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DIRECT DRIVE SERVOVALVES
WHY AND HOW
THE MAGNAGHI MILANO ANSWER

ING. D. LAFFRANCHI

MAGNAGHI MILANO S.P.A., ITALY

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For some years people are discussing on the direct drive valves (fig. 1).

It is not a new concept: in fact, it dates back to thirty years, when it showed problems mainly connected with the modest (when compared to a reasonable weight) forces which could be obtained from the then motors. At the same time, working intensely, electro-hydraulic servovalves (EHSV) with electro-hydraulic pre-amplified stage were improved (Fig.2). Even if with unavoidable dissipation of hydraulic power, due to the internal leakages of the pilot stage, these valves appeared more promising, as to weight/dimensions, available forces for the displacement of the metering spool of power hydraulic stage, and performances. During the last ten years, the possibility of buying from commerce new magnetic materials allowed to overcome the previous obstacle, drawing again attention to the D.D.V.

But, as it was not automatic to develop the steam engine from coal, what are real reasons of D.D.V.?

1. ADVANCED SERVOCONTROLS

Control laws for an unstable aircraft, with performances peculiar to an advanced weapon system, require a digital computer to be suitably implemented. Electric signals replace the mechanical ones and the reliability of the control loop would make different orders of amplitude worse if redundancies were not forecast.

Recent examples of effective application are the Agusta A129 anti-tank helicopter and the British Aerospace/Aeritalia E.A.P., which use the technology of active controls. Both aircraft are equipped with primary flight servocontrols also designed and manufactured by Magnaghi Milano.

Among the characteristics a servocontrol suitable for the above use (see Fig. 3) has to meet are:

- total FBW operativeness (often without mechanic back-up);
- supply from 2 hydraulic sources;
- Complete monitoring of system conditions;
- Tolerability of more failures;
- Insensitiveness to interferences;
- high reliability;
- low weight;

to which, recently, have been added:

- high supply pressures (28.0 to 35.0 --> 56 (?) MPa);
- low leakages in energy (hydraulic/electric);
- large bandwiths (higher harmonic control);
- safety critical equipment.

Now, we shall have a look at a possible schema of *servocontrol embodying* a D.D.V., suitable to meet the above requirements (see Fig. 4).

The intrinsic simplicity of the scheme, which, however, keeps the same redundancy level already seen, is evident. Performances too meet the requirements specified for future systems.

2. EXPERIENCE WITH EHSV AND THEIR LIMITS

Anyhow, we have not yet evidenced D.D.V. performance requirements or characteristics such as to exclude the use of EHSV (with, at the most, some adjustments) which can surely boast a demonstrated past of reliable use and very valid performances.

- The energy cost

It is useful to pay a little attention to the importance that energy losses are assuming on the today's aircraft.

During 20/25 years the increase in demands to be charged to the hydraulic system has raised of one order of magnitude the power used by the system itself. Likewise, actions as pressure increase and high resistance materials have limited in an efficient way the mass of systems and equipment. In conclusion, as a consequence of the installed powers, the greatest energies lost for the different efficiencies have available smaller masses to *be dissipated*, thus system limitations are represented by the max operating temperatures and weight of the heat-exchangers. Under this aspect, the diffusion of composite materials, characterized by low conductivity, does not represent a help.

We now remind that, because of first stage leakage, one EHSV can dissipate a hydraulic power from about 150 watt and over at 28 MPa. So, you can easily understand like, in a modern aircraft which uses *redundant servocontrols* of the type above mentioned, these energy losses constitute a potential problem, in addition to the losses of other servovalves for secondary actuation, steering, brakes etc.

From that point of view, the use of D.D.V.s appears advantageous even if, sometimes, this can result in a small increase in weight as regards the unit.

In addition, this does also justice to the "full" energy comparison of the D.D.V. as to the EHSV. Largely in favour of D.D.V. from the hydraulic point of view as *said before*, it is lightly unfavourable from the electric point of view; in fact the full flow absorbed power is, in one case, 3 watt against 0.1 watt peculiar to EHSV. But this can be considered as an additional advantage for the D.D.V., which is controlled by electric signals in a ratio of hundreds mA, where, as to the EHSV, these signals count only some mA. Although perfectly handlable by electronics without additional overstresses, these intensities ensure a higher immunity from external interferences, immunity which is so desirable in F.B.W. systems working in environments saturated with electro-magnetic and nuclear emissions.

- Manufacture aspect

Since 21 years Magnaghi are manufacturing on license or overhauling EHSV (single or multiple stage), flappers or jet pipes, which are fitted to their equipment installed on different aircraft, fixed or rotary wing. On the matter, the relationships with the American firm, Hydraulic Research Textron, surely a very cooperative leader in the field of the servocontrols for aerospace use, represented a big help in the past and still represent a stimulus for the future. All this experience allowed us to appreciate, along with the numerous merits, the extreme sophistication of the unit which makes it more similar to an exact watch than to a sturdy mechanic part. In our opinion, because of this characteristic, only few factories in the world can be justly considered as designers and manufacturers of excellent EHSV for aerospace use.

At this level, another decisive advantage of the D.D.V. on EHSV appears evident.

The new materials, like rare earth permanent magnets, have surely reduced the technology risk intrinsic in the development of the requested electric motors. Even if of reduced weight, these motors still have dimensions such as to allow manufacture and setting up by using traditional technologies of the mechanic construction. Therefore, final cost appears to be limited with interesting prospects of reduction, for instance as regards the contribution given by permanent magnets. High energy magnets used are rare earth-type, the present ones contain Samarium and Cobalt. They have two big disadvantages:

- Their high cost, partly due to the need of a strategic element like cobalt.

- Their extreme brittleness.

Recent studies forecast, for the next future, availability of boron neodymium magnets with improved characteristics of thermal stability. Thanks to the replacement of cobalt and new manufacturing processes, price will be much limited; in addition, they will have higher mechanic characteristics.

3. MAGNAGHI MILANO AND D.D.V.

Since 1985 MAGNAGHI MILANO undertook a research programme about the use of D.D.V. at the beginning in the aim of meeting an Aeritalia demand into the field of the primary servocontrols for future aircraft.

- D.D.V. description

Among many possible architectures we adopted the one, in our opinion, exalts at most the simplifications possible with this type of unit (Fig.5).

A metering spool is directly connected to a linear and bidirectional motor.

The motor consists of a rare earth powerful permanent magnet, radially magnetized. By magnet side are windings independent each other, which receive electric signals from the different control channels. Till now configurations from 1 to 4 channels have been realized. Magnet and windings are housed in a magnetic circuit which contains them in the three dimensions, by minimizing, in this way, the flow leakages unavoidable in the bidimensional circuits peculiar, for instance, to conventional torque motor.

The movable armature, located between magnetic poles, is immersed in hydraulic fluid. Thanks to this, any dynamic seal, either in spool or on motor shaft, has been eliminated, by reducing, thus, the consequential problems of hydraulic leakages and hysteresis. Only static seals prevent that fluid comes out. Being also inside the motor, the fluid ensures a higher conductivity with the consequential thermal dissipation.

A comparatively long shaft, having high radial flexibility, connects the motor armature to the metering spool. In this way, even keeping a positive and secured locking, this prevents that the unavoidable small misalignments existing between motor and hydraulic section are transformed in transverse forces, friction sources.

- The potential reliability

Various details contribute to improve actively the unit reliability. The movable armature is suspended inside the motor, with two springs having a high radial stiffness. The coupling of such a motor to a hydraulic stage does not involve, therefore, additional points of contact among parts in relative movement, in addition, of course, to the pre- existing spool and sleeve matching. In this way, it is not necessary to resort to rotating or sliding bearings with the consequential undesiderable increases in costs and types of failures modes.

Besides, the springs ensure the axial stiffness, i.e. in the direction of armature movement, necessary to generate a center return stabilizing force. On the other hand, this ensures another appreciable characteristic of the described solution as regards the conventional EHSV; in fact, in case of loss of the electric control signal, the EHSV does not ensure the final position of the metering spool. On the contrary, D.D.V. tends to come back to null position, by ensuring a type of failure, which is intrinsically sure.

Finally, the motor develops high forces, which exceed much more those required by the changes in momentum intrinsic with very high hydraulic flows, and this allows to overcome occasional stickings due, for instance, to contaminated fluid.

- Examples of applications

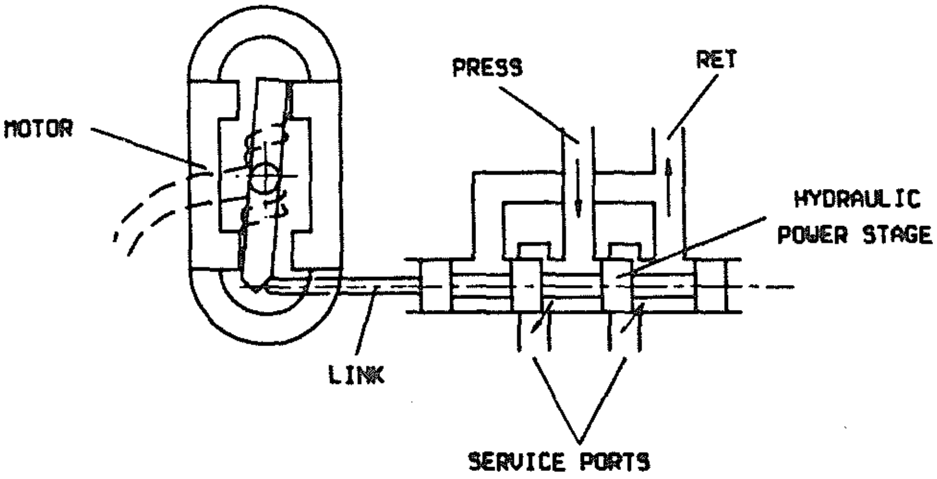
The scheme of the described motor lends itself flexibily to several applications and, as an example, we quote two extreme solutions, both fully developed by Magnaghi:

- D.D.V. at high flow, dual hydraulic system (see Fig.6)
- D.D.V. Pilot stage, single hydraulic system (see Fig.7)

The first D.D.V. is used with success in a primary flight servocontrol suitable for use on an superiority aircraft, having instability characteristics.

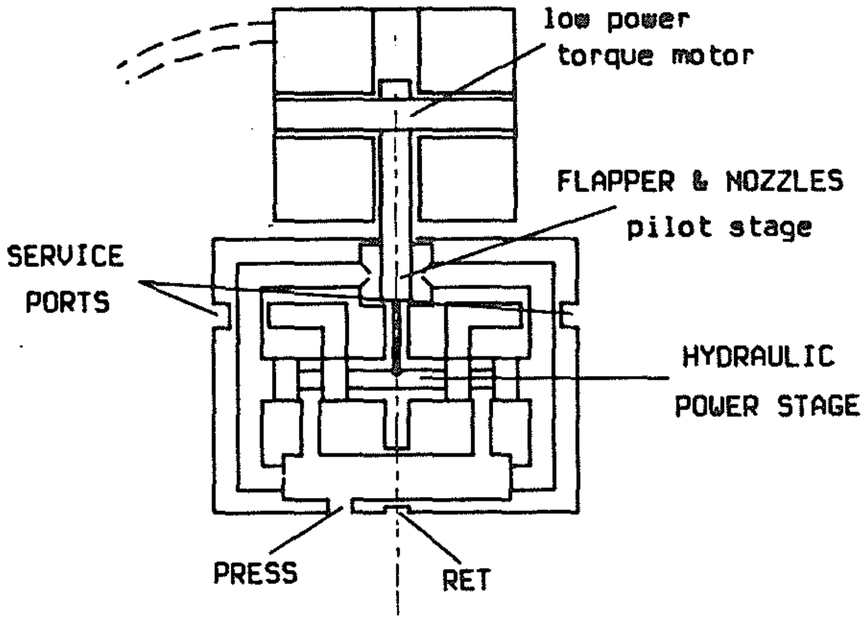
The system is controlled by 3 control electric lines and supplied by 2 independent hydraulic systems. Operativeness is requested after 2 electric failures, or 1 electric and 1 hydraulic.

The programme, still in progress, has till now evidenced the consistence and reliability of the developed units, which have shown to meet the requested requirements from the beginning of the tests. An example of a typical frequency response is herein mentioned (Fig.8). As to the D.D.V. main characteristics, they are listed in Table 1.



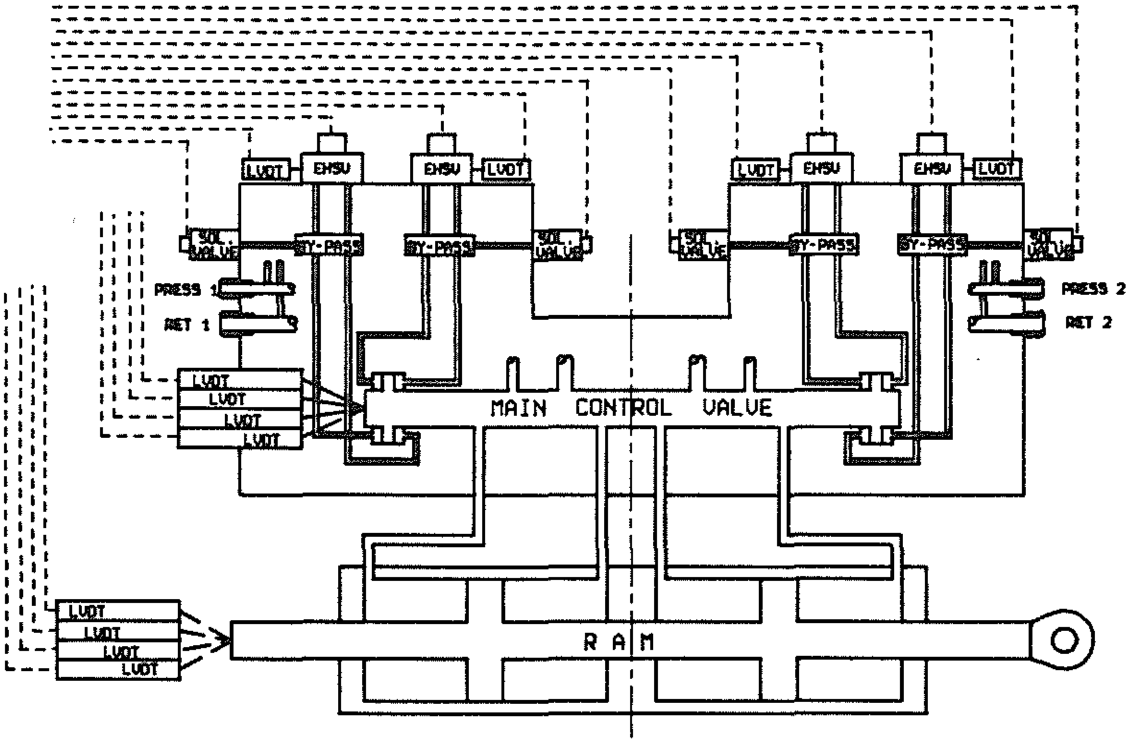
DIRECT DRIVE VALVE , schematic
(D D V)

- fig. 1 -



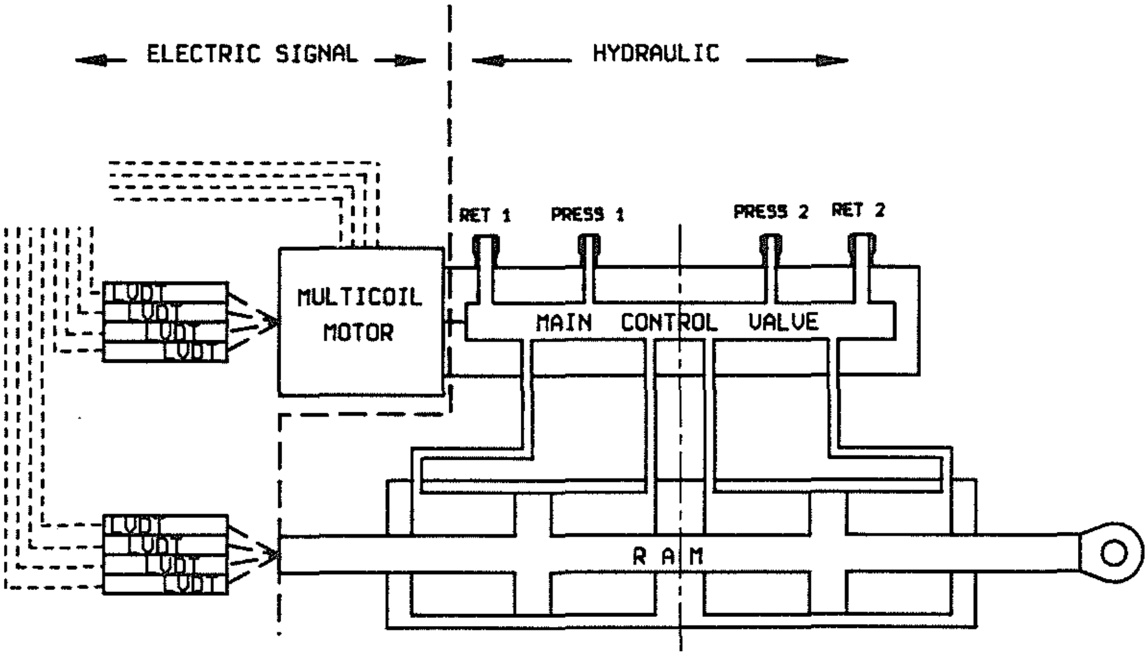
ELECTRO HYDRAULIC SERVOVALVE , schematic
(E H S V)

- Fig. 2 -



Dual Hydraulic / Quadruplex Electric Servoactuator , typical (with EHSV)

- Fig. 3 -



Dual Hydraulic / Quadruplex Electric Servoactuator , typical (with DDV)

- Fig. 4 -

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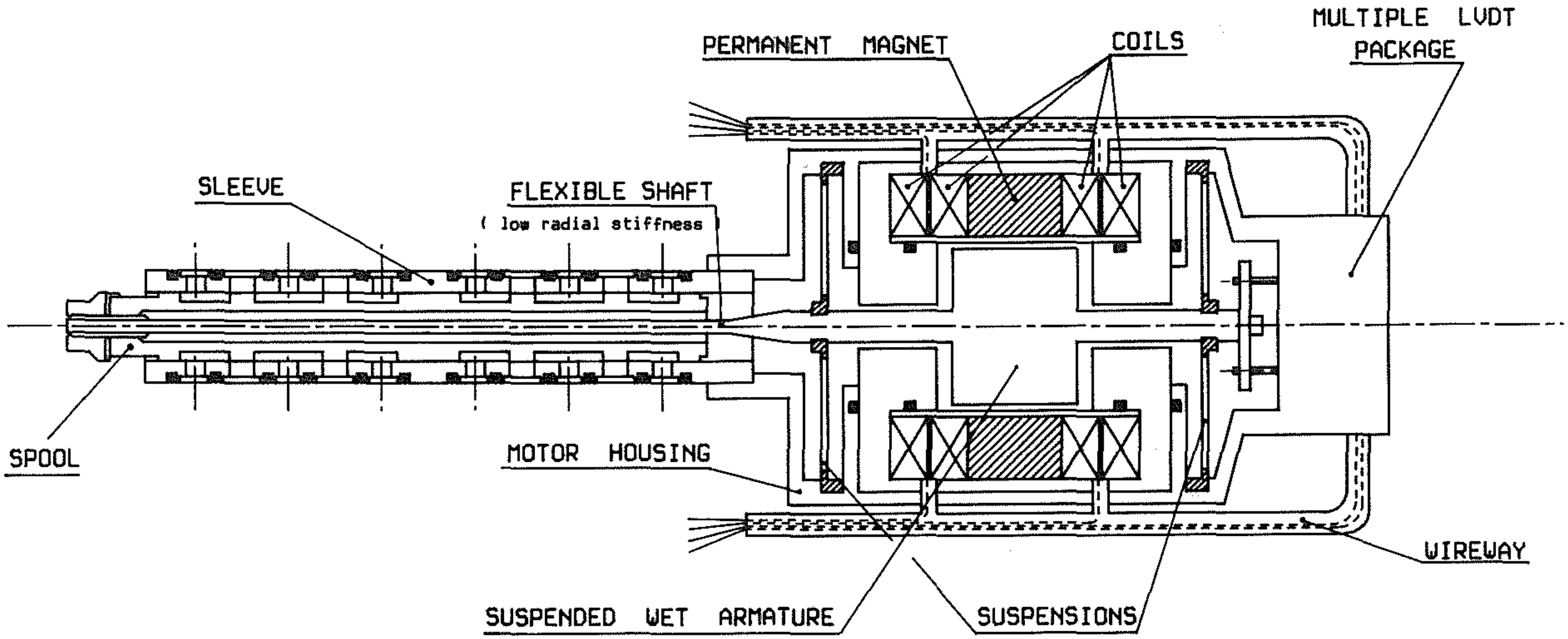

DIRECT DRIVE VALVE
with linear force motor

- Fig. 5 -

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Fig. 6

D.D.V. High Flow
Dual Hydraulic/Triplex electric

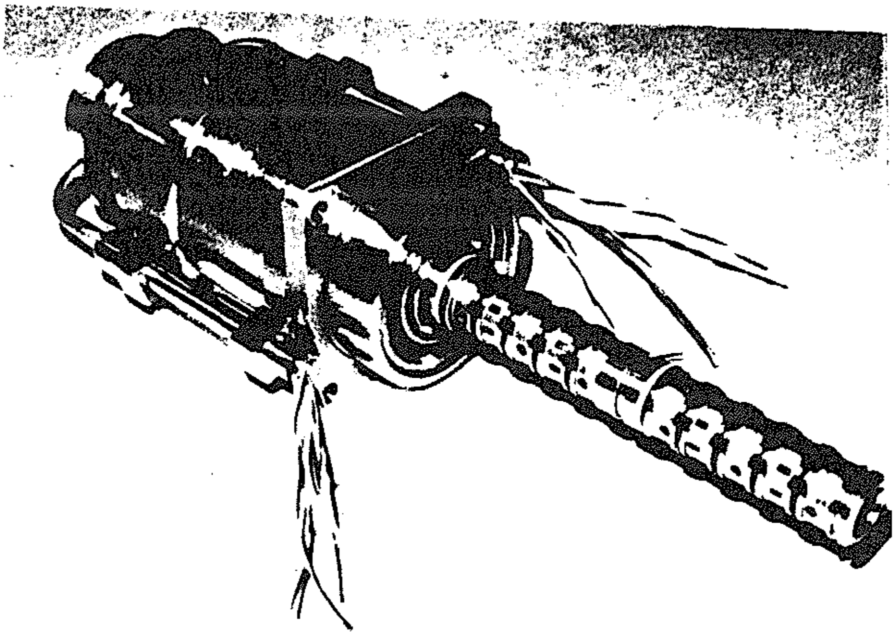

Fig. 7

Primary Flight Control Servoactuator
with D.D.V. Valve Block
& Pilot Stage D.D.V.

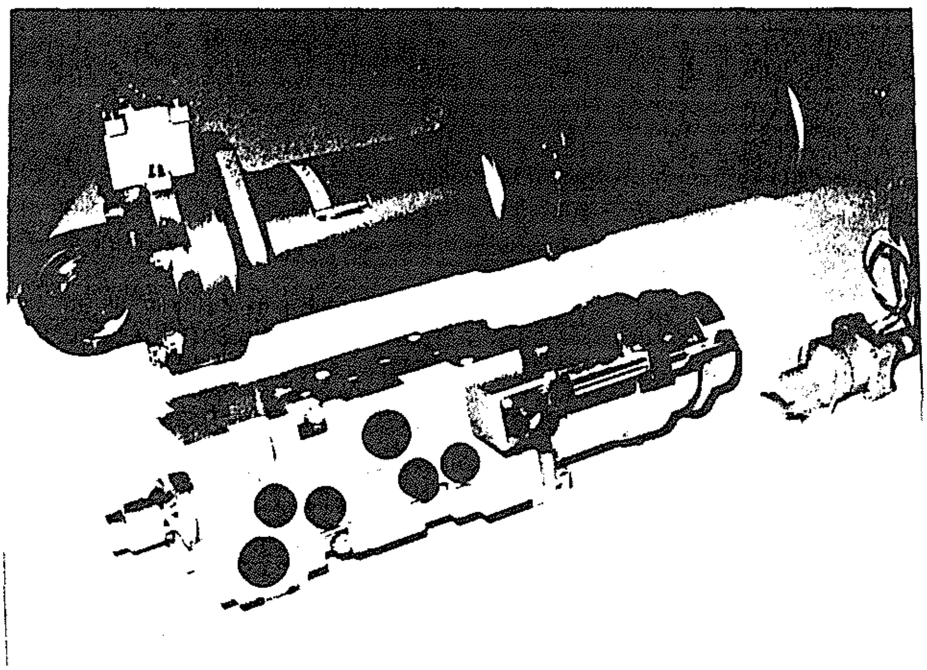

Fig. 8

Servoactuator with D.D.V.
Closed Loop Frequency Response
Demand = +/- 1 mm 2 hyd. sys./3 channel ON
Psupply = 28.0 MPa

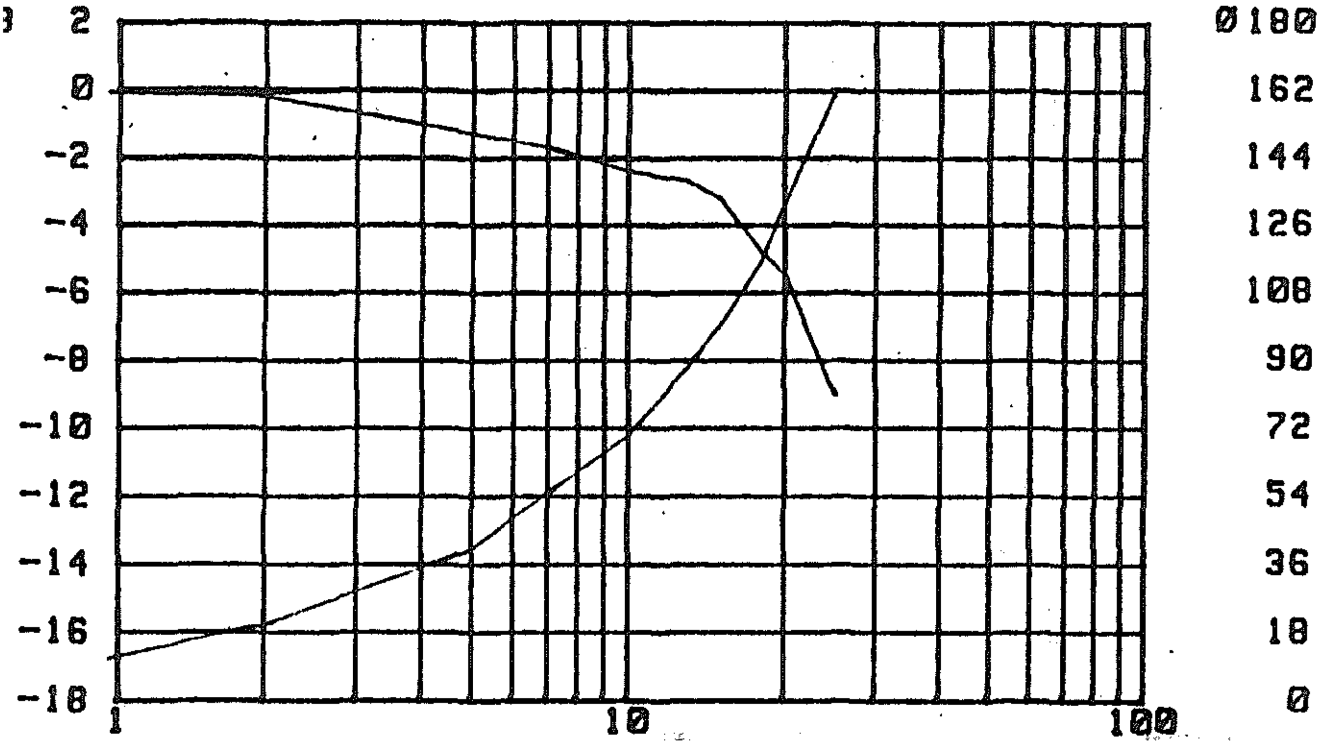

Fig. 9

Pilot Stage D.D.V.
Closed Loop Frequency Response
Demand = +/- 25% Psupply = 28.0 MPa

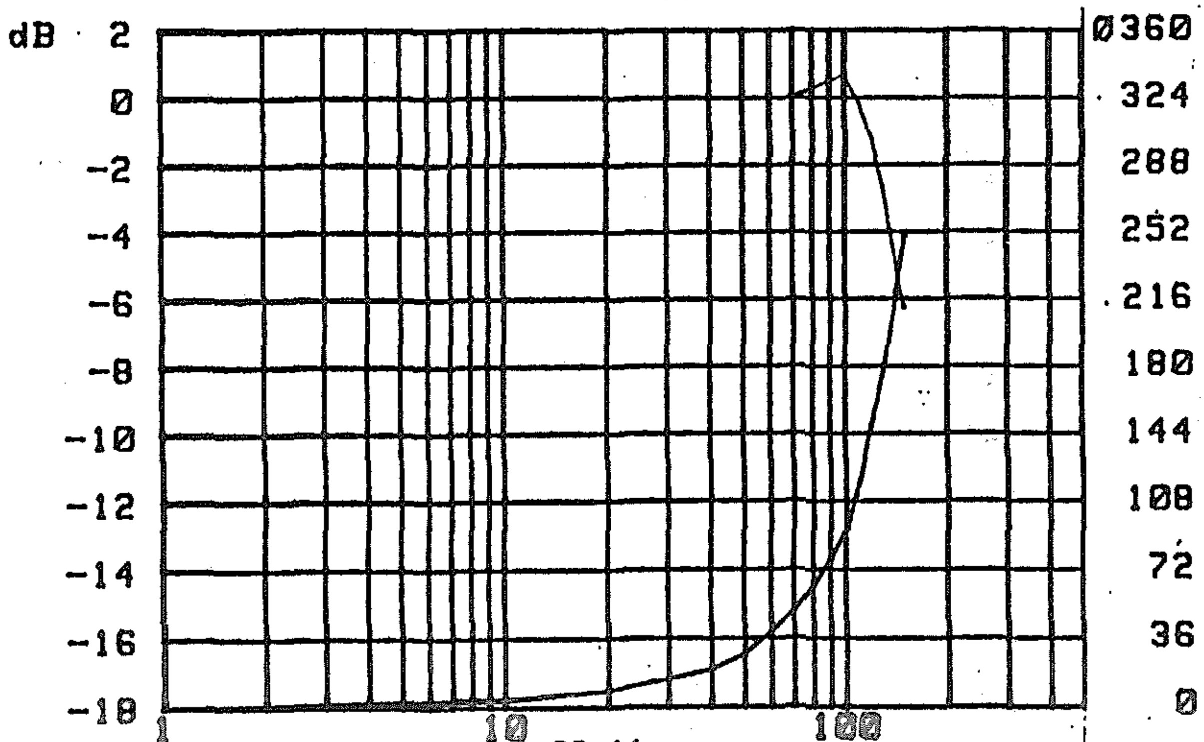

TABLE 1

	Large flow D.D.V.	Pilot stage D.D.V.
Hydraulic system n°	2	1
Operating pressure:		
- supply [MPa]	28	28
- max return [MPa]	28	28
Rated flow [lt/min]	2 x 40	0.8
Leakage flow [lt/min]	2 x 0.5	0.05
Coil n°	3	1
Coil resistance [ohm] (@ 20°C)	9	15
Full Flow current [Amp]	0.35	0.23
Chip shear current [Amp]	1.00	N/A
Chip shear force [N]	900	N/A
Stroke [mm]	± 0.65	± 0.25
Mass [Kg]	4.1	0.390

A more careful examination of the control scheme shows its simplicity characterized by:

- constant electric gains which ensure margins sufficient to meet the dynamic requirements provided in case of failure in 1 or 2 electric lines;

- absence of additional emergency modes. Maximum forces possible for motor, e.g. cheap shear, are available at any moment, also for long periods, without monitor additional circuits and switching functions.

The second application shows as, also with required reduced flows and high dynamic requirements, typical in the driving of the power stages, it is still possible to take advantage from the D.D.V. reduced internal leakages, simplicity and reliability. All this with masses extremely limited even if higher than pilot EHSV as per table 1. The large bandwith is shown in fig.9.

4. A FINAL BALANCE

On the ground of the above approach and thanks to the experience acquired during these years of design, manufacture and tests, as a conclusion of this matter we come back to the topic of the comparison between the servo-actuation with D.D.V. and more classic solutions.

As it is obvious, such comparison has not an absolute value, but it is related to the characteristics which, are considered as prioritary for the system. A clear example is the servocontrol supplied by only one hydraulic system; if weight, envelope and very high dynamic performances had to be priviliged, the solution controlled by EHSV should be higher than that with D.D.V. But, as already seen, if other characteristics, like reduced internal leakages, better reliability, costs, were intransgressible, such advantage could be not so evident.

The benefits with D.D.V. scheme are more considerable for the servocontrols supplied by 2 hydraulic systems, in most cases also as regards weight and dimensions. Coming back to the previous figures, it is possible to become aware of this situation.

In addition, such servocontrols are required when it is necessary to withstand multiple failures. To ensure this, it is essential to exactly define the unit condition and to surely handle its redundancies. It is evident that the schematic simplification intrinsic in the use of D.D.V. and the clear separation between electric and hydraulic section (Fig.4), with the corresponding possible failure modes and detection systems, represents a desiderable characteristic for the unit manufacturer, for associated electronics, for control software, for maintainability and design of pre-flight Built-in-Test with high determination percentages.

On the other end is a fact that a simpler scheme contains a single failure point, represented by the spool and sleeve assembly which can be considered as acceptable only if the system general reliability allows. There are some recent examples related to some units, with similar single point failures, which have been considered as acceptable, for military aircraft, even in safety critical applications. Magnaghi approach to increase, at most, safety aims at developing D.D.V. with high forces available for the metering of the control ports which, in turn, are divided in a number enough to let that, if the passage maximum area of one of them were unfortunately clogged by a metallic residue, force required to cut it is never higher than the chipshear capacity of the motor itself. As a measure redundant to this one, it is suggested to resort to filters, having a suitable filtrations, into the lines, which enter the servovalve.

5. THE FUTURE

Magnaghi Milano consider D.D.V. as an element essential for the future servocontrols and are devoting to them the suitable resources for a full development.

The experience, till now acquired, has allowed to Magnaghi to be present, authoritatively, in a multinational consortium which is studying the servo-controls for the EFA, the future European fighter; such experience has been validated by the manufacture of units also used by Aeritalia for their researches.

This technology has, so, attained at Magnaghi a maturity which is, now, available for the aerospace industry and we hope that it will be able to contribute to the success of future flying machines like the NH-90 european helicopter.