would appear that electrohydraulic servocontrols have reached a point where a major change seems unlikely, remember that their history has been one of evolution with few major changes. There are still several expected areas for growth.

- Higher Pressures — today capability exists for 4000 psi and higher hydraulic systems, though systems are commonly limited to 3000 psi. Since higher pressures represent better power and weight efficiency, we should see a trend toward higher pressure systems as better components are developed.

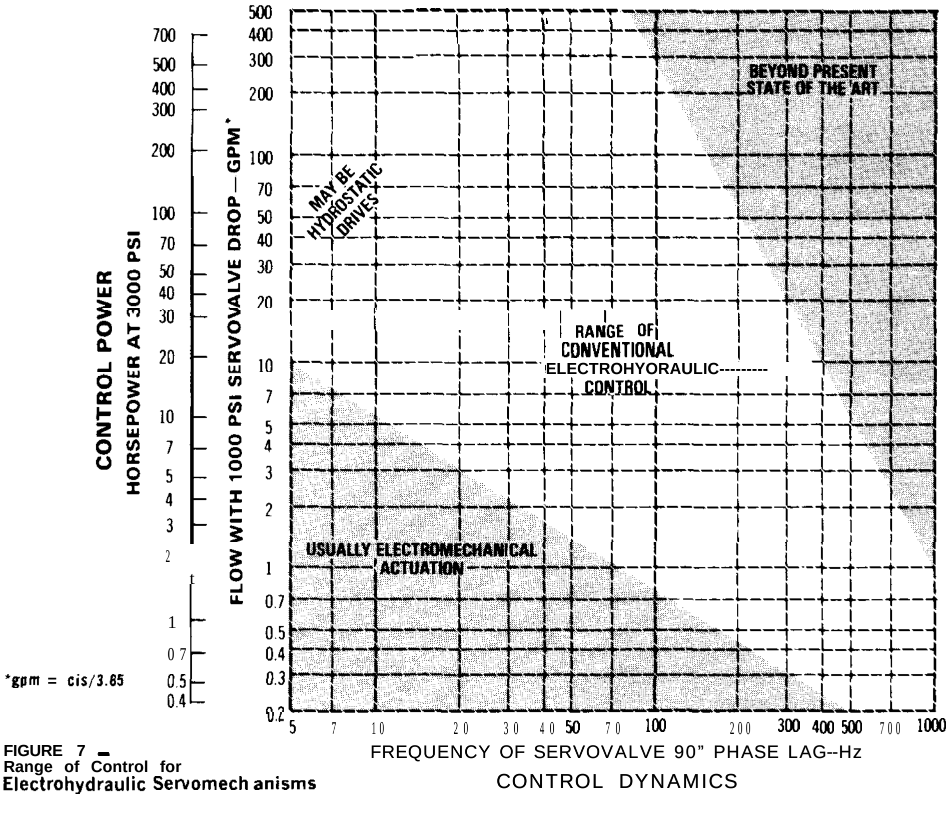


FIGURE 7 — Range of Control for Electrohydraulic Servomechanisms

- Higher Flow — the trend to automate higher power processes (such as die casting) will continue, coupled with the desire to go faster with existing systems for improved cycle time or efficiency. These will present demands to replace existing servovalves with those of higher flow capacities.

- Lower Cost — as fluid power technology moves downward into less sophisticated and more cost sensitive markets, there will be pressure to supply components to today's standards but at lower cost. One cause for this will be choosing electrohydraulics for reasons such as safety or operator convenience, rather than for performance. Since many of these potential areas represent a large market, the chances for volume production, hence lower cost, does exist.

- Better Response-frequency response represents a technical frontier to today's servovalve, and probably the greatest technological challenge. The need for higher response will be felt where servos must interface at the power end with electronics, for example in radar drives, laser pointers, and in the material test field.

- Energy Savings — as we become more energy conscious, brute force solutions will no longer be acceptable and control systems will be evaluated by their efficiency. The challenge is to avoid over-designing fluid power systems, and use smarter controls to average the demands or limit horsepower draw.

REFERENCES

1 Mayr, O., Origins of Feedback Control, MIT Press, 1970, p. 11.

2 U.S. Patent 2,234,326 H. W. Tiebel filed November 1939 — issued March 1941.

3 English Patent 620,688 Tinsley applied May 1946 — accepted March 1949.

4 Boyar, R. E., Johnson, B. A., and Schmid, L., "Hydraulic Servo Control Valves," WADC Technical Report 55-29, Wright-Patterson Air Force Base, Ohio, 1955, p. 23, 35.

5 Blackburn, J. F., Reethof, G., and Shearer, J. L., Fluid Power Control, The MIT Press and Wiley, 1960, pp. 403.406.

6 U.S. Patent 2,625,136 W. C. Moog filed April 1950 — issued Jan. 1953.

7 U.S. Patent 2,934,765 T. H. Carson filed Sept. 1955 — issued Apr. 1960.

8 U.S. Patent 2,767,689 W. C. Moog filed May 1953 — issued Oct. 1965.

9 U.S. Patent 3,209,782 M. P. Wolpin filed May 1955 — issued Oct. 1965.

10 U.S. Patent 2,884,907 R. D. Atchley filed Aug. 1957 — issued May 1959.

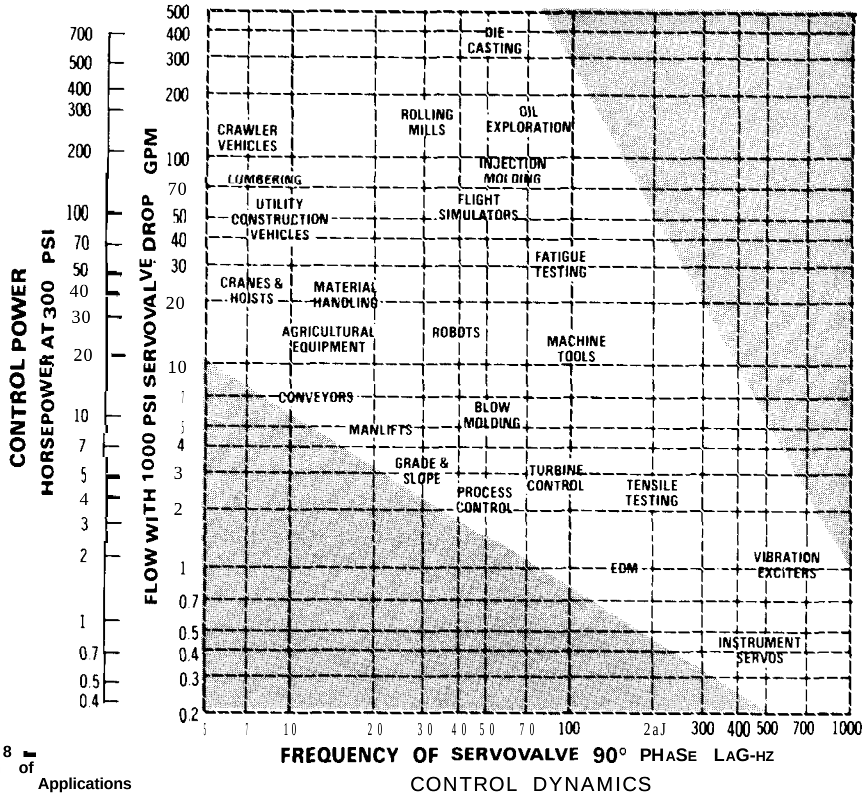


FIGURE 8 — Spectrum of Industrial Applications

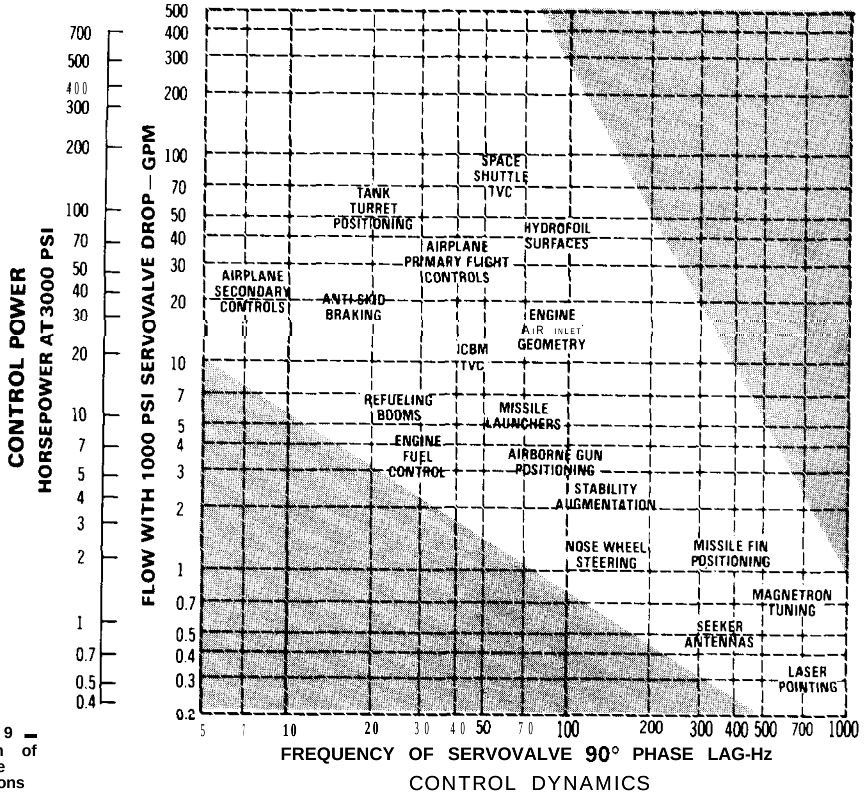


FIGURE 9 — Spectrum of Aerospace Applications