Area of Interest
Linear actuators

Our Reference
Marius Hendriksen & Thomas Wintjes

Contact
+31 411 65 1991
Large.cylinders@boschrexroth.nl

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Whitepaper

Developments in electromechanical and electrofluid driven linear actuators

Abstract

Linear actuators are widely deployed in various applications. The characteristics, which influence an engineer's choice for a linear actuator are power density, motion control, system components, environmental resistance, efficiency and maintenance of the devices. General requirements are low cost, durability and environmental concerns. Boosted by the current electrification trend the electromechanical linear actuator is storming the market but not always for the right reasons. Additionally hydraulic linear actuators are losing market to older mechanical designs for debatable arguments.

The ongoing debate for these two linear drive solutions forms the motivation for making this paper. The evolution of a hydraulic linear actuator to a hybrid form (electrofluid linear actuator) is compared to the electromechanical linear actuator. All key elements of these drive solutions are provided in a technical context to enable a proper drive choice; no solution fits all.

Rexroth designs, produces and utilizes the full technical spectrum of electromechanical and electrofluid linear actuators. To aid its own application engineering, sales staff and foremost its customers engineering departments, there was a need to describe these different linear actuator drive concepts.

Linear motion

Linear actuation or motions earliest reference can be found centuries ago. Starting with simple winches with ropes of natural fiber, rotational motion transformed into linear motion. Off course, one can only pull with a winch, and it took only a short while before a clever engineer combined a wooden pole with a winch, in order to create a linear pull and push motion. This combination, of winch and pole, was used to open and close miter gates.

During the first industrial revolution this principle was refined to handle larger loads by using a rack and pinon construction. For locks and bridges, a variant on the rack and pinon is designed: the Panama wheel. With a Panama wheel, the open gear parts are shielded against the environment and easily accessible for maintenance. Using hydraulic pressure in linear actuators dates back to 1795 when Joseph Bramah patented the first hydraulic press in England, paving the way for the for the industrial revolution to improve machines like printing presses, cranes, cutting and stamping devices and thus automating the manufacturing process. Main advantage of hydraulics

Example application of a panama wheel

is power density; creating high power machines with the absence of large open gears. Two marvels of engineering and construction of that era, using (water) hydraulic actuators, are the elevators in the Eiffel Tower in Paris and the movable Tower Bridge in London.

A big advantage of hydraulic systems used to be the controllability of flow and pressure of the hydraulic fluid for different actuators. Power is generated by electric motors. As the controllability and energy efficiency was not optimal, especially at low speeds under maximum torque operation, a good controllable fluid coupling was preferred over a mechanical geared coupling. A massive development in electric drives took place the last three decades. These drives have become more compact, reliable, power dense, environmental friendly and have an excellent controllability. They have also become incredibly economical to produce. This is steadily resulting in a switch from hydraulic to electric drives. First in rotary driven applications like winches and rack and pinon drives. Nowadays more electromechanical actuators are used, which are on the rise. Initially the market for electromechanical actuators was limited to low force applications, predominantly replacing pneumatic actuators. The last 15 years the development of large screw spindles and roller screws has come to the level of medium sized hydraulic actuators. Environmental legislation and customer awareness have led to a "back wind" for the development of "non-oil" linear actuators.

Two drive principles

The electrofluid actuator consists of an outer shell, bottom, head, piston, rod, accumulator (for volume compensation) and a "power box" mounted on the shell. This setup has two pressure chambers, one on either side of the piston. The power box contains a complete power unit in order to convert electric power into fluid power. This creates a hybrid actuator, power and control signals go in, and the fluid coupling creates a linear actuator.

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Electrofluid driven linear actuator

The electromechanical actuator consists of an outer shell, bottom with thrust bearing, drive shaft and connection for a drive module, anti-rotation device for the nut, hollow rod accommodating a screw spindle and a nut to transfer the rotating motion from the screw spindle to linear motion of the rod.

Electromechanical driven linear actuator

Both systems use an electric motor as power supply. The fundamental difference is the transmission from the rotational speed and torque of the electric motor to linear motion and force. Electrofluid actuator is based on a fluid coupling. Electromechanical is based on a mechanical gear coupling.

Fluid coupling
(Hydraulic) fluid is compressible (extreme stiff fluids exists, but are not within the scope of this paper). For hydrocarbon-based fluids, a rule of thumb for compressibility is 0.7 % per 100 bar (1450 PSI). The fluid acts like a spring, its characteristics depend on the quantity of fluid (and possible small amount of air) inside the actuator and the actuator geometry. This “spring” will compress under increasing load conditions and expand under decreasing load conditions, influencing the position of the actuator. A volume of fluid also expands when heated or contracts when cooled. Therefor temperature can influence the actuators motion. A pump driven by an electric motor pumps fluid into an actuator. Commercial available pumps use a few percentages of the compressed fluid for lubrication purposes.

The result of compressibility, thermal expansion and leakage, is twofold:
1. There is no accurate correlation between the rod position and the number of rotations of the electric motor. For accurate position information, a separate position measurement is required.
2. The (hydraulic) fluid acts as a lubricant and shock absorber.

Geared coupling
The mechanical actuator is extremely stiff compared to the fluid variant. The gear transmission will deflect under load increase and the spindle will twist but both are neglectable. There is a direct and accurate linear correlation between rotation angle of the electric motor and linear rod motion, independent of the load on the actuator. Measuring the rotational angle of the electric motor results in a direct and accurate measurement of the rod position, therefor:
1. (Usually) no need for a rod position sensor.
2. A lubricant, such as oil or grease, is required for lubrication and corrosion protection.

Additionally a cushioning device (spring) needs to be installed to protect against vibrations and shock loads, this to prevent catastrophic failure of the linear drive.

Overload

Linear actuators can experience overload situations by an external force. In electromechanical actuators the ball nut and roller screw usually have back driving capabilities, they will start rotating by an external force. Because of these back drive capabilities an external braking device is required to prevent the actuator from moving by an external load when the electric motor is off. There are also limits to the acceleration capabilities of the ball nut/roller screw. With an instant force (collision or shock load) the ball screw cannot decelerate fast enough, it “freezes” and the load will be transferred to the mechanical structure causing a bend or break situation. The mechanical strength of the actuator determines the resistance to the external force. The construction of an electromechanical actuator has to withstand the maximum anticipated overload. The result being an over dimensioned construction. With an electrofluid actuator there is a direct correlation between force acting on the actuator-rod and the pressure inside the actuator, the use of a pressure relieve valve is sufficient to prevent catastrophic failure under overload situations of the construction. The maximum speed of the actuator under an overload situation is determined by the size of the pressure relieve valve. The energy of the impact is dissipated into the fluid as heat.

Rules

The electrofluid actuator is a pressure vessel. The vessel needs to be constructed and tested to withstand the maximum pressure, were the electromechanical actuator needs to be constructed to withstand the external forces on the actuator construction. The electrofluid actuator

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requires seals to keep the fluid inside. The electromechanical actuator needs seals as well, first to keep dirt and moist outside away of the mechanical rotation parts. Second to keep the lubrication oil or grease, which is required for every electromechanical actuator, inside. In a conventional hydraulic system a lot of piping and hoses were required to drive the actuator. By creating a hybrid form, being the electrofluid actuator, the risk for high-pressure fluid leaks is reduced to a minimum. Some application HSE rules exclude hydraulics because of environmental laws and customer demands, based on valid leakage risk statistics. One could reconsider these arguments as the oil volume in a hybrid actuator system is reduced to a minimum (compared to a traditional system with a reservoir) and almost equals the leakage risk numbers of the electromechanical actuator because hoses and almost all piping is eliminated. One could also see environmental benefits in the reduced cellar- or building size, which is no longer required for a power unit or a counter weight (refer to 'Static load compensation').

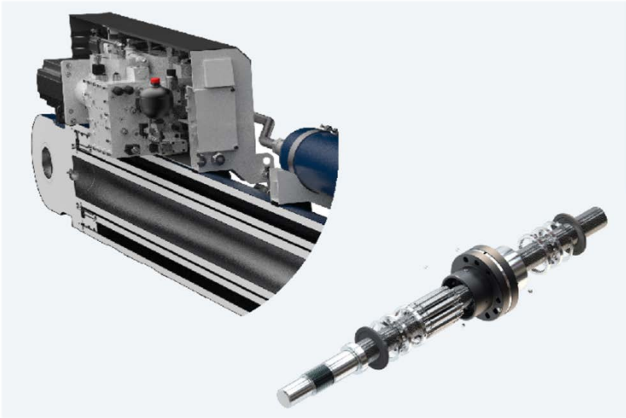
Limitations

The basic parts of an electrofluid actuator are relatively simple compared to an electromechanical variant. If a long stroke (>6meter) is required, two or more shells can be welded together. In theory, there is no limit. Practically, the maximum inner diameter is approximately 1.5 meter (5 feet). The maximum length can go up to 30 meter (100 feet). Often the limitation is the maximum hoisting capacity of the production facility and/or the possibilities for transportation to the working location. In practice a large actuator is wide and short (pressing applications) or slim and long (pulling applications).

The electromechanical actuator has a similar outer shell and rod. The working hart of the actuator is the spindle and roller screw. This is a high precision set of equipment, produced by only a handful of specialized companies. Limitation is the maximum available length of the spindle, combined with a maximum dynamic and static load limitation on the spindle and nut.

Speed

The linear speed is limited by different parameters. In both systems the installed power in combination with the load, is a well-known limiting factor. In theory both systems should be able to move equally fast under equal power and load conditions. In the case of the electromechanical actuator the electric motor has to be mechanically fixed to the actuator. In applications, >100 kilowatt (135 horsepower) the size and weight of the electric motor becomes a limiting factor. Here an additional limiting factor is found in terms of redundancy, adding an electric motor in the drive train is not ideal. Adding a pump motor group in a fluid coupled drive is far more efficient.



Power box and spindle

In an electrofluid actuator, the maximum speed of the rod, is defined by the quantity of fluid, pumped into the actuator, in relation to the piston and rod surface area. The limiting factor is therefor in the Power box, as soon as the Power box no longer fits onto the actuator. If a higher speed is required then a conventional hydraulic linear actuator with a Power unit is selected.

In electromechanical actuators the maximum speed is determined by the rotational speed of the spindle, in relation to the pitch and lead of the nut. Friction between the spindle and nut is a limiting factor, which can be diminished by lubrication. This rotational speed is limited by the out-of-roundness (ovality) of the spindle and the deflection of the spindle in horizontal position by its own weight. Both cause vibrations in high-speed situations, were these vibrations could lead to catastrophic failure of the nut or support bearings. All these factors are highly dependent on production quality, diameter and length of the spindle and the nut type used.

Cushioning

Even though both actuators have accurate position capabilities, a form of cushioning is usually still required. The system is able to ramp down at defined end positions and prevent an overrun. In practice, one needs a form of cushioning in case of a technical failure. For low power electromechanical actuators, a simple rubber ring is sufficient. For high power applications and applications were an abrupt stop (man riding machines) causes too much dynamic forces cushioning is required. Cushioning is available in many forms such as a rubber ring, metal spring or a onetime use crumple element. In its core, the cushioning requirement is to absorb the kinetic energy of the installation over a predetermined distance. In case of an electrofluid actuator, cushioning is traditionally done by

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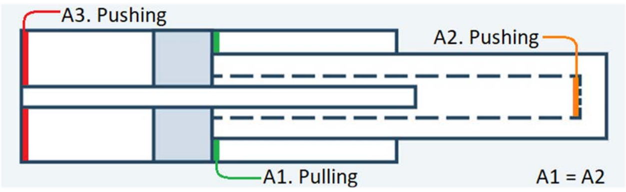
limiting the fluid, via a restriction (variable), from a certain position. This mechanical variant can be used multiple times and is not dependent on electronics.

Motion control
Motion control is rapidly increasing, simultaneous with the electrification trend. Infinite control over position, velocity, acceleration and force is preferred, but depending on the application not always required. Here the electromechanical and electrofluid actuators do not differ that much. Both are controlled by servo electric motors, and were the fluid coupling has its specific characteristics the possibility of using a variable displacement pumps counters this in combination with the drive and control system. The desired performance of the vast majority of applications is covered by both solutions.

Static load compensation

In applications, were a static load is permanently present, there is a possibility to apply a gas spring for permanent static load compensation. The gas spring compensates the static load while the drive system only needs to control the dynamic movement. This enables a significant reduction in installed power. An everyday example were this principle is applied is the power electric backdoor of a car trunk. Examples of applications were a continuous static load is present: motion systems, movable structures and cranes. With special linear actuators, electromechanical or electrofluid, a static load compensation is possible.



Schematic of a three chamber hydraulic cylinder

In electromechanical actuators, this compensation is achieved by sealing the actuator and filling it with nitrogen gas. The same principle can be applied in a three-chamber electrofluid actuator. This is the preferred standard setup of the hybrid linear actuator, where two chambers (A1 & A2) are equal in size, which reduces the accumulator size. The third bottom side chamber (A3) is usually not used but can also be filled with gas.

Summary

In linear actuation, the transformation from rotational to linear motion can be realized by a mechanical coupling, or a fluid coupling. Both solutions have their specific advantages and limitations. There is no “one solution fits all”. General physical limitations are force, stroke and power on both solutions. An electrofluid linear actuator is used in applications with the following characteristics:

- Power greater than 100 kilowatt (135 horsepower).
- Stroke greater than 6 meter (20 feet).
- Shock loads and (heavy) vibrations.
- Risk for (unexpected) high external forces (overload).
- Frequent start/stop operation with load.
- Frequent motion by external force (freewheel).
- Applications with a high speed/force spectrum (low speed – high force).
- (Emergency) Hand operation is required with maximum load.

In applications were these characteristics do not apply an electromechanical linear actuator can be used.

Call to action

Understanding both electromechanical and electrofluid drives is essential in order to select an optimal solution for any application. In the authors experience, hydraulic actuators are exchanged for electromechanical actuators due to a lack of technical knowledge of hydraulic systems or their hybrid forms. The electrification trend has led to a rise in electrically oriented technical studies. At the same time one can see a stiff decline in education possibilities and attention for hydraulics in technical studies. As a result, the majority of young engineers has a vast knowledge of electrical drive and control but little to no knowledge, let alone experience, with hydraulic drive and control. This imbalance can lead to “surprising” engineering solutions.

As an example: Civil engineering in The Netherlands. The last 40 years, miter gate doors and movable bridges have predominantly been opened and closed, using hydraulic actuators. The last 15 years these actuators have steadily been replaced by electromechanical linear actuators. This mostly for environmental reasons. As electromechanical linear actuators have their limitations (power, shock loads, vibrations, etc.) a solution needed to be found. The solution was found in the Panama wheel which is experiencing a revival in civil engineering. The fact that this solution is space consuming, expensive and has open gears exposing the environment to heavy grease is to the authors opinion a technological step back in time. A technical better step forward in this application is combining the best of both worlds. Using an electric drive, utilizing all its technical advantages and combining this with a fluid coupling, capable of handling shock loads, vibrations and overload situations and building far more compact (eliminating large cellars) and cost effective; a hybrid. ●