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ELECTROHYDRAULIC SERVOACTUATOR USING DIGITAL INPUT SIGNALS

Günter Diessel

FEINMECHANISCHE WERKE MAINZ GMBH
MAINZ, WEST-GERMANY

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by
Günter Diessel
Feinmechanische Werke Mainz GmbH
Mainz, West-Germany

ABSTRACT

Digital signal structures will be more and more introduced in military and commercial aircraft and helicopters for flight control. It is logical to maintain this structure also into the electrohydraulic actuators, thus eliminating digital to analog conversion in the input channel and to digital conversion in the feedback system.

In the past numerous attempts have been made by different *manufacturers to develop actuating* systems which accept digital input signals. Some of these actuators use conventional analogue electrohydraulic servovalves, however, the actuator control unit is completely digital. Others use switching valves which directly control the actuator or supply fluid to binary coded pistons.

This article deals with an actuator using two fast-switching valves and a second stage spool valve that controls fluid to the actuator. The advantage of this arrangement is in the good resolution and the pulse-free movement of the actuator combined with acceptable dynamic performance and a high reliability of the system.

1. Introduction

The development of control engineering in the recent years is charcterized by the introduction of digital computers for flight control systems. Control systems with digital computers do not only offer the processing of the pilot's input signals in fly-by-wire controls but also the processing of specific flight parameters. These control systems provide more flexibility, because they can easily be adapted to a variety of flight conditions and they can accomplish several functions at the same time such as stability augmentation and auto-pilot functions.

Therefore there is a current trend to replace analog control systems by their digital equivalents. Modern avionics and fly-by-wire computers already use digital signal structures. These structures eliminate signal conversions and allow for simplification of the monitoring systems.

In order to keep up with these trends and to take full advantage of digital structures the manufacturers of hydraulic and flight control equipment as well as research institutions have been trying to develop an electrohydraulic servoactuator concept which is compatible with digital technology. The interfaces play an important role between the digital computer, the electronic actuator control and the electrohydraulic servoactuator. These interfaces may have an effect on reliability, resolution and dynamic performance of the controlled system. One of these concepts and the developed hardware will be described in this paper.

2. Digital Actuator Designs

Within the last 25 years a great number of developments of digital actuators have been performed. It cannot be within the scope of this paper to describe or evaluate the results of these developments, however, at least a brief survey should be given in order to facilitate the evaluation of the concept and hardware of the actuator to be described later on more detailed.

2.1 Charcteristics of Digital Controls

Because it is difficult to distinguish digital control mechanisms according to different designs and system techniques, they must be distinguished according to signal structure. Therefore the breakdown results in

- parallel -digital control
- incremental-digital control

The **parallel-digital signals**, often called "absolute digital signals", are prepared by coding devices, for instance binary coded, so that after a signal is fed into the actuator, the entire input information (lead valvue, set point) is generated during the same time interval in the electrohydraulic valves.

The incremental digital signal reflects only a change in switching state. To reach a given position or velocity of the actuator output, a chronological sequence of single pulses in the form of a pulse train is required.

A slight deviation from the incremental digital signal and from the pulse train is the

pulse modulated signal

whereas this modulation can be either

- pulse amplitude modulation (PAM) or
- pulse width modulation (PWM) or
- pulse frequency modulation (PFM) or
- differential pulse modulation of the above three versions (DPAM, DPWM, DPFM)

2.2 Parallel Digital Actuators

This kind of actuator is being used for special applications, mainly for positioning.

2.2.1 Torque Motor with Binary Coded Coils

The torque motor of a conventional servovalve is equipped with a number of coils, each creating a torque which is half of the torque of the following coil. The sum of the torques and therefore of the spool positions is 2^n, where n equals the number of coils (30) .
The piston position is proportional to the sum of the input signals into each coil.

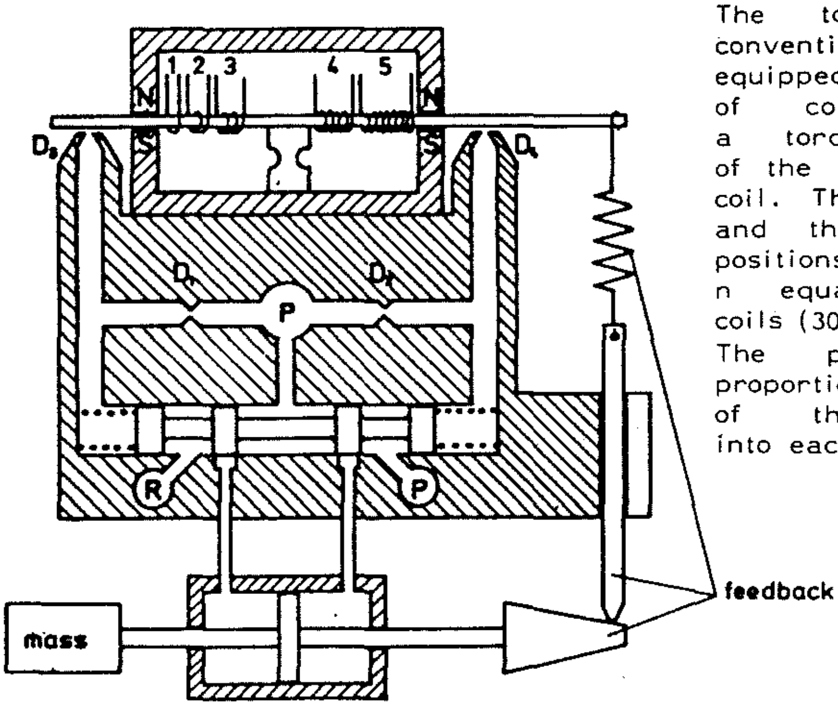
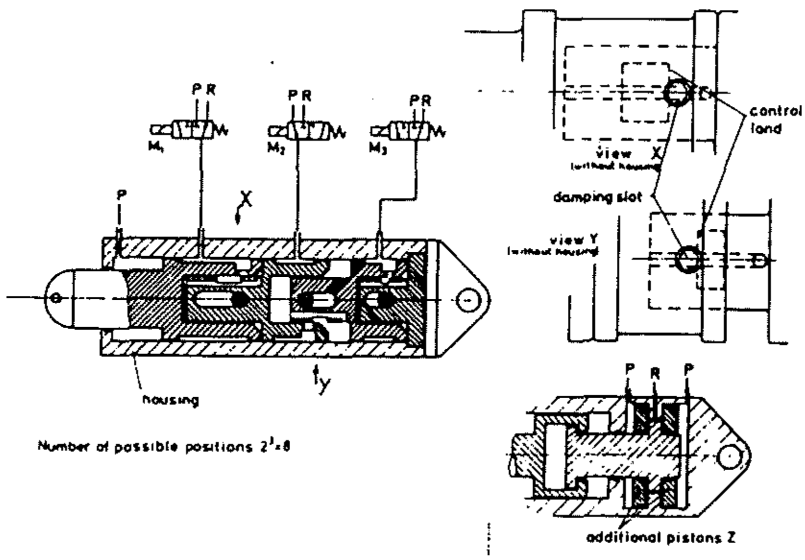


Fig. 1: Binary Coded Coil

2.2.2 Actuator with Fixed Point Control



The number of positions is equal to the number of pistons and their solenoid valves, whereas the stroke of each piston is half of the stroke of the following piston.

The dynamic response depends on the switching time of the solenoid valves and the velocity of the single pistons relative to each other. If the velocities are also binary coded the response is equivalent to that of an analog actuator The response is not acceptable for direct actuation under external loads (4), (4a), (10).

Fig. 2: Binary Coded Piston Strokes

2.2.3 Actuator with Digitized Fluid Volumes

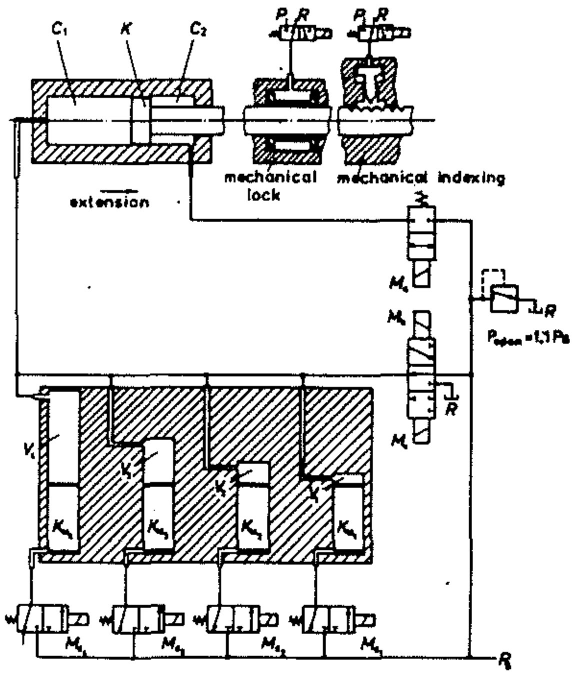


Table of state

	M	M	M	M
stop	off	off	off	off
extend	on	off	on	on
prepare retract	off	.on	off	on
retract	on	off	on	off

Fig. 3: Digitizer Piston

The stroke of the piston is determined by the volume of the fluid each digitized piston supplies. Each Digitizer Piston is activated by its correspondant solenoid. The fluid volumes of the digitizer pistons are binary coded. Two separate solenoid valves provide, directional control.

Due to stiffness problems and to the high number of solenoid valves this configuration cannot be applied to surface and rotor control (9), (10a).

2.2.4 Fixed Point Control

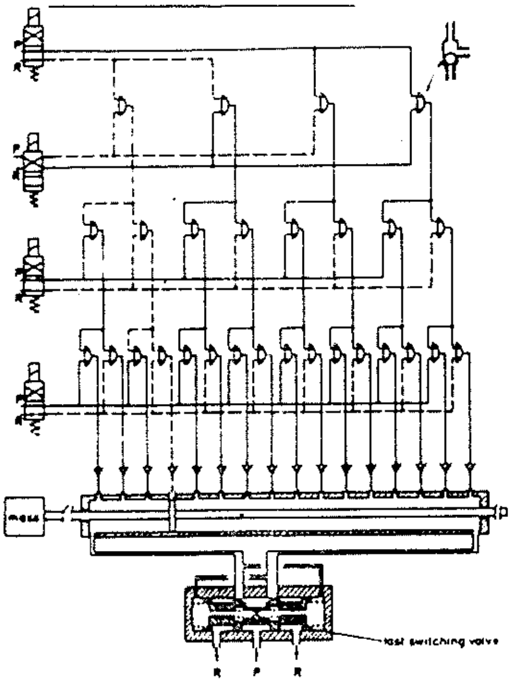


Fig. 4: Outlet Position Control with Decoder

The actuator piston moves into a position related to the port which is connected to return. In this position it remains due to equal forces acting on both sides of the equal area, thus resulting in high stiffness.

The number of **positions** is proportional to 2^n, whereby n is the number of the solenoid valves.

The position of the switching valve is defined by the position of the decoders (10a).

2.2.5 Evaluation of Parallel Digital Actuators

In addition to the four examples there are several other developments. One of these configurations use a so-called four-land outlet position control, where the piston is mechanically connected to the spool which closes the supply or the return port (10a) . Another system uses a rotary valve, the ports of which are opened by solenoid valves (10a), (13).

In all cases the resolution of the actuator is defined by the smallest stroke possible. For a given actuator stroke the number of solenoid valves will increase the smaller the resolution is. This is the major disadvantage of parallel digital actuators. Another disadvantage is the influence of changing loads on the actuator's dynamics. And finally the required precision in manufacture is very high. Even for sophisticated actuators, the ports, valves and pistons — which are not binary coded and therefore need less solenoid valves — the manufacturing efforts are enormous (14), (31).

These disadvantages are not being compensated by the advantages which are reliability and no need of feedback systems.

2.3 Incremental Digital Actuators with Pulse-Sum Information

For this type of actuators the total information is represented by the algebraic sum of single pulses.

A typical actuator of this kind is the Electrohydraulic Stepping Motor (12), which uses an electrical stepping motor that drives a valve, the valve controls a motor or cylinder, the output position of which is mechanically fed back into the valve.

Fig. 5 shows a stepper motor using two solenoid valves which control the motor via a rotary valve. The output shaft of the motor is mechanically connected to the spool of the rotary valve. As soon as the port lands of the spool cover the slots in the sleeve the motor comes to a stop. Switching of the solenoid valve then opens the fluid passage to another slot and the motor starts again.

If continuous running is required for an additional mode of operation an arrangement per Fig. 6 can be provided (15).

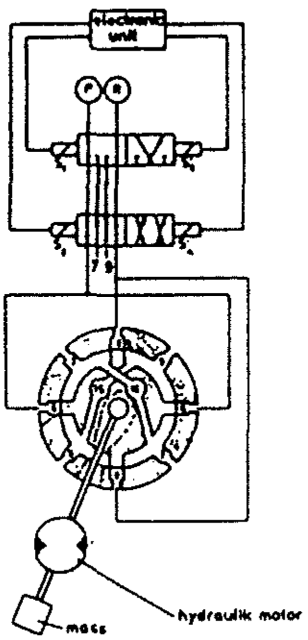


Fig. 5: Electrohydraulic Stepper Motor using solenoid valves

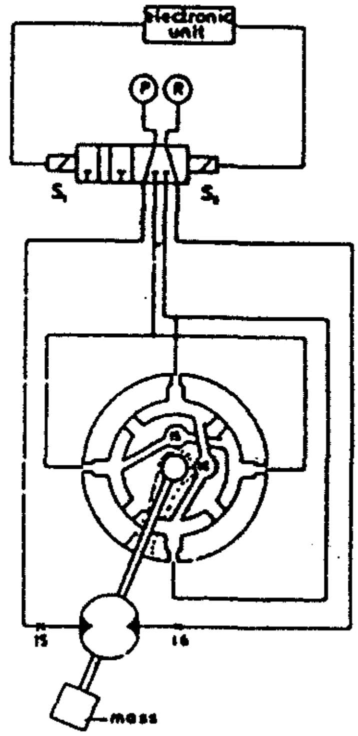


Fig. 6: Combined Stepper and continuously running motor

Incremental digital actuators cannot be applied to Primary Flight Control Systems in fighters or helicopters due to poor dynamic response . Therefore the different types of actuators shall not be discussed any further in this paper.

2.4 Digital Actuators with Pulse Modulation

While incremental digital actuators with pulse sum information only can be applied to actuation mechanisms with low dynamic performance, for instance flap and slat control, actuators with pulse modulated signals offer dynamic response almost equivalent to that of analog servoactuators.

The use of pulse width modulated signals became known in the late 1950 years. In 1957 Chubbuck (16) used a so-called acceleration switching valve, similar to the construction of a servo valve. Further experimental work was done by Sawamura, Hanafusa, Inui (17), who used a servo valve and a cylinder and pulse width modulated signals into the servo valve. Similar efforts are known from Gordan (18) Boddy (19), Tsai, Ukrainetz (20), Goldstein, Richardson (21).

The results of these developments were satisfying with regards to resolution, linearity between input and output signal and frequency response.

Due to the quiescent internal leakage and the costs as well as other disadvantages of two-stage servo valves several attempts have been made to employ fast-switching solenoid valves for electro-hydraulic servo actuators using pulse-width modulated input signals (22), (23), (26). All these developments are still remaining in the laboratory and experimental stage. Only for missile applications hardware has been introduced using hot or cold gas as a fluid medium.

2.4.1 Signal Configuration

The analysis of the different kinds of pulse-modulated signals has resulted into the selection of the "differential pulse-width modulation" This signal type is most suitable for quasi-continuous control of fluid flows, because the number of switching cycles of the valves is lower, thus offering lower flow pulsations. Characteristical for the differential processing is zero output signal at the modulator at zero input signal.

2.4.2 Valve Requirements

The mathematical analysis of servo actuators with pulse-width modulated input signals has resulted in the requirements for the switching valves as per table 1:

switching times $\leq$ 1 msec

small dead times T_t and small switching on and off times T_s

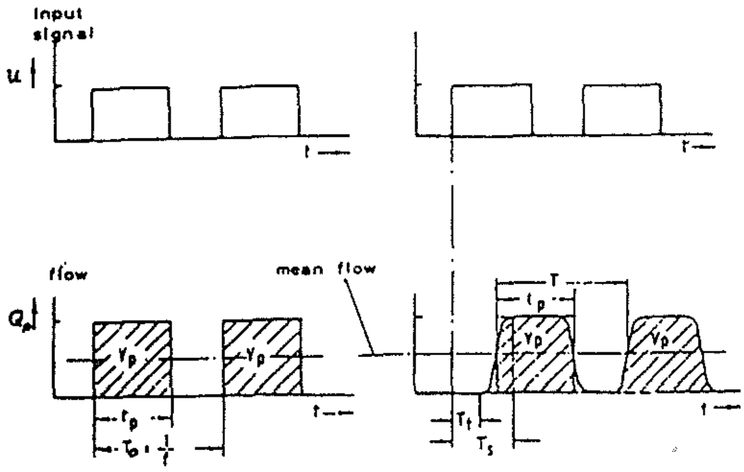
switching on and off times to be equal

reproduceable opening and closing features

independence of switching times from pressure drops across the valve

small internal leakage

Table 1: Valve Requirements



a) Ideal Valve

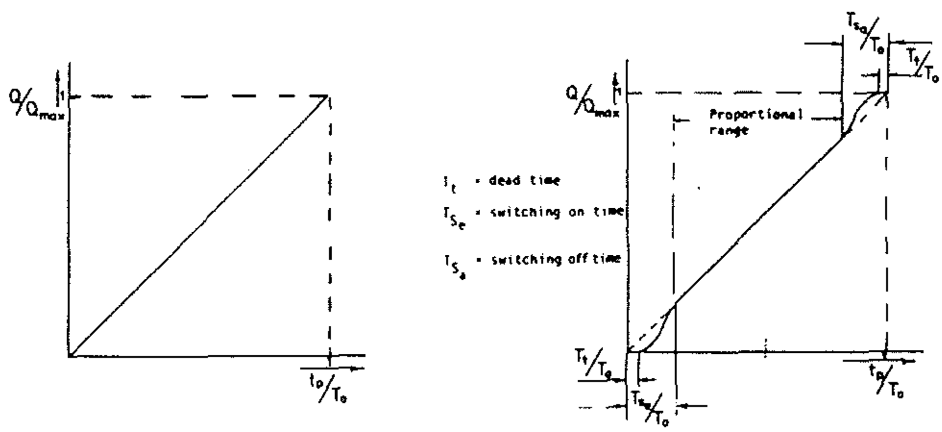
b) Real Valve

Fig. 7: Impulse versus time for ideal and real valve

Fig. 7 shows pulse modulated signals U time t and flow Q time t. The change in versus time for a real during opening and (of the valve depend electric, and magnetic fe as well as on mech transition factors.

Fig. 7 shows that for equal opening and closing char teristics of the switching valve the flow values are equal for the ideal and real valve. If there are differences between two characteristics there will be no proportionalities betweee mean flow and the parameters of the pulse signals which c modulated such as pulse-width.

Fig. 8 presents the mean flow of the valve versus the keying It is obvious that the opening and closing characteristics c real valve influence the range of modulation to such an exten only a certain part of the characteristic curve offers proportior



a) Ideal Valve

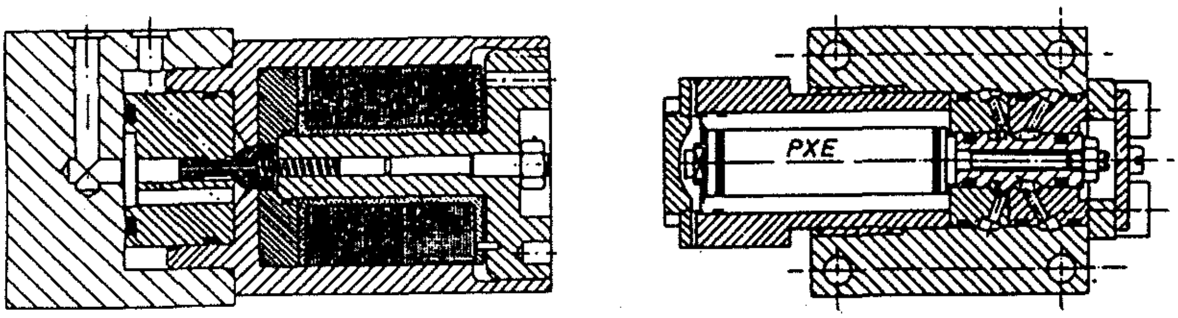
b) Real Valve

Fig. 8: Influence on Flow of Real Valve Characteristics

Standard switching valves have relatively large switching These cause threshold for the controlled actuator. If there is a (nation of two valves, each of them controls an actuator int opposite direction, there would be a relatively large threshold (re span) when the actuator is to reverse.

The other important factors are equal switching on (T_{se}) ar (T_{sa}) times as well as reproduceable features. In order to eli the influence of switching times the digital computer takes care of the switching times and delays - provided they are equal and reproduceable - ,eliminates their influence and offers an approach towards an ideal valve.

Special emphasis therefore was extended to the development of switching valves with equal characteristics for both opening and closing. Fig. 9 a shows a solenoid valve, Fig. 9 b a valve with a piezoceramic transformer. Both valves are of the poppet and pressure balanced type. These valves meet the requirements as per table 1.



a) Solenoid Valve　　　　b) Valve with Piezoceramic Transformer

Fig. 9: 2/2-Way Pressure Balanced Poppet Valves

<u>Technical Data:</u>

	Solenoid	Piezoceramic
Rated flow, at Δp = 50 bar	0,65 l/min	0,6 l/min
Rated pressure	100 bar	
Switching Time	0,7 msec	0,3 msec
Internal leakage (viscosity $2{,}2 \cdot 10^{-2}$ $\frac{Nsec}{m^2}$, Δp=50 bar)		
when new: after $2{,}5 \cdot 10^{8}$ cycles	0,19 cm^3/min 0,21 cm^3/min	
Voltage	24 VDC	24 VDC
Electrical Power	40 Watt	$2 \cdot 10^{-3}$ Watt, when stationary
Current, when switched on	-	0,004 in A
Current, to charge during 0,1 msec	-	0,8 A , (within electronic control box)
Voltage, to charge during 0,1 msec	-	500 V
Average Power, during cycling with 100 Hz and 50% impulsewidth		10 Watt

Table 2: Technical Data of Switching Valves

2.4.3 Evaluation of Actuator Systems

To design a servoactuator with pulse-width modulated signals using discrete switching valves of the 2/2-way typ there is a number of possible solutions. Fig. 10 presents a systematics with 12 different solutions. The number of possible solutions using both 2/2-way and 3/2-way valves is considerably higher.

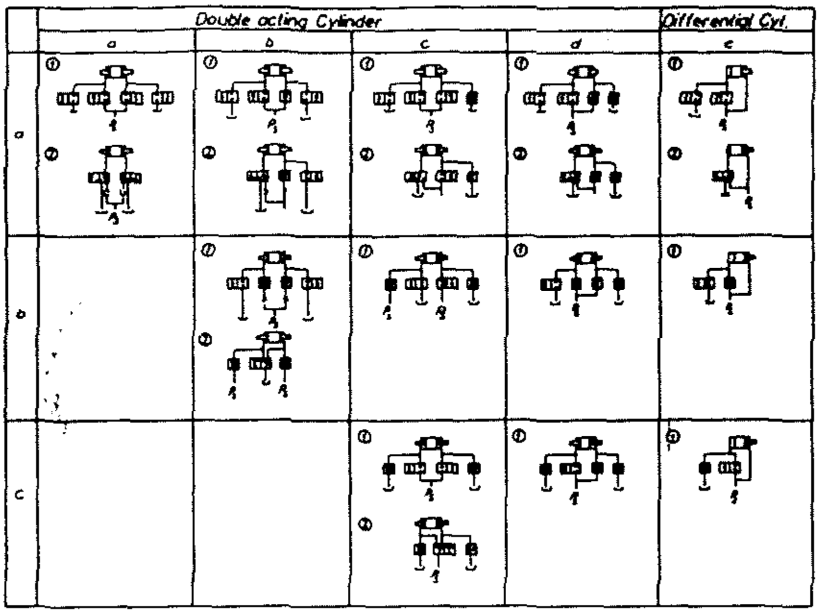
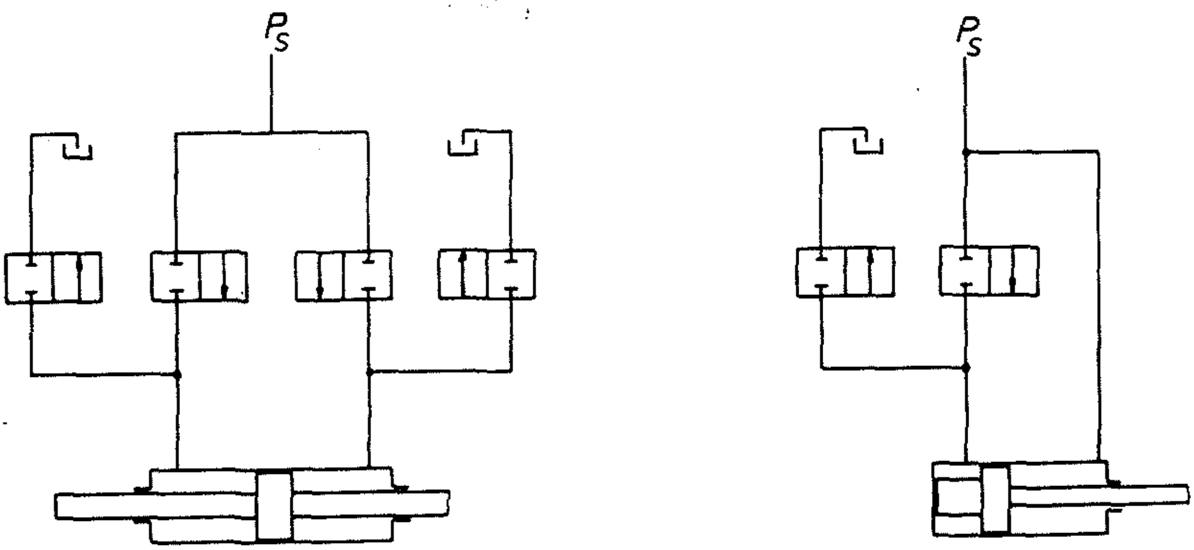


Fig. 10: Systematics of Actuator Design Principles

If equal motions in both directions of the actuator output and locking of the obtained position without continuous internal leakage are required, only 2 actuator versions are left, fig. 11.



a) Version a-a1, Double Acting Cylinder **b) Version a-e1, Differential Cylinder**

Fig. 11: Selection of Digital Actuator Principles

These versions do not require check valves to lock the piston in the desired position.

If the analog servovalve is replaced by two switching valves as per block diagram of fig.12, very fast switching valves and small loads at the actuator output do not solve the problem of pressure pulsation in the cylinder and of unstability of the system. Computer analysis and hardware tests have confirmed this fact (26), (28).

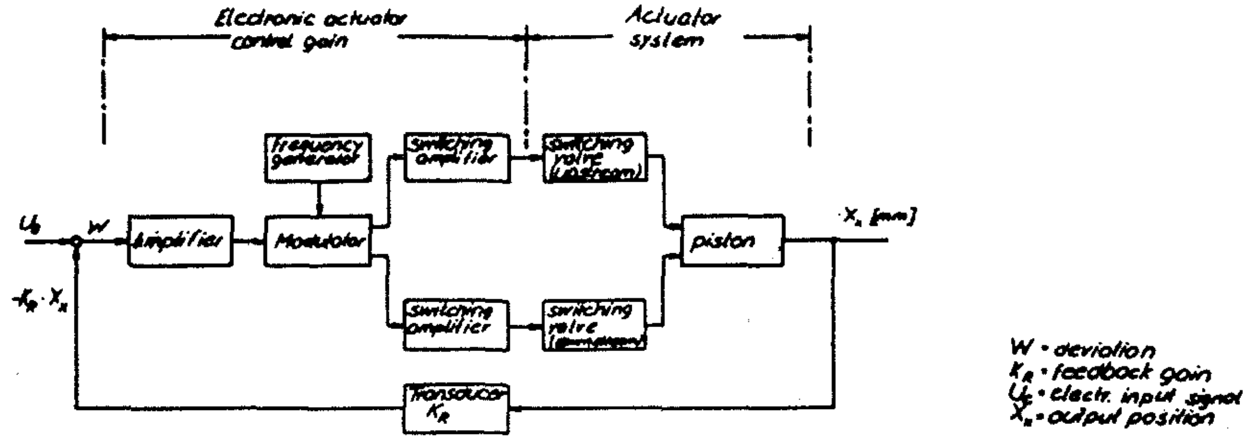


Fig. 12: Actuator with Switching Valves

The *digitized fluid volumes directly applied to the* actuator cause pulsations at the load which are unacceptable.

Several means are investigated to use an actuator concept per fig. 12 without the above mentioned disadvantages. One of them is an optimisation of the relation between the cylinder and the load and another one the introduction of hydraulic low-pass filters to obtain a low-pass behaviour, thus a smoothed and quasi-steady motion of the actuation output (26).

3. Description of the selected Actuator Concept and its Hardware

3.1 Concept and Design

The company Feinmechanische Werke Mainz GmbH, (FWM), has been involved in electrohydraulic digital actuation mechanism concepts since 1965. FWM has developed hardware and also evaluated different actutor concepts of other firms and institutions. It favors a solution as shown by fig. 13 and fig. 14.

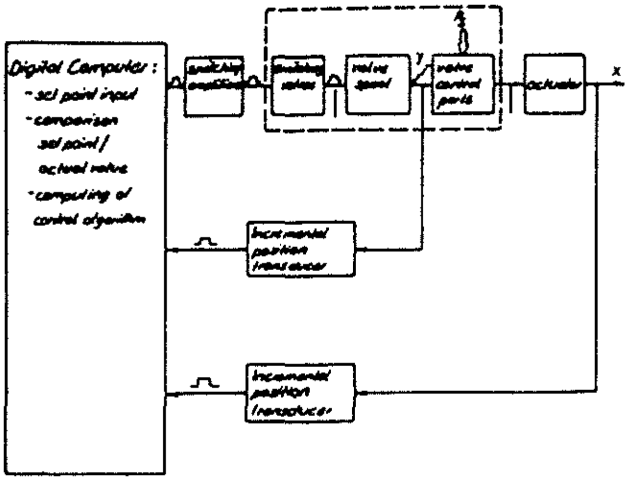


Fig. 13: Actuator Concept, Block Diagram

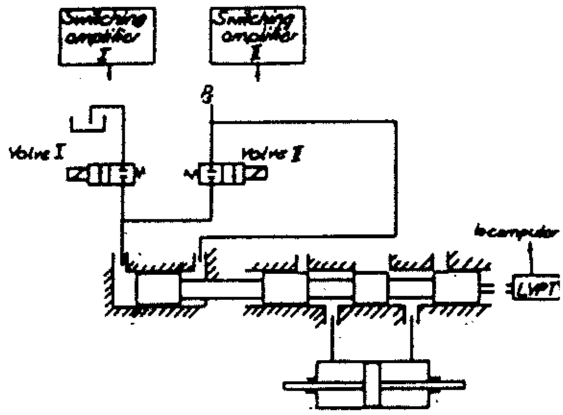


Fig. 14: Hydraulic Function

This concept corresponds to the principle a-e1 of fig.10 and as also shown in fig.11b. Two fast-switching valves control the position of a 4/3-way spool valv This is being accomplished by the piston of a differential actuator that mechanically positions the spool of the 4/3-way valve (27), (28).

The digital computer supplies electrical input signals to the two switching valves I and II. If valve I is switched off it blocks the fluid passage between the large piston area and the return line. Valve II blocks the supply line to the small piston area. If valve I is switched "On" system pressure causes the piston to move and with it the spool of the 4/3-way valve.

If valve II is switched on while valve I is deenergized, supply pressure at the large piston area causes the piston and therefore the spool to move into the other direction.

The spool's position is sensed and compared with the set point. The value of the difference defines the pulse width necessary to obtain the desired position in conformity with or close to the set point. The direction of the spool's movement and with it of the piston's movement is defined by energizing one of the two switching valves.

This internal closed-loop position control system is superimposed by an external control loop consisting of the actuator, position sensor and digital computer.

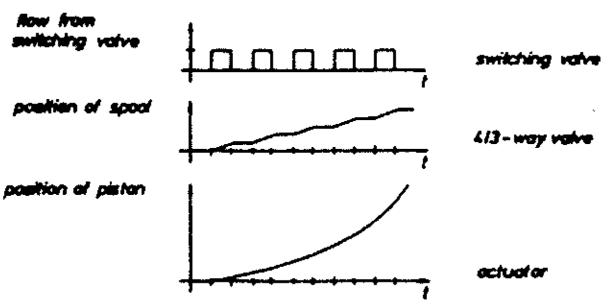


Fig. 15: Double Integration of Valve Opening Pulses

If the switching valve's characteristics would correspond to fig. 7a and if there would be no influence from friction, mass and fluid compressibility the spool of the 4/3-way control valve would move step by step as shown in fig. 15. In reality the valve has integrating features of the spool and the actuator, due to the influence of mass, friction, and fluid compressibility. The actuator output is quasi-analog.

The design offers high reliability with regard to the influence of contaminated fluid. The poppet valves have self cleaning effect, and the force acting on the spool is proportional to system pressure and piston area thus providing high chip shearing capability.

The digital actuator was designed and manufactured in order to prove the function and performance of the selected concept. The velocity and output force requirements were not specifically oriented at helicopter flight requirements.

3.2 Control Loop and Dynamic Response of the Control Valve

To control the position of the spool of the discrete controllable proportional valve, i. g. the 4/3-way valve, sample rate methods are being applied. Fig. 16 shows the block diagram of the control loop. The sample rate period Tp was choosen as the reciprocal value of the switching frequency of the switching (pilot) valves (28).

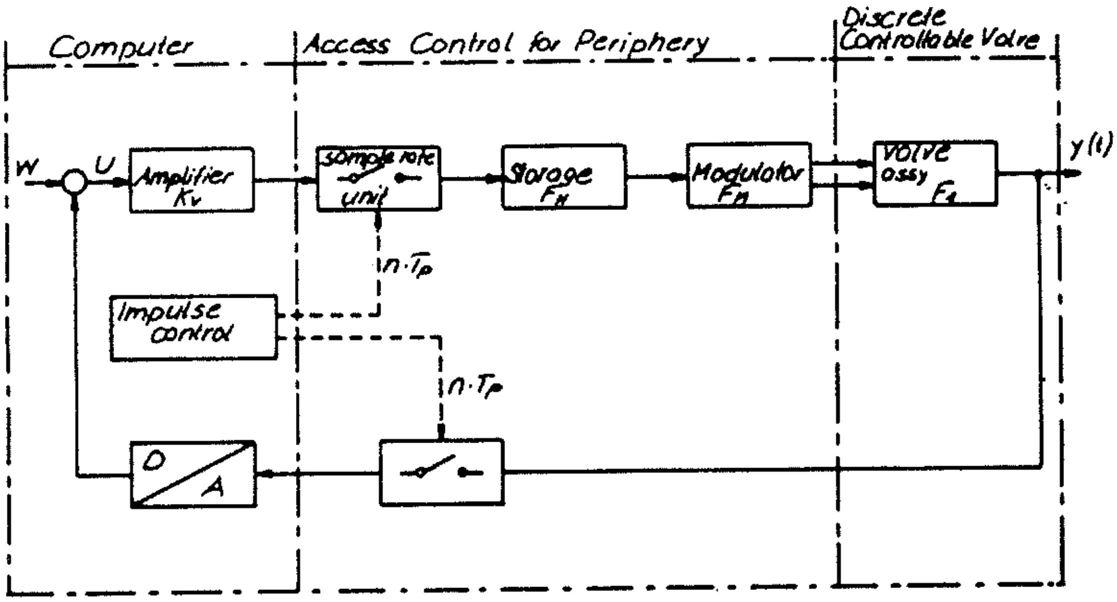


Fig. 16: Sample Rate Control Loop of Valve

The position of the spool was measured periodically at time intervals n · Tp. The difference between set position and measured position is amplified by a factor K_v and is being transferred to the output of the digital computer after having been passed through a programmed computing process. The output serves for modulation of the input pulses to the switching valves.

The value for the amplification factor (gain) K_v defines the transient response. Saturation as well as threshold values and sign digit are to be regarded.

Based on the switching time of the switching valves the minimum pulse width is τ_{min} = 0,7 msec. and the maximum pulse width is τ_{max} = 9,3 msec. The sample frequency is $f_p = 0,1 \frac{1}{msec}$, i.g. equal to the reciprocal value of the sample time of T_p = 10 msec. The maximum velocity of the spool derives from these values as $\dot{y}$ = 45 mm/sec and the minimum step as Δy = 0,003 mm.

The drift of the spool has been measured with closed switching valves obtaining 0,009 mm/sec. Between two sample points the displacement of the spool only becomes $0{,}092 \cdot 10^{-3}$ mm which is neglectible small compared to the smallest spool step of 0,003 mm. In order to compensate for this drift a new pulse has to be applied after 33 sample intervals.

Fig. 17 shows the transient response of the spool due to a sine curve of the set point with a frequency of 5 Hz, and K_v = 1,56 at p_s = 100 bar. The input signal is 100 % .

The pulses, the sine curve and the stepped spool displacement can be seen from the graph below.

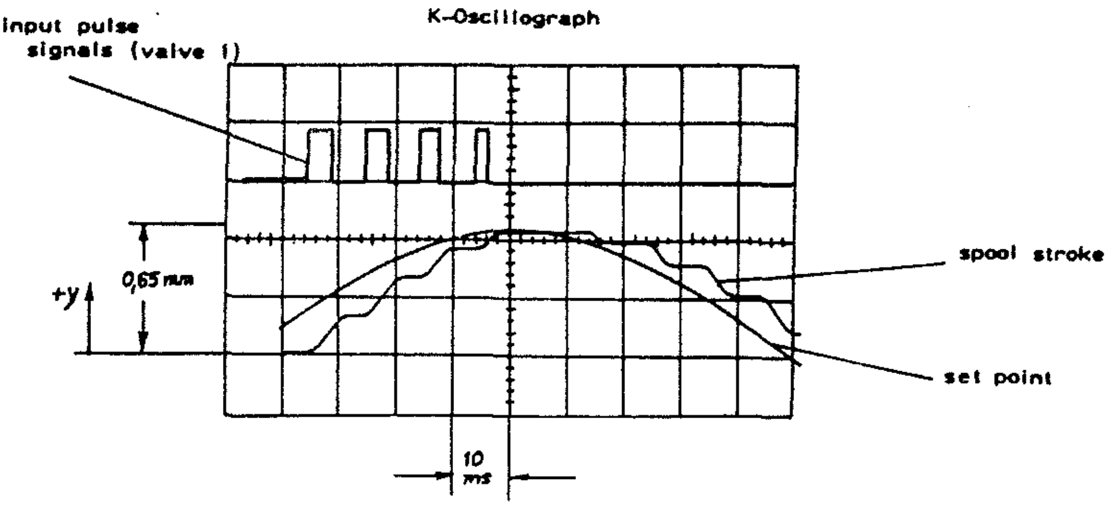
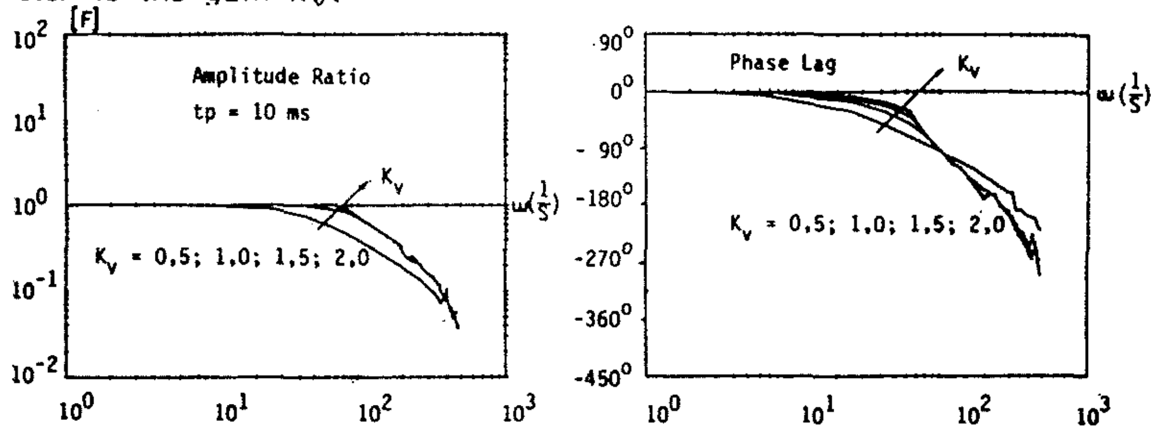


Fig. 17: Transient Response of Digitally Controlled Spool

The frequency response of the valve can be seen from fig. 18. Parameter is the gain K_v.



a) Amplitude Ratio

b) Phase Lag

Fig. 18: Frequency Response of the Valve

It has been proven that the noise of the valve does not exceed the noise of conventional valves. Pressure drop across the orifices and the flow derived from that define the noise.

3.3 Dynamic Response of the outer Closed-Loop Position Control System

The main purpose of the development was to obtain a good performance from a valve arrangement receiving pulse modulated input signals. Therefore no special emphasis was extended to the actuator control loop. It was built up by use of a conventional PID-Controller, see fig. 19.

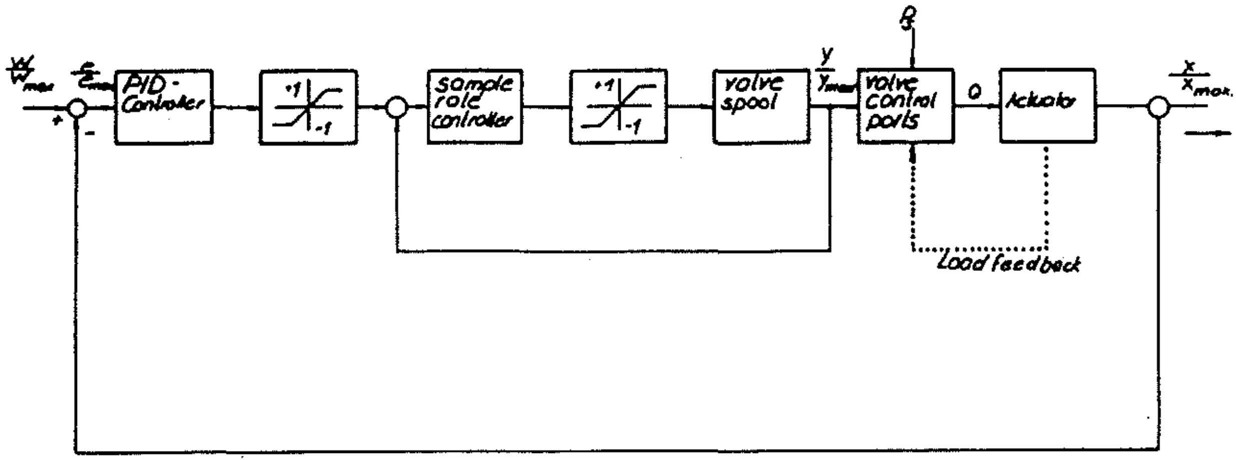
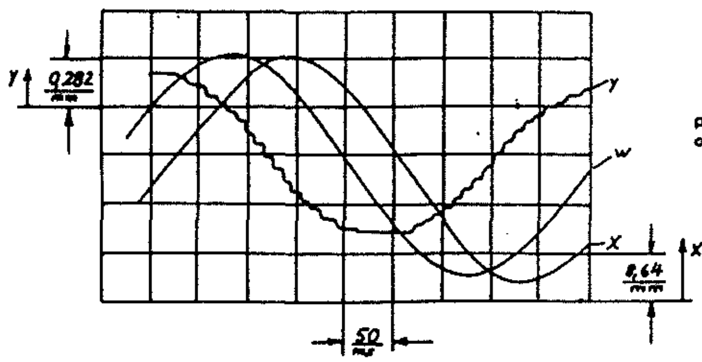


Fig. 19: Closed-Loop Position Control System

In order to evaluate the valve's transient response of the total servo actuator mechanism without having any influence from the PID-Controller only the gain Kp of the p-portion was adjusted for the further tests. The dynamic performance is shown in fig. 20a and 20b (28).



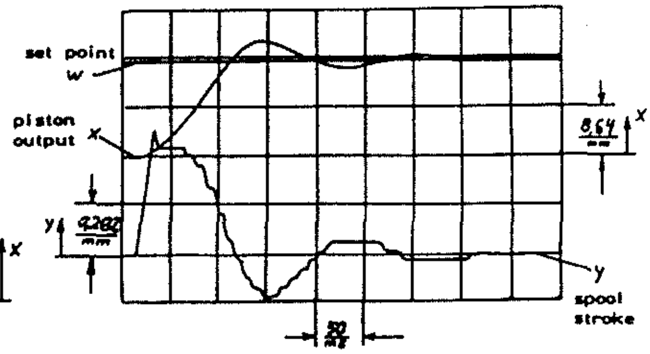


Fig. 20a: Actuator Response

Fig. 20b: Step Function Response

The actuator output is smooth due to integrating feature of the spool and the actuator. The actuator output does not show any pulsations or steps due to the integration by the valve's flow and actuator's motion, while the spool stroke is still stepped.

The frequency response (see fig. 21) was measured with 100 % input signal and with the p-controller. The gain K_R of the p-portion of the controller was changed.

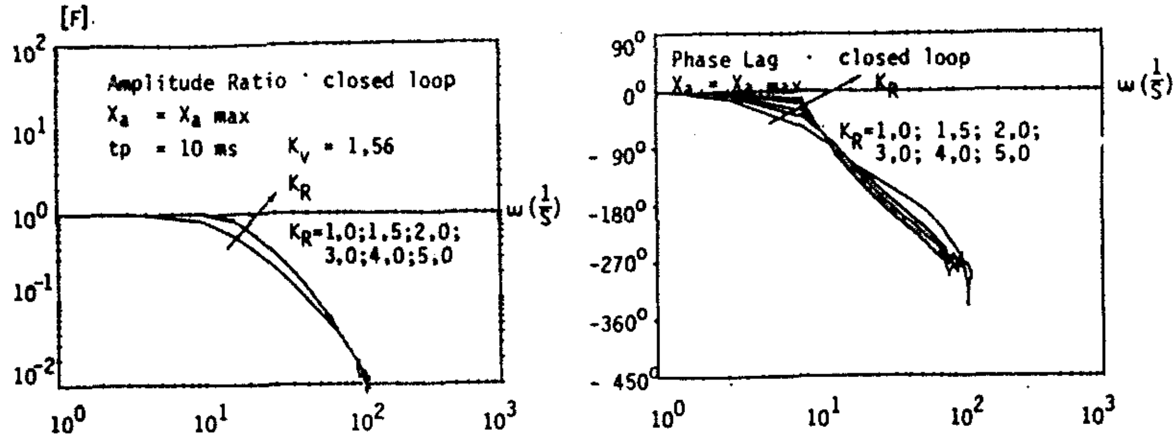


Fig. 21: Actuator Frequency Response

An increase of the gain did not influence the amplitude ratio and only improved the phase frequency characteristic.

The natural frequency is 3 Hz for 100 % input signal.

<u>Technical Data</u>

a) Discrete controllable 4/3-way valve:

Rated flow	Q_N	= 16 l/min at Δp = 10 bar
Stroke	y	= $\pm$ 0,65 mm
Diameter of drive piston	d	= 12 Ø mm

b) Actuator:

Piston Area	A	= 4,8 cm^2
Stroke	X	= $\pm$ 40 mm
Load (mass)	m	= 5 kg

Table 3: Technical Data of the Actuator

The laboratory model is shown in fig. 22. Housing and control valve are oversized.

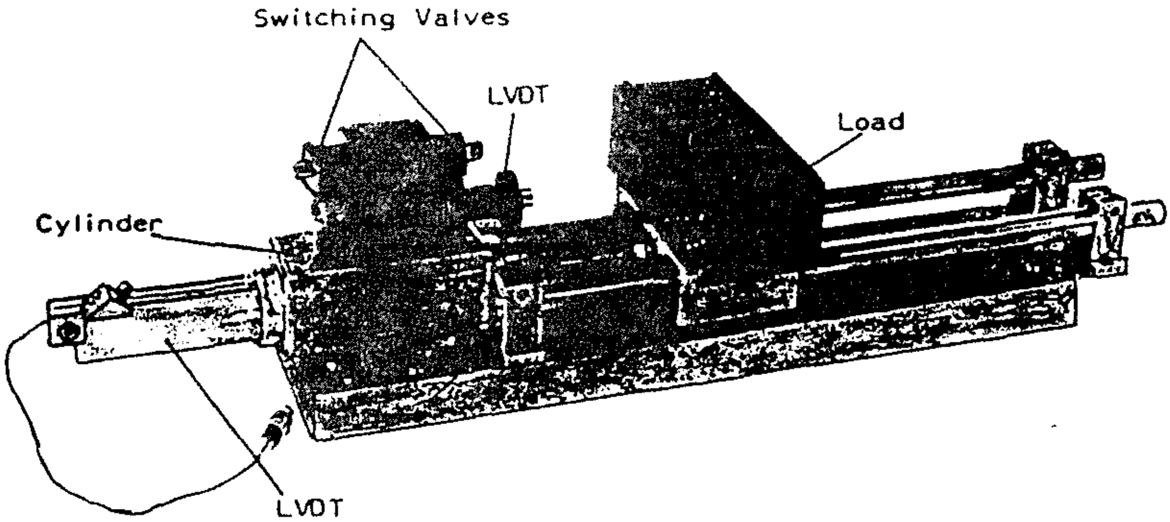


Fig. 22: Laboratory Model with Mass Load

It has been demonstrated that an electro-hydraulic digital actuator using pulse-width modulated input signals is achievable and that its performance is acceptable, although it has not been designed in the early stage of the development for specific helicopter application and aircraft requirements.

3.4 Digital Actuator System with Digital Sensors

A fully digitized actuator mechanism would not employ a PID-Controller. Fig. 23 shows the block diagram of the system, whereas a digital computer performs all computing necessary for position and velocity control. The feed back transducers are digital sensors, such as optical sensors or Linear Variable Phase Transducers (LVPT).

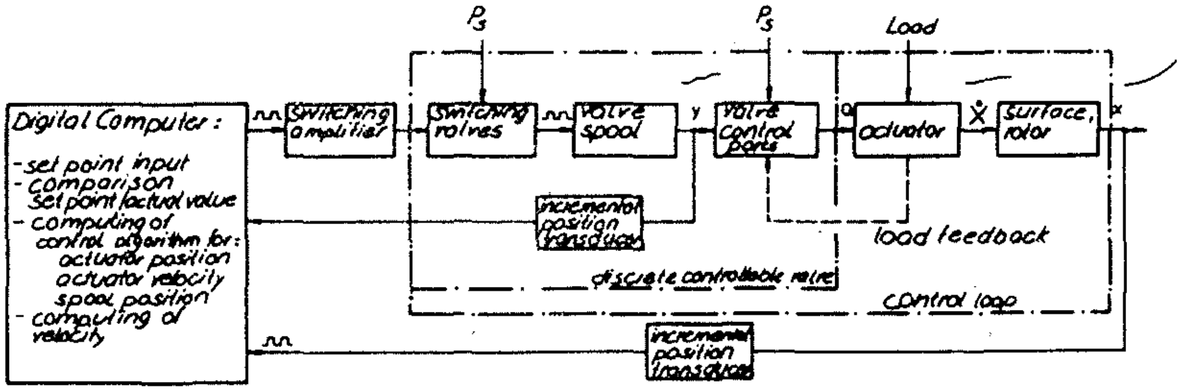


Fig. 23: Block Diagram of a Digital Actuator System

4. Redundant Actuator System

For the control of commercial aircraft surfaces two or three single actuators, mechanically connected to one surface, can be provided to form a redundant system. For military aircraft surfaces and specifically for helicopter rotor control duplex, triplex, or quadruplex actuators are required.

The described digital actuator per paragr. 3 is suitable for integration into duplex, triplex, and quadruplex actuators. Economical considerations and an evaluation of different designs resulted in the layout of a quadruplex electronic actuator control unit, of an arrangement of two valve systems as per fig. 14 and of a tandem actuator.

All electric and electronic components such as coils and LVPT are doubled for each simplex system to allow for duplex signalling and sensing. Monitoring of the input signals, of the switching valves function, of the control valves function, and of mismatch and force fighting will be accomplished by means of two electronic model channels.

This configuration allows for Double Fail Operative Function i.e. provides a function, if a hydraulic and/or mechanical failure in System I and simultaneously one electrical failure in System II occurs. A total of four bypass valves are to be provided, one each for the drive actuators of the control valves and one each for the tandem actuator. Spring loaded overriding mechanisms take care of a blocking of the spool valves or of a rupture of the control valves by opening the bypass for one of the tandem actuators.

Minimization of mismatch or force fighting requires certain tolerances of the valves switching times and fine adjustments on the flow to the control valves's drive actuator.

Due to the fact that the electrical power supply for a digital system is not as pretentious as for an analog system and that the failure detection can be more easily accomplished due to the existence of only two variables of state, the digital duplex actuator must be considered more economical and reliable.

5. Summary and Conclusions

Test results and the analysis of different electrohydraulic digital actuator systems have proven that the use of pulse width modulated input signals is superior to other kinds of signals.

Of importance are pulsation-free output motions of the actuator. The described system has proven the possibility to achive output motions equal to those of analog systems. The software for the electronic actuator control unit including the necessary monitors as well as the hardware for both the electronics, sensors and fast switching valves with high life endurance have been developed and their performance proven to be satisfactory.

The use of two simplex actuators to form a duplex system has been investigated theoretically with success.

Further development is to be applied to an optimization of hardware subcomponents as well as to redundancy and reliability.

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