Electrohydraulic proportional controls: user's guidelines

1 WHAT IS PROPORTIONAL ELECTROHYDRAULICS?

Electrohydraulic proportional controls modulate hydraulic parameters according to the electronic reference signals.
They are the ideal interface between hydraulic and electronic systems and are used in open or in closed-loop controls, see section 3, to achieve the fast, smooth and accurate motions required by today's modern machines and plants.
The electrohydraulic system is a section of the overall automation architecture unit where information, controls, alarms can be transmitted in a "transparent" way to the centralized electronic control unit and viceversa also via standard fieldbus, see tab. F002 for "Digital solutions".

Proportional electrohydraulics is easily programmable like electromechanical systems and allow a flexible automation. In comparison with the electromechanical systems, electrohydraulics provides the following advantages:

- intrinsic overload protection
- self lubrification of the system
- high power density
- automatic force adaption
- simple stepless variation in speed, forces and torques
- fast operating response
- energy storage capability
- long service life and high reliability

2 WHAT IS A PROPORTIONAL VALVE?

The core of electrohydraulic controls is the proportional valve that regulates a pressure P or a flow Q according to the reference signal (normally ±10 V_{DC}). Particularly the proportional valve must be operated by an electronic driver which regulates a proper electrical current supplied to the valve's solenoid according to the reference signal. The solenoid converts the electrical current into a mechanical force acting the spool against a return spring: rising of the current produces a corresponding increasing in the output force and consequent compression of the return spring, thus the movement of the spool.

In pilot operated executions the proportional pilot valve regulates flow and pressure acting on the main operated stage.

When electrical failure occurs, return springs restore the neutral position according to valve configuration, to ensure a fail-safe operation, i.e. to ensure that in case of absence of reference signal or, generally, in case of electric system breakdown, the system configuration does not cause damages. Fail-safe can be realized directly by the proportional valve (fail-safe operation intrinsic in valve configuration) or it can be realized by consequential operation of a group of valves.

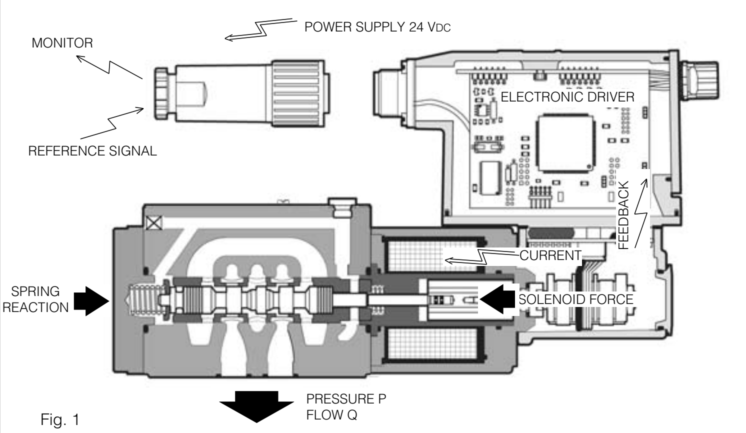


Fig. 1

3 CONTROL LOOPS

The motion control of modern machines is substantially a problem of axis control. Today industrial machines are multi-axis machines, more and more electrohydraulically controlled by proportional devices. The axis motion can be operated in "open loop" or in "closed loop" control, depending to the accuracy level required in the application. In many applications the motion cycles do not require extreme accuracy, so they are performed in open loop, while each time the application requires the positioning of an actuator, a closed loop control must be provided.

OPEN LOOP MOTION CONTROL

Axis control is provided through the supply of an input reference signal to the proportional valve without any feedback of the valve's regulated hydraulic parameter.
The accuracy of the open loop controls is strictly dependent of the good quality of the hydraulic system and particularly of the proportional valve and of the relevant driver.

CLOSED LOOP MOTION CONTROL

Axis control is provided through the supply of an input reference signal to a closed loop controller which receive the feedback signal of the valve's regulated hydraulic parameter by the actuator's transducer and compare the two signals.
The resulting error is then processed by the controller to the proportional valve, in order to align its regulation to the PID control loop requirements.
The accuracy of the closed loop controls is much better respect to the open loop ones and it is less influenced by the external environmental disturbances, thanks to the presence of the feedback.
Anyway the best is the overall quality of the hydraulic system, the best is the accuracy of the axis control.

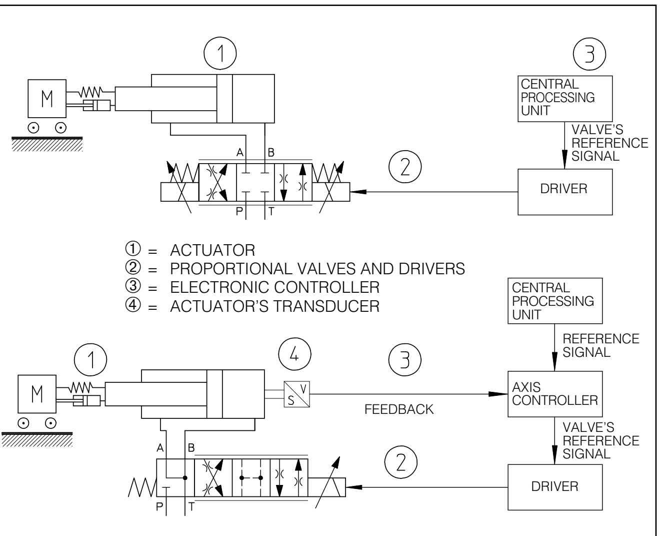


Fig 2: Electrohydraulic axes: a basic block diagrams

Atos proportional valves can work in open loop (valves without transducer) or in closed loop (valves with LVDT position transducer), see fig. 1.
The proportional valves without transducer are fed through electronic drivers supplying a modulated current to the solenoid proportionally to the reference signal. To assure the best operation the driver should be supplied by the manufacturer of the valve.
The proportional valves with LVDT position or pressure transducer are fed through electronic drivers supplying a modulated current in order to control the regulated parameter (spool position or pressure) proportionally to the reference signal.
Proportional valves with transducer are the best choice for closed loop electrohydraulic motion controls as they enhance the system performances.

4 PROPORTIONAL VALVES AND DRIVERS

Atos, a leader in pioneering proportional electrohydraulics, offer today one of the most advanced lines.
Atos valves may be of spool type (originated from solenoid valves) or in cartridge execution (from logic elements) and can be grouped in three different functional families:

- **pressure control valves: relief valves** and **reducing valves** regulate the hydraulic system pressure proportionally to the reference signal;
- **4-way directional control valves:** direct and modulate the flow to an actuator proportionally to the command signal to the valve. These valves can be used in open or closed loop control system to determine the direction, speed and acceleration of actuators;
- **flow control valves:** 2 or 3-way, pressure compensated, to modulate the flow in the system, indipendentely to the user loads.

Atos proportional valves are equipped with **ZO** and **ZOR**, efficient solenoids (30 W and 40 W) respectively designed for direct-acting valves of ISO 4401 size 06 and 10 and they are assembled in different options as follows:

ZO(R)-A: without integral transducer, open loop;
ZO(R)-AE: as ZO-A plus integral electronic driver;
ZO(R)-T, -L: with integral LVDT single/double position transducer, closed loop, featuring high static and dynamic performances;
ZO(R)-TE, -LE: as ZO-T, -L plus integral electronic driver

In the new generation of -AE, -TE, -LE valves, the electronic driver is integral to the proportional valves and it is factory preset to ensure fine functionality plus valve-to-valve interchangeability and to simplify installation wiring and system set-up. Thanks to these enhanced features they are used more and more in the modern applications and systems. Electronics are housed and resin encapsulated in a metal box to IP67, ensuring antivibration, antishock and weather-proof features; coils are fully plastic encapsulated.
Electronic drivers include:

- **separated drivers for proportional valves without transducer:** E-MI-AC, E-BM-AC, E-ME-AC (see tab. G010, G025, G035)
- **integral drivers for proportional valves without transducer:** E-RI-AE (see tab. G110)
- **separated drivers for proportional valves with LVDT transducer:** : E-ME-T, E-ME-L (see tab. G140, G150)
- **integral drivers for proportional valves with LVDT transducer:** E-RI-TE (see tab. G200)
- **integral drivers for proportional valves with pressure transducer:** E-RI-TERS (see tab. G205)

The reference signal to the electric drivers is normally voltage type (Volt); alternatively it may be current (Ampere), the latter used when great lengths apply to reference and feedback connections, causing interferences and electrical noise.
In any case pay attention to shield the electrical cables with shield or cablebraid type connected to the ground - see table F003, section 5.
For detailed information on drivers, see technical tables on section G.

5 ELECTRONIC CONTROL SYSTEM

The electronic control system includes a control unit and one or more axes cards. The overall performances of the electro-hydraulic axis controls are strictly dependent to the correct choice of the proportional valve and of the electronic control system which must be selected by an electrohydraulic specialist.

A large number of electronic System integrators can provide to the customers the best standard hardware and customized software.

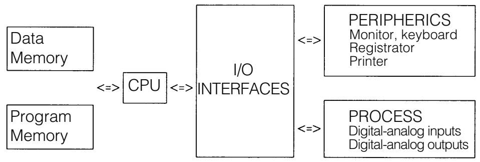


Fig. 3: Block diagram of a control unit

The machine control unit includes a data processing unit (PLC, PIC, CNC) to elaborate the Input/Output signals (Fig. 3).
This data processing unit is equipped with a terminal board to input the programming data and it is fitted with dedicated peripheral units, i.e. axis cards and other electronic controllers for coordination of various axes.
The electrohydraulic control system can be optimized on both hydraulics and electronics side. Atos Technology Department ais available to cooperate with the customer's system integrator for a detailed application analysis.

The axes card is the interface between the control processing unit (which processes the overall machine cycle and program) and the electrohydraulic systems.
Digital axes cards are directly interfaceable with encoders linear and rotative and magnetosonic transducers and easily with inductive ones, by means of proper auxiliary cards. To interface an analog transducer with an axes card, an A/D converter must be provided. A resolution of 12 bit or better, is recommended for good performances.
Essentially, an axes card compares reference and feed-back signals obtaining the relevant error and the performs the computing controller of the output reference signal to the proportional valve. The most common controller is the PID type where adjustable parameters are:
P: proportional to the error; **I**: proportional to the steady state error; **D**: proportional to the rate of change of the error.
Several manufacturers offer advanced axes controllers and regulation cards: SIEMENS, OMRON, ALLEN BRADLEY, TELEMECANIQUE, etc.
Atos Technology Department is available to cooperate with customers and system integrators a the detailed application analysis and for the best choice of the electrohydraulic system characteristics.

6 ACTUATORS AND TRANSDUCERS

Electrohydraulic motion is resolved by linear or rotative actuators. The former can be monitored by analog or digital position transducers that can be directly mounted on the actuator (built-in transducer). Usually the servocylinders are equipped with integral proportional valves to increase the stiffness of the system.
Atos servocylinders are in low friction execution with high static and dynamic characteristics to improve the control performances, see tab. B310.

7 CLOSED LOOP CONTROLS SELECTION GUIDELINES

Single solenoid valves are the best choice for running a closed loop system, by making the control easier and cost effective.
While selecting the proper proportional valve, consider:

- select spool with zero overlapping (i.e. valve type DLHZO, table F180);
- choose a valve with a frequency response characteristic of at least 30 Hz at 90° phase shift (Bode diagram);
- choose the proper fail-safe configuration (Fig. 4) to prevent from damages in case of electric breakdown;
- use a linear spool for position controls (/L* version in the code);
- repeatibility and hysteresis ≥0.2%.

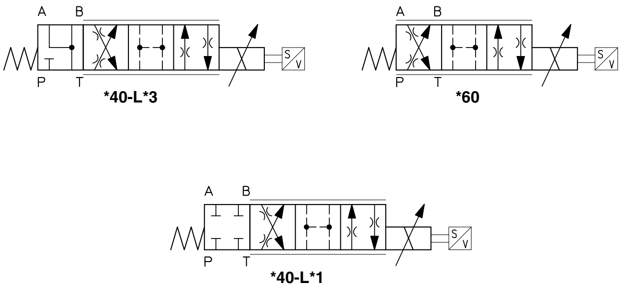


Fig. 4: Fail-safe configurations.

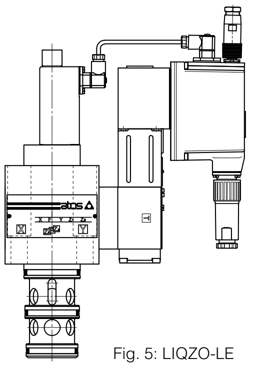


Fig. 5: LIQZO-LE

- select spools with max flow rate 10÷25% more than max regulated flow (better control of minimum flow rate and of hydraulic gains).
- if high speeds and accurate positioning requirements are combined, use the “breaked” regulation of series “T” valves and relative drivers (see table F180).

For high flow rate, proportional cartridge valves, 2 way and 3 way are available too, see Fig. 5 (see also tab. F300 to F340). They are standard elements for manifold mounting resulting in compact and cost effective solutions.
Atos proportional valves and relative drivers are marked “CE” according to the EMC (72/23/CEE) and to the Low Voltage Directives, see tab. P004.
For complete information about proportional valves and controls see specific technical tables.

8 CLOSED LOOP SYSTEM ANALYSIS

This section is designed to provide a basic and practical approach to performance estimation of closed-loop systems.
The basic concepts described in the following are nowdays integrated with the tools of advanced simulation programmes. With them it’s possible to build up complex circuits connecting the different functional blocks to represent the loop, after determining every element’s output characteristics. Furthermore, it’s possible to simulate the behaviour of complex systems and to analize their dynamic response: in particular it’s easy to develop parametric studies (varing stiffness, mass, type and size of proportional valves).

The electrohydraulic applications may be essentially classified into:

- dynamic applications: movement of loads at high speed/frequency;
- force applications: to transmit high forces at low speed.

The problems arising in dynamic applications are of difficult evaluation but of great importance. Most malfunctioning derive from neglecting a frequency approach to the system.
Two aspects are to be considered:

- hydraulic stiffness of the system;
- inertia of the loads.

In many applications, hydraulic fluid is considered to be incompressible. This is not correct in absolute, since when pressurized, a fluid will compress in the same way as a very riged spring (Fig. 6).

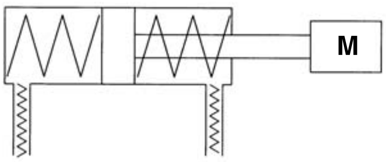


Fig. 6: Actuator as a spring/mass system

In fast-acting servo systems with high dynamic loads even piping may be seen as elastic, above all for high values of pressure. Attention should be paid to the presence of accumulators: as they make the system more critical from the dynamic point of view.

A closed loop control system analysis can be simplified by regarding components (or set of components) as blocks (Fig. 7). The relationship between the input and output of a single block is the **transfer function** (G).
The system loop gain ***Kv*** (fig. 8) can be got multiplying the gains of the single blocks of the loop (amplifier ***GD’***, proportional valve ***Gv’***, cylinder ***Gc’***, feedback). The higher the system open loop gain, the better overall performances.

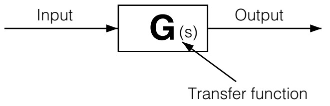
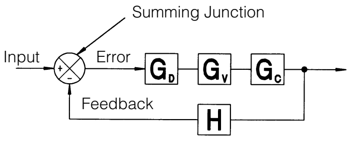


Fig. 7: System transfer function

However, an excessive gain may cause the system to get unstable (Fig. 9).
In this situation the overshoots and undershoots diverge. The maximun value of the gain, that can be used to assure system stability is determined by:

- the load mass (M); the bigger the mass, the greater the inertia forces, the greater the tendency to oscillate.



Open loop: $K_V = G_D \times G_V \times G_C$

Closed loop: $\frac{K_V\,(s)}{1 + K_V\,(s) \times H\,(s)}$

Fig. 8: System loop gain

- the stiffness of the actuator (***C_H***); low stiffness means high tendency to oscillate, so the stiffness should be as high as possible;
- the damping coefficient (ξ) of the system (tipically $\xi = 0.05 \div 0.3$). This parameter is mainly influenced by the characteristic of the valve (non linear characteristics, etc.) and by the system friction.
  To ensure the system stability: $K_V \geq 2\xi\omega_S$

  where ω_S, the natural frequency of the complete closed loop system, is the minimun among:
  - ω_V: natural frequency of the valve (assumed to be the frequency at 90° phase shift; see tables F165, F172, F180);
  - $\omega_o = \sqrt{C_H/M}$: natural frequency of the mechanical system (generally $10 \div 100$ Hz);
  - $\omega_{\alpha\tau}$: natural frequency of amplifier and feedback transducer (usually ignored, because at least ten times higher than ω_V, ω_o).

  In industrial electrohydraulic applications the critical frequency is always ω_o.

For linear actuators ω_o is calculated with the following formula:

$$\omega_o = \sqrt{\frac{40\,EA_1}{cM}}\;\frac{1+\sqrt{\alpha}}{2}\left[\frac{rad}{sec}\right]$$

$E = 1.4\ 10^7$ Kg/cm.sec^2 (oil elastic modulus)
c = stroke (mm)
M = mass (kg)
A1 = piston area (cm^2)
A2 = anulus area (cm^2)

$\alpha = A2/A1$ = anular/piston cross section ratio

The natural frequency ω_o for a cylinder-mass system is directly related to the minimum acceleration/deceleration time permissible to maintain the functional stability (Route-Hurwitz criterium).

$\mathbf{t_{min}} = 35/\omega_o$ (s)

Experience has shown that if the $\mathbf{t_{min}}$ to assure stability in a system is lower than approximately 0.1 seconds, the system should be re-examined (see fig. 11). Once fixed the total cycle time and stroke, it is possible to obtain the maximum speed:

$\mathbf{V_{max}} = \mathbf{S_{tot}} / (\mathbf{t_{tot}} - \mathbf{t_{min}})$ $\mathbf{S_{tot}}$ = total stroke (mm) $\mathbf{t_{tot}}$ = total cycle time (s)

and consequently the maximum acceleration

$\mathbf{a_{max}} = \mathbf{V_{max}} / \mathbf{t_{min}}$

Overall stiffness is important even to determine the performance in terms of how accurately the electrohydraulic axis achieves and maintains a demand position, being more reactive to possible external disturbances: reactive loads on actuators (tool forces, shock loads), load weight (vertically mounted cylinders), friction on slides, gap at joint.
Further parameters to strictly monitor are: valve null shift due to temperature or pressure variations, accuracy or resolution of feedback transducer.

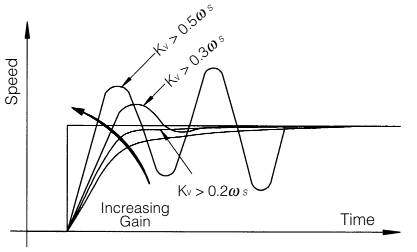


Fig. 9: Answer to a step signal increasing gain

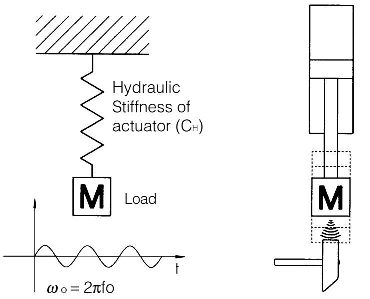


Fig. 10: The mass/spring mechanism.

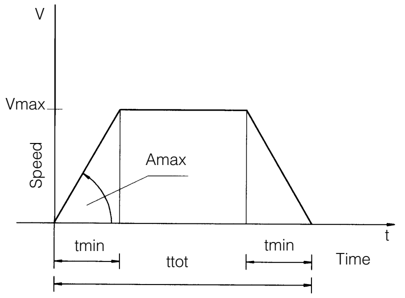


Fig. 11: Positioning cycle

9 CLOSED LOOP SYSTEM ANALYSIS: AN EXAMPLE

The following example shows the great influence of the dynamic characteristics in a closed-loop system.
Consider the simple sketch in Fig. 12. The cylinder is connected to a proportional valve; the machine cycle requires that the cylinder must complete its forward stroke in a time of 2 sec.
Using the relations of section 8, we get:

$\omega_o = 69.12$ rad/sec

$\mathbf{t_{min}} = 0.51$ sec

$\mathbf{V_{max}} = 0.67$ m/sec

$\mathbf{a_{max}} = 1.31$ m/sec^2

$\mathbf{Q_{max}} = \mathbf{V_{max}} \times A1 = 0.67 \times 19.6 \times 60/10 = 78.9$ l/min

Finertia = M xa = 2620N

$\mathbf{P_{min}} = (\mathbf{F_{inertia}} + \mathbf{F_{load}})/A1 = (2620 + 19620)/19.6\ [\frac{N}{cm.^2}] = 1.135\ [\frac{N}{cm.^2}] = 113.5$ bar

$\mathbf{P_{required}} = \mathbf{P_{min}} + \mathbf{\Delta p_{nom.valve}} + \mathbf{\Delta p_{circuit\text{-}drops}} = 113.5 + 70 + 16 = 199.5$ bar

$\mathbf{P_{required}}$ is the value of pressure supplied by the hydraulic power unit.

Select a proportional valve with a $\mathbf{\Delta p_{nom.valve}}$ in the range shown in the technical tables. In the previous example you may choose a DLKZO-TE-040-L71 valve (Q = 100l/min, $\mathbf{\Delta p_{nom.valve}}$ = 70 bar).
The above calculations determine the needed pressure to perform the cycle with the required dynamics.

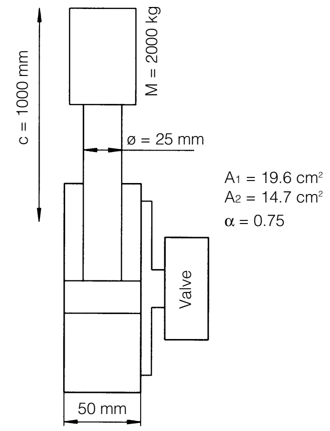


Fig. 12: The system analysed on the example.

10 TYPICAL ELECTROHYDRAULIC TERMS

Repeatability: The maximum difference between subsequent values of a hydraulic parameter obtained at same hydraulic and electrical conditions and the same reference signal, after variable commands are sent to the valve. Repeatability is measured in percent with reference to the maximum value of the regulated hydraulic parameter and in open loop applications is strictly connected with system accuracy performances.

Leakage: The amount of fluid passing through pressure port P to tank port T when valve's oil passages are closed, it is directly connected with the quality of the valve's mechanical execution and it gives an idea of the size of the valve's minimum controlled flow.

Reference signal: The electric signal which is fed into the electronic regulator to obtain the required driving current to the valve.

Driving current: The current required for driving the solenoid valves, expressed in milliampere [mA].

Bias current: Static offset added to the reference signal required for bringing the valve to its null point.

Dither: The pulse frequency of the valve regulation used to minimize the hysteresis.

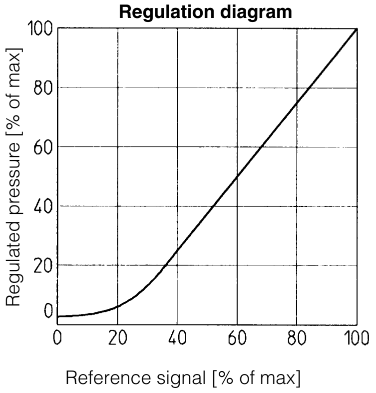
Regulation scale: Setting of the valve regulation with the max reference signal.

Ramp time: Time (in sec.) required to operate the valve from zero to the max regulation.

Electric gain (Gd): Transfer function between error signal and reference signal.

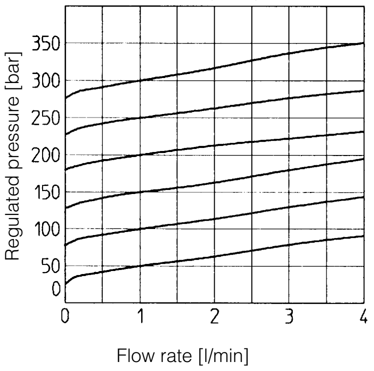
11 TYPICAL DIAGRAMS OF PROPORTIONAL CONTROLS

PRESSURE CONTROL VALVES



Regulation diagram

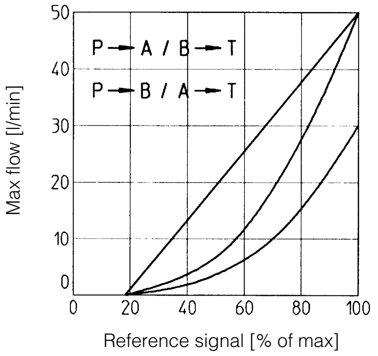
Valve's-regulated pressure variation according to the reference signal



Operating diagram

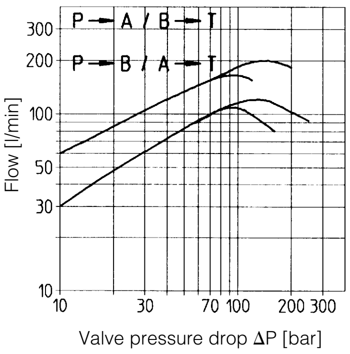
Valve's-regulated pressure variation according to the flow passing through the valve

DIRECTIONAL AND FLOW CONTROL VALVES



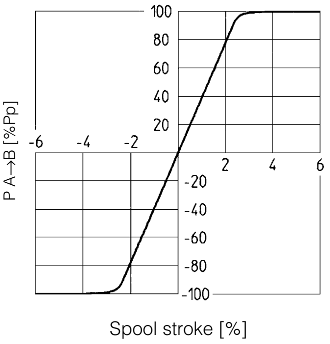
Regulation diagram at characteristic Δp

Valve's-regulated flow variation according to the electric reference signal



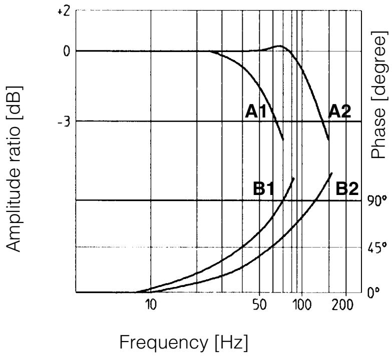
Regulation diagram at max reference signal

Regulated flow vs. functional Δp at max reference electric signal
Valve's-regulated flow variation according to the valve pressure drop.



Pressure gain diagram

Outlet pressure on use ports plugged variation according to the spool stroke only for valves with zero overlapping in rest position.
On X-axis, spool stroke is expressed in percentage of full stroke.
On Y-axis, the Δp between A and B ports is expressed in percentage of inlet pressure.
Pressure gain is the value of spool stroke [%] at which Δp between A and B ports corresponds to 80% of inlet pressure.

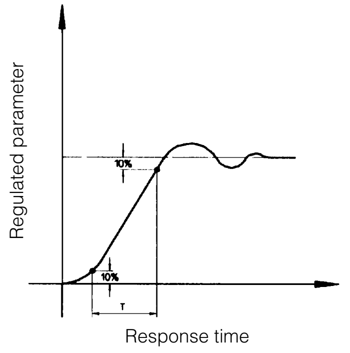


Bode diagram

The curve shows for typical regulation ranges (±5% and ± 90%):

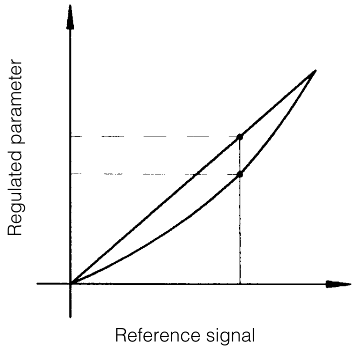
A) how the amplitude ratio (between the amplitude of reference signal and the actual amplitude of spool stroke) varies with the frequency of a sinusoidal reference signal;

B) how the phase (between a reference sinusoidal signal and the actual spool stroke) varies with the frequency of reference signal



Response time - step input

The time lag required for the valve to reach the requested hydraulic ragulation following a step change in the reference signal (usually 0÷100%).
Response time is measured in millisecond [ms] from 10 to 90 % of the step valve and it is an easy parameter to evaluate the dynamics of the valve.



Hysteresis

The maximum difference between two regulated hydraulic parameter values obtained reaching the same set of the command from 0 to maximum and then from maximum to 0.
Hysteresis is measured in percent of the maximum value of the regulated hydraulic parameter.