

Electro-hydraulic System Design: Making the right system choices

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Designers who understand and can take advantage of the differences between fluid power and traditional electromechanical power can build machines that produce higher quality output with lower lifecycle costs. Particularly for applications where precise control of large forces and smooth motion are required, fluid power can deliver significant benefits. Care must be taken, however, in selecting and sizing the hydraulic system elements and in tuning the motion controller for optimal performance.

Comparing electric and hydraulic power sources

Conventional electric motors are well suited to applications where the predominant form of motion is rotational. They are generally easy to control and can be the least expensive power source in small systems that have few axes or light loads. Linear electric motors have an advantage in positioning applications where motion is linear and requires quick direction changes, although they can be more expensive than conventional motors. Hydraulic motors and actuators can do virtually everything that electric motors can do, but with several advantages that may be key to meeting productivity goals.

For example, hydraulic actuators can lift and hold heavy loads without the need for braking, can move heavy objects at slow speeds or apply torque without the need for gearing, and consume less space and produce less heat at the actuator than electric motors. Electric motors must be sized for the maximum load that will be applied, whereas pumps need to be sized only for the average load. Hydraulic actuators are

comparatively small, even for applications that involve heavy loads. The hydraulic advantage is greatest when there are breaks in the motion as the accumulator (a hydraulic fluid reservoir) stores energy while the system is not moving. On the other hand, electric motors make sense in applications with continuous motion such as conveyor applications.

An electric motor is typically located close to or directly on the motion axis. With hydraulic power, the fluid pump – along with its noise and weight – may be located remotely. Only the accumulator and pressure control valves must be located near the actuators. This can make fluid power an ideal motive force for robotics applications with many axes. The pump can be mounted in a base location, keeping the weight on the arms as low as possible. And sharing a pump between multiple axis actuators can result in a cost per axis that is lower than the equivalent system employing electric motors.

Fluid power has the additional advantage that pressure can be held constant without applying significant additional amounts of energy. By comparison, driving an electric motor to apply constant torque could cause the motor to overheat. In material transfer applications that are prone to binding due to mishandling of material, fluid power – with its more compressible power transport medium – may be more forgiving of jams than electromechanical power. The key to unlocking the benefits of hydraulic power is understanding the system requirements.

Selecting/sizing electro-hydraulic system components

Designers developing electro-hydraulic systems for the first time will have to deal with some new design issues. The most common use of hydraulic power is linear motion and the most important factor in planning linear motion systems is sizing the actuator cylinders. Figure 1 shows the hydraulic circuit and the motion controller connection to the valve and transducers.

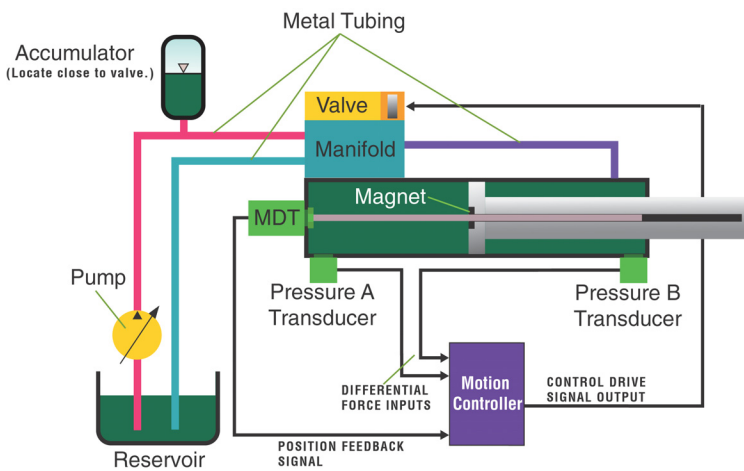


Figure 1. Electro-hydraulic system components

Clearly, the cylinder selected needs to be long enough for the stroke required. Where mistakes are sometimes made is in specifying the diameter of the cylinder. The cylinder choice is crucial, since the natural frequency of the system is roughly proportional to the diameter of the cylinder. The natural frequency determines the maximum acceleration rate the system can achieve under control. Therefore if a system needs to accelerate twice as quickly, the natural frequency of the system must be twice as high and to do this the cylinder diameter must be twice as big. A common error is to use small diameter cylinders that are capable of moving very quickly under relatively light loads. Unfortunately, under higher loads the piston in a

narrow cylinder provides little surface area that the hydraulic pressure can push on to provide the required force. Consequently, the system may not get to the desired speed in the distance required. If a large amount of hydraulic force is applied, a small diameter cylinder can act as a hydraulic spring. The effect of this is to cause the system to oscillate when it is no longer accelerating as the hydraulic spring attempts to return to its uncompressed state.

Because fluid is compressible, a fluid power system is much stiffer with a large diameter piston compared to a system using a small piston in a long, thin cylinder. Hence, systems with larger cylinder diameters will not compress as much when accelerating and are capable of quicker acceleration and deceleration because there is more surface area to push against. Because of the compressibility of the fluid medium, it is harder to keep long, thin cylinders under precise control than shorter, wider ones. As a rule of thumb, in order to be precisely controllable, the diameter of a hydraulic cylinder must double to decrease acceleration times by half.

After choosing the piston/cylinder diameter for the desired acceleration, the pump size must be calculated to provide fluid flow for the speed and acceleration needed. If the pump is too large, however, fluid and the power that pumps it may be wasted. Fortunately, the calculation is relatively simple: The required volume of oil flow matches the required change in internal volume of the cylinder over time. To achieve double the acceleration requires double the diameter or four times the surface area. With four times the area and twice the speed, the oil flow must be eight times higher.

The accumulator in a fluid power system serves two purposes. First, it serves as a buffer, allowing the

power requirements from the pump to be time-averaged. Second, it allows the system pressure to remain relatively constant, so that the effects of motion control inputs remain relatively constant. This avoids the need to continually change the control input-response relationships used by the motion controller to maintain precise control. A good rule of thumb is to make the accumulator large enough so that the pressure doesn't change by more than ten percent during the system's operating cycle. Further, in order to minimize system pressure losses in the system, it's important that the accumulator be located close to the valve rather than close to the pump.

Selecting valves

There are two types of valves used in fluid power systems: servo valves and proportional valves. With servo valves, a linear increase in the current through the valve coil directly moves the spool, causing a linear increase in the flow of oil through the valve. Proportional valves, on the other hand, have position feedback on the spool, which the valve amplifier uses to linearize the valve. Proportional valves are generally less expensive and more tolerant of contaminants than servo valves, but these benefits often come at the expense of performance. Precise hydraulic motion control requires the use of servo-quality proportional valves. Valves often have an overlap or "dead band" in the center where the flow is blocked. The presence of the dead band causes a non-linearity in the response of the system, for which the motion controller must compensate. Zero-overlap valves are often necessary for optimum performance.

For maximum system responsiveness to control inputs, valves should be sized to provide the required flow plus another 10 to 20 percent. On the other hand, if the valve is too large compared to the size of

the cylinder, control of the valve will be coarse as only a small part of the control range is being used.

In laying out the system topology, mount the valves as close to the cylinder as possible and use tubing instead of hoses. This reduces the volume of trapped oil and reduces compressibility. Also, the valve should be on top of the cylinder so that any air in the system will automatically be carried back to the fluid reservoir.

Pressure sensing

For monitoring pressure, sensors should be placed in the bottom of the cylinders on either end where they are not affected by trapped air and where there is less oil motion. A common mistake is to mount the pressure sensor in the manifold, where the venturi effects of moving oil can decrease pressure readings. Turbulence in the oil flow may reduce the venturi effect, but in any event, the pressure at the manifold may not be the same as the pressure in the cylinder.

Position sensing

Linear motion systems driven by a conventional electric motor typically calculate position using inputs from quadrature encoders connected to the motor shaft. Although this is convenient, it can lead to imprecise motion if backlash exists in the system (backlash refers to the condition that results when the inertia of a moving load causes the actual position of the load to differ from its measured position as provided by the encoder). Using linear transducers such as linear magnetostrictive displacement transducers (MDTs) avoids this. Unlike quadrature encoders, MDTs measure absolute position and do not require homing. MDTs also have pressure and temperature specifications that allow them to be inserted directly into hydraulic cylinders.

Selecting a motion controller

Critical to delivering the benefits of electro-hydraulics is a motion controller that is specially designed for the job. Designers should look for an electronic motion controller that:

- 1.) Provides a direct interface to transducers for position and pressure information, thereby avoiding extra interface costs and performance delays due to signal propagation.
- 2.) Supports the control of proportional valves in order to generate precise hydraulic motion.
- 3.) Has the ability to perform smooth transition between position and pressure control modes in order to avoid discontinuities in the motion that can impact performance and quality of output.
- 4.) Can coordinate multiple axes simultaneously by “gearing” one axis motion to another, so that precise, repeatable motion can be assured while improving throughput.
- 5.) Supports the execution of high-level commands, such as higher order function interpolations, to smooth the motion without requiring complex and time consuming low-level programming.
- 6.) Is supported by graphical tuning tools to speed the optimization of designs.
- 7.) Provides direct interface between the motion controller and factory or fieldbus networks if the machine being controlled is part of a larger plant environment.



Figure 2. – A well-connected motion controller provides direct interfaces to transducers as well as system buses. This is the RMC100 from Delta Computer Systems, Inc.

Many of the characteristics listed are also useful for electro-mechanical control. In fact, some designers are building complex systems that coordinate control of both electro-mechanical and hydraulic motion axes.

Tuning the motion

Tuning fluid power systems is similar to tuning electro-mechanical systems. Electric servos have two main modes of operation. In velocity mode, the speed is proportional to the control output from the motion controller to the drive amplifier. In torque mode, the torque or acceleration of the servo is roughly proportional to the control output to the amplifier. Hydraulic systems only operate in a velocity mode, as the flow of oil is ideally proportional to control output from the motion controller. Velocity mode is more intuitive than torque mode and is easier to set up by running the system with open loop controls (i.e., without feedback). In torque mode, the system must always be on closed loop control because a

constant open loop voltage will cause the servo motor to accelerate and keep accelerating. Sending a zero control output does not cause the servo to stop, it just allows the servo to coast to a stop.

Tuning the proportional, integral and differential terms (P, I and D) is similar for tuning a velocity mode or torque mode controller. However the importance of the differential term is much greater in controlling an electric motor in torque mode. Torque mode requires the differential term, which relates to the rate of change in the error between the system's actual position and its target position, to provide speed stability. In contrast, electric servo velocity-mode systems are easier to set up and usually do not require a differentiator because the motor's drive amplifier provides this function. The downside is that the drive amplifier must be properly tuned as well as the motion controller, increasing the tuning effort required to ensure proper system operation. It is often easier to fix the gain of the drive amplifier to a constant value and let the motion controller manage the motion profile solely in relation to its internal PID values so that all the gains are in one place. Since fluid power systems always operate in velocity mode, they share the advantages of simpler tuning with velocity-mode electric motor controls.

In addition to P, I and D control parameters, many motion controllers also provide feed forward parameters. Feed forward terms in the control algorithm provide the ability for a control system to anticipate and proactively drive the motion rather than react to transducer stimulus. In electro-hydraulic systems and electro-mechanical systems using velocity-mode controls, the velocity feed forward is the most important term in a correctly designed algorithm. It provides a component to the control output proportional to the velocity. Acceleration feed

forwards are required only to give the control signal an extra boost while accelerating and braking while decelerating, but the acceleration feed forwards have no effect while the system is moving at a constant velocity.

After the feed forwards are set up, the designer will typically tweak the P, I and D gains to get the desired control. Tuning the PID takes a certain amount of output to make a system move. The controller generates this output using five terms, generated by the acceleration feed forward, velocity feed forward, proportional gain, integral gain and differential gain. The goal is to make the feed forwards do most of the work. This way, the PID contribution to the control output is small and therefore the error between the target and actual position is small.

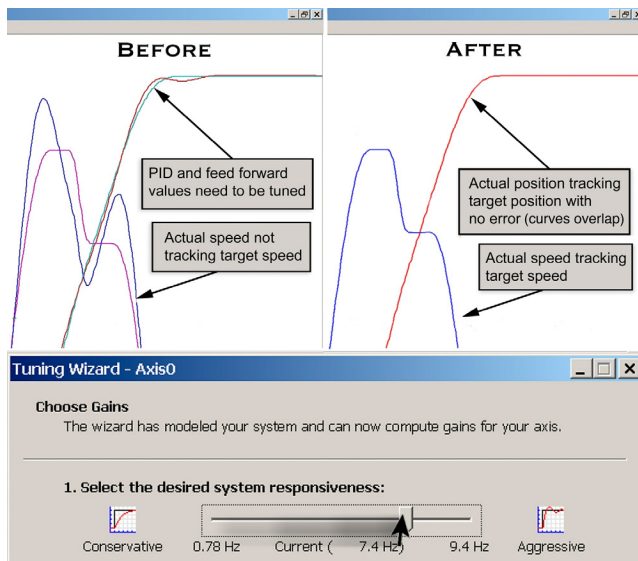
Another difference between electric servos and fluid power actuators is that electric servos typically require only one set of gains. Fluid power motion controllers require two sets of gains for linear cylinder applications. This is because the surface area on either side of the cylinder piston is different because of the cylinder rod. This difference in area causes the maximum force – and therefore system gain – to be greater when the piston is extending than when retracting. A typical electric servo controller will have a hard time controlling a hydraulic system because it usually has only one set of gains. The electric servo controller can be tuned to work properly in one direction only. Hydraulic motion controllers should have two sets of gains; one for extending and one for retracting. Having two sets of gains is also handy in vertical applications where the load changes greatly depending on whether the system is moving up or down.

A recent trend in the motion industry is the availability of automated tuning tools that simplify and shorten the setup, tuning and optimization process. An example of such a product is a Tuning Wizard (see Figure 3), that builds a set of mathematical system models and determines which model best fits the real system. The Tuning Wizard next prompts the user to set the desired system response between “conservative and aggressive” using a computer mouse and slider bar and computes the optimum PID and feed-forward gains. This allows the engineer or technician to easily and quickly determine which gain values match the best practical performance needs of his machine. The tool is also valuable for retuning a system after replacement maintenance of closed loop devices including valves or position sensors.

Proper selection and configuration of system elements makes fluid power advantages possible

Machine designers and integrators are faced with a wealth of options, including a choice of power sources to drive their designs. Hydraulic power has many advantages for key industrial applications, and hydraulic motion control has benefited from recent advances in the performance of electro-hydraulic actuators and motion controllers. Beyond the advanced closed-loop control capabilities that are provided by new electro-hydraulic motion controllers, the latest tuning tools make it easier to develop optimized designs much more quickly.

The result is machine control systems that deliver to their owners improved quality, increased production and longer machine life



This manuscript includes material that was provided to Machine Design magazine for an article that ran in April, 2004.

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Figure 3. Delta Computer Systems' Tuning wizard adjusts motion plots to reduce motion errors.