Fluid Power vs. Electromechanical Power

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Many engineers use electric motors when fluid power using hydraulics or pneumatics would actually be a better power choice. Traditionally, hydraulics and pneumatics have not been thought of as power sources for precise motion. In the past, many hydraulic or pneumatic driven machines used two-position actuators, with motion limited only by limit switches. This gave valve control for such systems the nickname “bang-bang” control due to the sound and shock of the actuators. Due in large part to advances in motion control technologies, fluid power control systems have come a long way, and open up new opportunities in improving quality and cutting life cycle costs for machinery designers.

Fluid power vs. electromechanical power

Electric motors must be sized for the maximum load that will be applied, whereas fluid power sources (pumps) need to be sized only for the average load. Fluid power actuators are comparatively small, even for applications that involve heavy loads. The fluid power advantage is greatest when the motion duty cycle is not 100%. The reason for this is that the accumulator in a fluid power system 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.

In electromechanical power systems, the electric motor is typically located close to or directly on the motion axis. With fluid power, the hydraulic or pneumatic pump may be located remotely along with the noise and weight that comes along with it. Only the accumulator, the fluid pressure storage tank, must be located near the actuators.

In a system employing fluid power, a single pump can provide the power for multiple actuators. This makes fluid power an ideal motive force for robotics applications with many axes. The pumps can be mounted in a base location, keeping the weight on the arms as low as possible.

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, such as would be required in a press type of application, could cause the motor to overheat.

Fluid power is also much easier and more cost effective in applications that require both pressure and position control. Machinery such as presses, injection molding machines, and material transport systems that involve grabbing things (such as log positioning systems in sawmills) often require position control to move an actuator into place and then pressure control to fine tune the motion and ensure a controlled amount of “grip.” Other systems, such as press rolls in steel rolling mills or sawmills, position heavy rollers above the work in process and then apply a controlled amount of pressure on the roll.

Electric motors can be used to apply a pressure force by generating torque, but holding torque requires continuous power. If the torque is not limited by the control system, the motor might burn out.

If the application involves only rotary motion, and that motion is continuous, such as in a conveyor system, then there may be no advantage to using fluid power because the pump may be running all the time. On the other hand, if there are multiple conveyers in the system, then hydraulics may provide a less expensive source of power because the hydraulic motors are small and only one power source may be needed. Also, with 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 to “jams” than electromechanical power.

Unique issues associated with fluid power system design

Designers developing fluid power systems for the first time will have to deal with some new design issues. The most common use of fluid power is linear motion, and the most important factor in planning linear motion systems is sizing the actuator cylinders. 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 are capable of moving very quickly, but a large amount of hydraulic force goes to compressing the ‘hydraulic spring’ associated with the small diameter cylinder. This will cause the system to oscillate when it is no longer accelerating and the ‘hydraulic spring’ can return to its uncompressed state. Also there is 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.

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 are capable of quicker acceleration and deceleration because of 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. In general the diameter must double to decrease the acceleration times by half.

Selecting/sizing hydraulic system components

After choosing the piston diameter for the desired acceleration, you need a pump that will provide the fluid flow for the speed and acceleration you need. If the pump is too large, however, fluid and the power that pumps it may be wasted. Fortunately, the calculation is relatively simple: If you want to be able to travel at 60 inches per second and you have a 3 inch diameter cylinder, then you can compute the minimum fluid flow that is needed, which is 424 cu in per second: vol=pi*r^2, 424=3.14*$(1.5)^2$*60. The speed of motion varies proportionately with the speed of oil flow, but if the goal is to make the system move in half the time, accelerations and decelerations must double to make the same quality move. To achieve double the acceleration requires double the diameter or 4 times the surface area. With four times the area and twice the speed, the oil flow must be 8 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 to ensure that the pressure doesn't change by more than 10% 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 tolerance of contaminants than servo valves, but these benefits often come at the expense of performance. Motion control requires 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.

Proportional valves also have the problem that at high pressures, the spool is harder to move because it must move against the oil pressure. Sometimes dual-staged valves are used to get around this problem.

Servo systems function similarly to the power steering system on a car. Turning the wheel slightly diverts a little oil, which ports oil to either end of the valve spool which causes the spool to move.

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 a position/pressure application this is critical because the system gain, when controlling pressure, is very high. This requires the controller gains to be very low to compensate, making the system harder to control. If you need a larger valve for position control, then you might need two valves in the system: a coarse valve and a fine valve. The larger coarse valve would be used when traveling and the smaller fine valve would be used while in pressure control. Another way of solving this problem is to use jack rams. A jack ram is a smaller parallel cylinder that is used while moving. While moving a small valve can be used to move the smaller diameter cylinder at the required speed because there is no load. The smaller cylinder also is moving the larger cylinder which is filling itself from the tank. Just before the system goes into pressure controller the valve that lets the larger cylinder draw oil from the tank is shut and the small valve is then used to fill both cylinders. Now the system gain is reduced and the small valve can easily control pressure.

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, the 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

Electric motor systems typically use quadrature encoders connected to the motor shaft. Although this is convenient, it can lead to imprecise motion if backlash exists in the system. Using linear transducers such as 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.

The same types of encoders are used to measure rotation in rotary hydraulic applications as in electromechanical applications. Some of the newest encoders and MDTs provide synchronous serial interfaces (SSI) to connect to the motion controller. Direct SSI interfaces allow for very precise control, providing 24 bits of position information, which allows position resolution down to two microns.

Using motion controllers in fluid power vs. electromechanical systems

Smooth motion with linearly changing acceleration extends the life of machines and improves the quality of the products they produce. Fluid power systems are capable of very smooth, precise motion when controlled by the right motion controller.

The motion controller should be capable of performing both pressure and position control, and should have the ability to interface directly with servo valves and transducers, without requiring additional translators or interface elements. The RMC100 motion controller from Delta Computer Systems, Inc. (figure 1) can mix and match these transducers.

The motion controller provides gearing and complex motion control for fluid power systems with splines. With spline functions, implementing smoothly curving motion profiles is as easy as providing the motion controller with endpoint coordinates and instructing it to connect the dots.

The motion curve defined by the spline represents the position an axis will be at as a function of time or another axis' position. Velocities and accelerations are determined by differentiating the spline equation at each axis position. With splines, complex motion profiles can be easily specified graphically. The machine designer defines only the positions; the spline algorithm computes the acceleration and velocity necessary to get smoothly from one point to another. Under ideal situations, these points can be defined graphically with a CAD type of tool, and the machine designer is relieved of the tedious calculations for each segment between the defining points.

Tuning

Tuning fluid power systems is similar to tuning electromechanical 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 derivative 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 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 drive amplifier provides this function. The down side 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.

Another difference between the torque mode and velocity mode is how the feed forward gains are set up. 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 velocity mode, 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. This means that if the motion profile is a trapezoid, control output will also look like a trapezoid (see figure 2). 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. In torque mode, the acceleration feed forwards are the most important term after the differentiator, and the velocity feed forward play a minor part of overcoming frictional forces proportional to speed. In torque mode the control out will rise proportionately to the acceleration and then drop to almost zero while in the constant velocity part of the profile (see figure 3). During the constant velocity part of the profile, the velocity feed forward is supplying the output necessary to overcome friction as a function of speed. During the deceleration part of the motion profile, the control output goes negative because the acceleration is negative. This causes a braking action that stops the motor rather than just letting it coast to a stop.

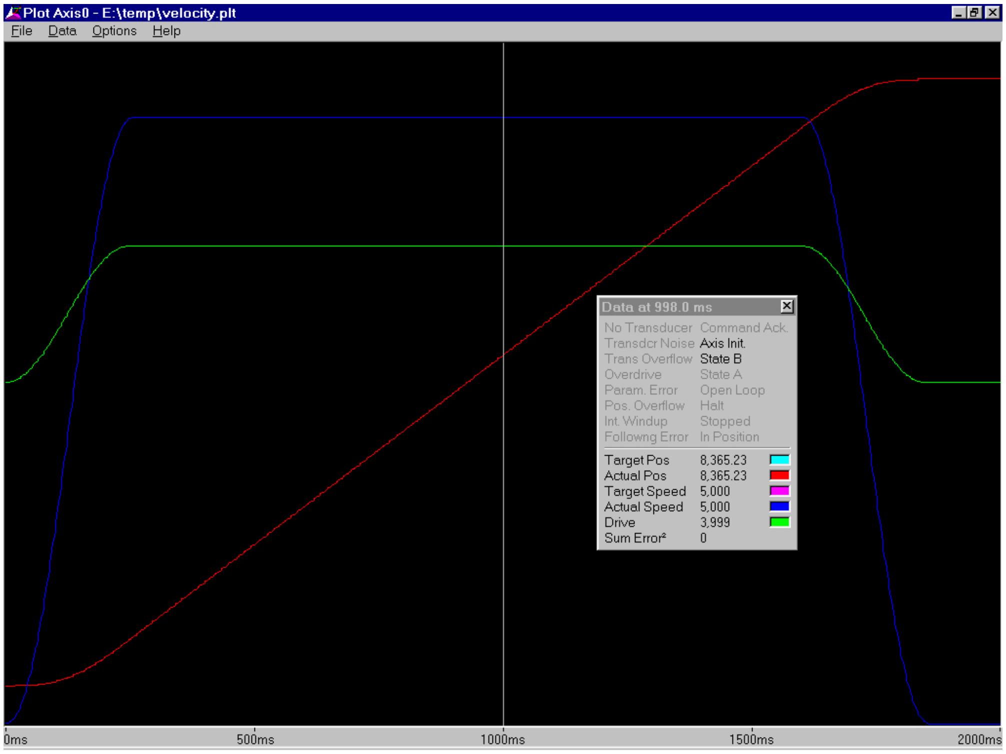
After the feed forwards are set up, the designer will typically tweak the P, I, and D gains to get the desired control. Tuning the PID is similar in torque mode and velocity mode, however it takes a certain amount of output to make a system move. The controller generates this output using five terms, 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 are rotational whereas hydraulics may be rotational or linear. Rotational systems require only one set of gains. Fluid power motion controllers, for example hydraulic controllers, require two sets of gains for linear cylinder applications. 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 extending than when retracting. A typical electric servo controller will have a hard time controlling 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.

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

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, especially in applications where precise control of large forces and smooth motion are required. In order to deliver the benefits of fluid power control, however, care must be taken in selecting and sizing the hydraulic system elements and in tuning the motion controller for optimal performance.

Figure 1 – Delta Computer Systems RMC100 motion controller

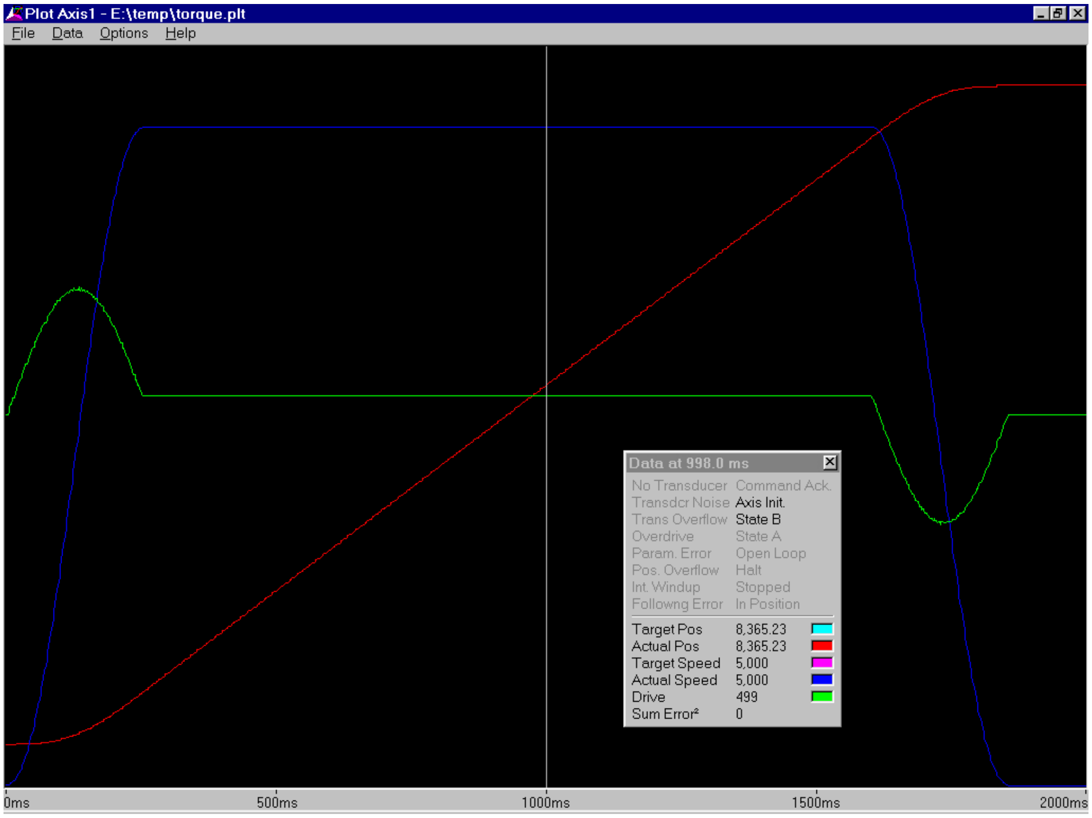


Data at 998.0 ms

No Transducer
Transdcr Noise
Trans Overflow
Overdrive
Param. Error
Pos. Overflow
Int. Windup
Followng Error
Command Ack.
Axis Init.
State B
State A
Open Loop
Halt
Stopped
In Position

Target Pos	8,365.23	🟦
Actual Pos	8,365.23	🟥
Target Speed	5,000	🟪
Actual Speed	5,000	🟦
Drive	3,999	🟩
Sum Error²	0	

Figure 2 – This plot shows a velocity mode move. The green line is the control output. The red line is the position and the blue line is the velocity.



Data at 998.0 ms

No Transducer Command Ack.
Transdcr Noise Axis Init.
Trans Overflow State B
Overdrive State A
Param. Error Open Loop
Pos. Overflow Halt
Int. Windup Stopped
Followng Error In Position

Target Pos	8,365.23	🟦
Actual Pos	8,365.23	🟥
Target Speed	5,000	🟪
Actual Speed	5,000	🟦
Drive	499	🟩
Sum Error²	0	

Figure 3 – This plot shows the same mode with a motor in torque mode. Notice how the drive must be large while accelerating and very little while at constant velocity. This is similar to the action of an accelerator on a car.