MacTaggart Scott
Innovators since 1898

Electric Actuation of Submarine Control Surfaces

Cameron Williamson

MacTaggart Scott

Introduction

Control surfaces take the form of hydroplanes, rudderons, or rudders, depending on their position and orientation. They are used to change the roll, pitch, and yaw of the vessel, which controls the depth and bearing of the submarine and providing stability. A high level of precision is required from the actuators to ensure that the submarine can be as stable and manoeuvrable as possible. However, they must also be very powerful, as the forces they are required to generate and withstand are significant.

Each control surface is mounted on a shaft along their axis of rotation, to which the linear actuator is connected via a tiller arm, giving a beneficial lever, allowing rotation of less than 180°. This is shown in a simple form in Figure 1.

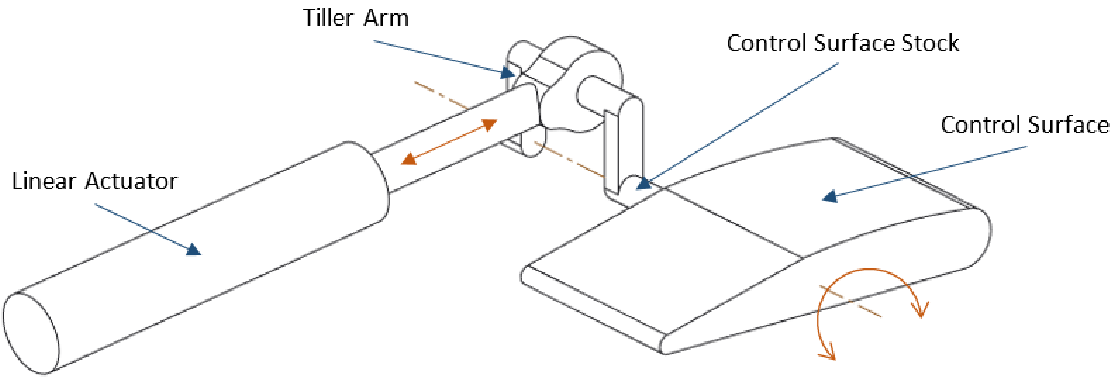

Figure 1 - Linear actuator and control surface assembly diagram

Currently, the actuation method for a control surface is a hydraulic system with a double-acting cylinder. This has historically been the preferred option, as hydraulic systems have a very high power density and they can be controlled with sufficient accuracy. Most submarines also already had many hydraulic systems in place, meaning they already had a sufficiently skilled workforce in place to deal with further hydraulic equipment, and could make use of the existing hydraulic power unit (HPU). An example control surface actuator system showing two bulkhead penetrations and a compound joint to constrain the actuator to purely axial motion, while allowing the tiller arm to rotate, can be seen in Figure 2.

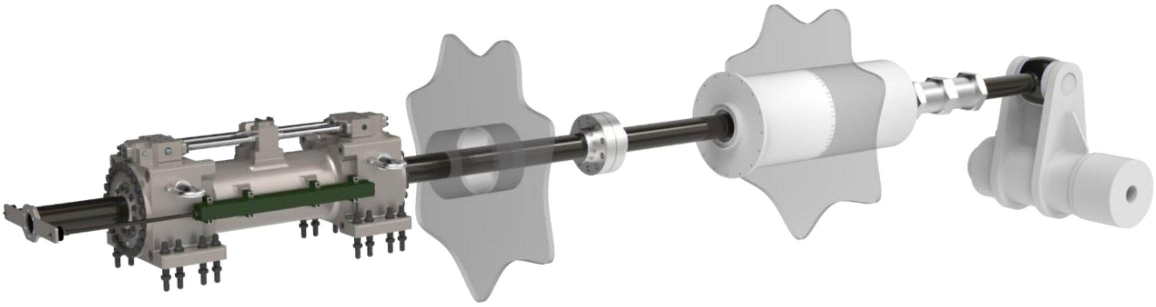

Figure 2 - Control surface hydraulic linear actuator with two bulkhead penetrations

Hydraulic actuators are still a very effective solution to the problem, but many modern shipbuilders are now becoming interested in the option of an all-electric boat. This would require that the submarine be designed with the intention of not using any hydraulic equipment. The main advantage of this change would be the reduction in the skill-set required of the crew, as hydraulic engineers and technicians would no longer be necessary. The second advantage to the all-electric boat is a significant reduction in maintenance requirements, as hydraulic equipment must be regularly inspected to ensure that filters and seals are working correctly. This maintenance is much reduced on an electric system, and condition-monitoring feedback from the system is more readily available, allowing maintenance activities to be proactively scheduled.

System Requirements

Control surfaces are mission critical components. While shipbuilders ensure redundancy in hydroplane, steering and diving systems, each actuator is a critical single point in the control of each surface. They are often positioned in locations that would be inaccessible while the boat is at sea, and so may not be repairable in the event of a failure. It is therefore essential that all aspects of the control surface system be robust and reliable.

The environmental requirements that must be designed for are severe, with significant loads caused by the depth pressure and impacts from debris or ice, and by the hydrodynamic forces generated by the speed of the vessel relative to the sea and from wave-slap or sea-slam.

The most significant loads are experienced during wave-slap or sea-slam. These occur when the submarine is surfaced and waves impact against the control surface. The forces generated by wave-slap or sea-slam events are often very large, as they can be applied to the whole surface area of the hydroplane or rudder. The system must be designed to withstand or dissipate these forces without damage to the equipment or the vessel.

The surface area of a control surface can be large, often greater than $30m^2$, and as such, the forces required for actuation can also be great, particularly when the submarine is travelling rapidly. Even negating wave slap and sea slam loading, the actuator must therefore be capable of producing forces in excess of 2000 kN.

Actuator Design Types

In the past the only viable option for high power actuation, with low speed and fine control was by using hydraulics. At the time, direct current (DC) motors were large and inefficient, with short life expectancies and alternating current (AC) motors could only be controlled coarsely. However, the variable frequency drive (VFD) has been improved significantly since its conception and now allows AC synchronous motors to be controlled at varying speeds and torques, to high precision with the addition of a relatively low cost drive panel.

This has led to a change, allowing alternative actuator types to be employed to move control surfaces with the power and accuracy required.

Hydraulic Actuation

Hydraulic linear actuators have been used extensively in the control of submarine hydroplanes, rudders, and rudderons and typically employ a double acting hydraulic cylinder, shown in Figure 3. The system requires an HPU, flow control, and other valves, depending on the interface to the HPU in use. The extension of the cylinder is controlled by adjusting the proportional flow valves, allowing hydraulic fluid to the cylinder at the desired flow rate and direction.

Submarines fitted with hydraulic equipment will typically use a large, centralised HPU, used to provide power to many hydraulic systems distributed across the ship. Where this is the case, a hydraulic linear actuator may take advantage of this existing architecture and avoid the necessity of an individual HPU, reducing the space consumption and cost.

This is one of the main strengths of the hydraulic system as, when considering only the actuator, the hydraulic system has a very high power density compared to any alternative option.

One of the main disadvantages associated with hydraulic systems, aside from the specific skills required for operation and maintenance, is the level of hydraulic fluid cleanliness required to ensure reliable operation of the hydraulic equipment. One of the greatest contamination risks to hydraulic circuits in the marine environment is the potential for seawater contamination, which can result in corrosion and increased wear, each of which can eventually incapacitate a system.

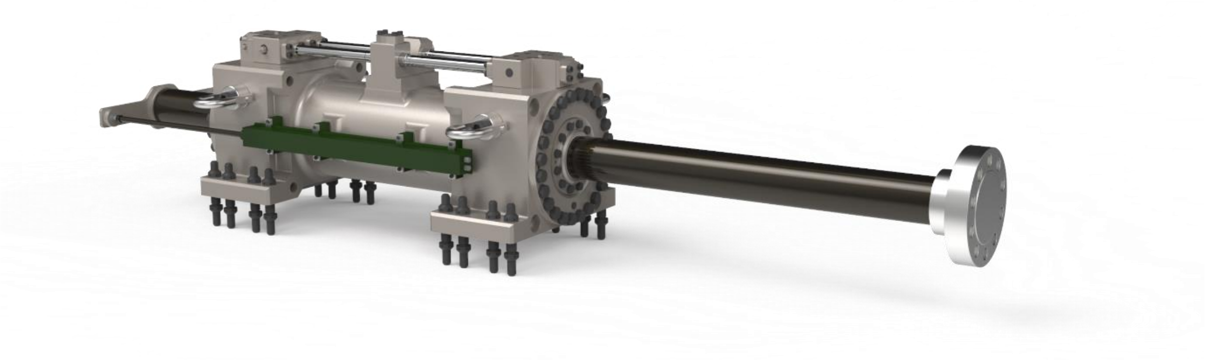

Figure 3 - Hydraulic linear actuator

Electro-Hydraulic Actuation

If the submarine does not contain an accessible main HPU, a hydraulic actuator can still be used, by providing a dedicated HPU for the linear actuator. An advantage of this is that the HPU can be sized specifically for the linear actuator and eliminates cross contamination from other hydraulic systems. Shorter pipe runs with fewer bends are then required for the connections to the actuator resulting in higher efficiencies and improved HPU reliability.

Standard HPUs rely on an electric motor running at a fixed speed, driving a fixed displacement pump to charge an accumulator bank from which the hydraulic fluid can be controlled by proportional flow valves. This allows the HPU to switch on and off intermittently, becoming active when the accumulators drop below a certain pressure.

A more flexible option with fewer components is now possible by using a VFD to provide variable speed control to the electric motor, which drives a fixed displacement pump. This removes the need for proportional flow valves, as the system can be driven directly by the pump and can be controlled at high precision more easily than previous systems.

These electro-hydrostatic systems generally require less maintenance than a standard hydraulic system, as the hydraulic components are simpler and will generally have lifetime filters.

A disadvantage to this system is the necessity for both a VFD panel and an HPU, and poor efficiency when the system is required to operate at low speed.

The issue of inefficiency at low speed can be countered by implementing a variable displacement pump in the HPU, allowing fine control via the VFD, while ensuring that the motor is never required to run at inefficient low speeds.

This variable displacement pump will often take the form of an axial piston pump, controlled by two proportional solenoids, which position the swash plate of the pump, giving variable flow rate and direction.

While the electro-hydrostatic actuator can improve the efficiency of a hydraulic system, it still relies on hydraulic components to carry out its duty. Consequently, this suggests that some level of hydraulic knowledge would still be required to operate and maintain such a system. Since some of the hydraulic components would be relocated from an accessible central location to a remote local position, it may prove troublesome when accessing the actuator for maintenance or repair.

Electric Actuation

The availability of high power and high precision VFDs mean that a fully electric linear actuator is also now possible. This design would involve using a VFD to control an electric motor, which would then be coupled to the control surface tiller arm by a mechanical arrangement, which converts the rotational motion into linear movement providing a mechanical advantage. The system would require a mechanical brake located at the motor, to take advantage of the gearing ratio of the system.

The most suitable mechanism to convert rotational motion into linear movement is a screw design. There are three distinctions to the screw design: the lead screw, the ball screw, and the roller screw, each with inherent advantages and disadvantages. A suitably sized roller screw based actuator can be seen in Figure 4.

Of the three, lead screws perform the lowest in efficiency, precision, load capacity, and life; however, they are also difficult to back-drive. This would often be considered as a negative attribute but in this context, it could be beneficial by reducing the requirements of the holding brake. The leadscrew is also the quietest of the three options, which is an important consideration, due to the stringent Noise and Vibration (N&V) specifications set to submarine manufacturers. Despite this, the low load carrying capacity, coupled with poor shock performance means that any lead screw design would require a very large screw diameter.

In comparison, ball screws and roller screws are highly efficient, often with efficiencies in excess of 90%. They can handle large loads and have long lifetimes, but can be easily back-driven, meaning the system would require a larger mechanical brake.

Roller screws have a higher load capacity than equivalent ball screws, but also produce more noise, so the specific boat requirements should be used to determine the most appropriate option.

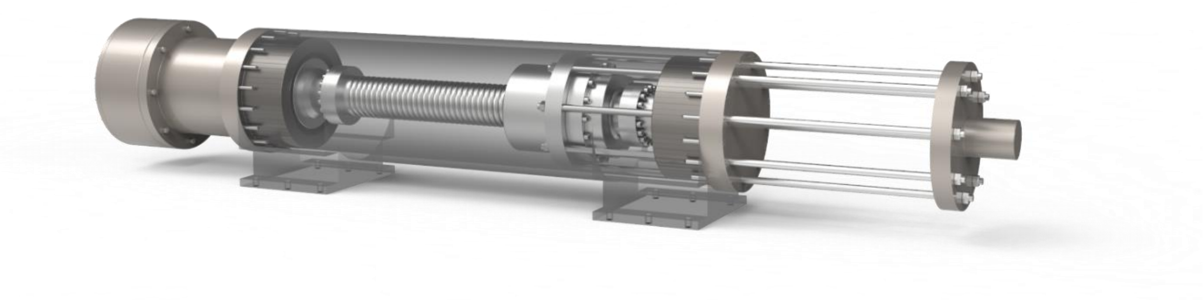

Figure 4 - Electric linear actuator (roller screw)

The selected motor could be either a high torque, low speed motor that would be directly coupled to the screw, or a high speed, low torque motor, coupled to the screw via a reduction gearbox. The direct drive option involves fewer components, which is positive from a maintenance perspective, but would be larger and require a much larger brake. The gearbox version would allow for a smaller brake and would likely be able to operate at higher efficiency.

The main disadvantages of the system are the reduced power density when compared to a hydraulic actuator and the higher susceptibility to damage from water ingress. Where the hydraulic system would suffer from reduced functionality if subjected to low level water ingress, the electrical system could suffer from complete failure due to short-circuiting if water ingress is not suitably protected against. This simply means that more care would be required in the specification of sealing arrangements.

Extreme Hydrodynamic Loading

In normal operation, control surface actuators are required to provide forces in the order of 2000 kN. The load requirements increase significantly for wave-slap and sea-slam forces, as it is normal to be required to survive forces in excess of 7500 kN. There are multiple design strategies, which can be employed to ensure the system survives forces of this magnitude. The first is to accept that forces applied to the system beyond the normal working load will back-drive the actuator, and ensure that there is capacity to manage the considerable energy produced. The second option is to sense when excess force is applied to the control surface and use heave compensation techniques to move the actuator and actively compensate for expected loads. The final option is simply to lock the actuator with sufficient force to prevent any movement. Each one of these options is more practical with different actuator designs, and may be influenced by vessel design approaches and the ratio of operating load to extreme survival load.

In existing hydraulic cylinder designs, the preferred option is to allow the excessive loads to back-drive the actuator. This results in an increase in pressure in the hydraulic fluid, which is allowed to escape back into the main circuit via pressure relief valves. This method removes the excess energy of the high-pressure fluid by introducing heat and noise into the hydraulic circuit.

Allowing the actuator to be back-driven is possible without modification with the electro-hydrostatic system, but to do so with the electrical system would require it to be back drivable. If this were the case, the electric motor would then act as a generator, supplying electricity back into the VFD. The resultant increase in the voltage on the DC bus of the VFD would need to be reduced to avoid damage to the drive. This could be achieved by regenerating the energy back to the submarines supply, but this is generally not accepted by shipbuilders, as it is seen as an unnecessary risk. The alternative is to use the energy to heat banks of braking resistors, but the large amount of energy generated in the events could require very large resistors and therefore, a large amount of space.

An option, which appears more suited to an electrically actuated system, is to attempt to mitigate the force generated by using heave compensation techniques to move the control surface with the load that is applied, thereby reducing the impact on the actuation system. This method could work well when dealing with large forces generated by vertical wave motion as the control surface could lift itself with the wave and avoid any generation. However, if the wave amplitude exceeds the stroke or speed of the actuator, the majority of the load could still be applied. This technique would rely on the existence of a reliable, high speed feedback method and an equivalently responsive control system and actuator. These requirements mean that this solution is the least likely to be viable.

The third option is to avoid the issue of excess energy production by applying a mechanical brake to the actuator, so that no movement of the control surfaces can occur. This requires all components in the load chain be sufficiently rated, which results in an increase in actuator and linkage size. This method would be particularly effective for actuators that restrict back-driving motion, as they would lower the requirement of the mechanical brake. The negative aspect of this method is the motion induced in the submarine, due to the force of the waves against the rigid control surfaces.

Discussion

Hydraulic and electric linear actuators each have their own strengths, with different considerations to be taken at the boat construction stage. However, if the shipbuilder wishes to pursue the objective of a fully electric submarine, there is now a viable option for control surface actuation.

MacTaggart Scott believe that the best of such solutions, which is technically achievable at this time, is to use a sufficiently strong roller screw and suitably powerful brake to allow the system to lock when necessary. This allows the actuator to use a lower sized motor, which is capable of achieving the desired operational loads, and avoids the necessity of installing large banks of braking resistors. The proposed solution can be produced to fit within a similar space envelope as the hydraulic actuator, with the only concession being the addition of a variable frequency drive panel. If the proposed electrical solution is compared against a discrete hydraulic system, with its own HPU, then the results are even more favourable.

MacTaggart Scott will further investigate alternative methods of handling back-driving loads. Although using a mechanical brake provides an achievable solution, a system, which would not transfer all of the wave energy into motion of the vessel, is preferable. Ideally, this solution will decrease the design size without increasing the complexity of the hardware or control system.

Conclusion

Although the current methods of control surface actuation are sufficiently powerful and reliable, changes in user demands and improvement in available technology means that there is now both the requirement and the potential for an electrically actuated submarine control surface.

MacTaggart Scott have a long history in the design and manufacture of hydraulic linear actuators and growing experience in high power electric motors. MacTaggart Scott also have patents in Europe [1][2] and the United States [3][4] on electric linear actuators for use in controlling the movement of a component of a seagoing vessel. This has facilitated the development of high power electric linear actuators and will allow MacTaggart Scott to provide customers with the choice between hydraulic and electric linear actuators for future submarines.

References

[1] EP 2325080 A1, An actuator for use in controlling the movement of a component of a seagoing vessel, May 2011.
[2] EP 2325080 B1, An electric linear actuator for use in controlling the movement of a component of a seagoing vessel, August 2016.
[3] US 20110114008 A1, An actuator for use in controlling the movement of a component of a seagoing vessel, May 2011.
[4] US 8689715 B2, An electric linear actuator for use in controlling the movement of a component of a seagoing vessel, April 2014.