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Advances achieved from use of Electromechanical Actuators for the FORD-Class carrier's Jet Blast Deflectors



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Introduction

Hydraulics have traditionally been used across the Navy for many decades in systems that include valves, capstans, winches, windlasses, underway replenishment, elevators, hangar doors, and much more. For a particular ship-class such as the carrier, the aggregate applications showed that these hydraulic systems required a significant amount of space and weight, hours for maintenance, environmental hazards due to leaks, and energy consumption inefficiencies even while at rest. These reasons led the Navy to conduct a business case analysis and earlier studies to evaluate electromechanical actuators against hydraulic systems to determine suitability and applicability for shipboard systems. In many of the aforementioned applications, the benefits that could be achieved, as shown in Table A, included reductions of more than 3X machinery weight, 9X machinery space, 2X energy efficiency, 2X maintenance, and 2X machinery complexity.

TABLE A: Benefits of EMA Technology for Navy Applications

Benefit	Reduction
Machinery weight	3.23X
Machinery space	9.18X
Energy efficiency	2.32X
Maintenance	2.70X
Machinery complexity	2.23X
Personnel required	2.92X

Notwithstanding that impressive background, the most significant reason why electromechanical actuators were deployed for the Jet Blast Deflectors (JBD) is their faster cycle-time to move the deflectors up and down versus hydraulic counterparts. That capability supported the requirement for increased sortie rates. With advances in electromechanical hardware, the Jet Blast Deflector actuation systems on the USS FORD carrier utilize modified commercial-off-the-shelf electromechanical actuators in concert with automation controls and variable frequency drives. The electromechanical actuators (EMAs) that lift and lower the Jet Blast Deflectors on the FORD Class carrier are among the highest force capable EMAs in the Navy. Jet Blast Deflectors require the most force/in³ of any actuator application; and EMAs along with VFD-based control are operating them extremely well both in high seas and extreme temperatures.



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This new design improves affordability and meets the ever increasing set of mission demands supporting the National Defense Strategy (NDS). The Navy has emphasized the six pillars of the “Navy the Nation Needs” as, “Readiness, Capability, Capacity, Manning, Networks, and Operating Concepts.” This use of automation and electromechanical technologies on the ship plays an important role in accomplishing the pillars of readiness, capability and operating concepts.

Increased Speed and Performance of Jet Blast Deflectors:

Electromechanical Actuator (EMA) and Programmable Automation Controller (PAC)

The Jet Blast Deflectors’ EMAs are controlled by a commercial-off-the-shelf Programmable Automation Controller (PAC) system. The control architecture comprises a PAC and associated I/O modules, Variable Frequency Drives (VFD), Electromechanical Operators (push buttons, pilot lights, etc.), electronic human machine interface (HMI), and 11 remote operator stations for the areas comprising the Aircraft Launch and Recovery system, i.e. the Jet Blast Deflectors, Integrated Catapult Control Station actuators, Landing Signal Officer platform, and Barricade Stanchions. Overall coordination, monitoring, health status, and alarms are handled by logic inside the PAC developed with tools in compliance with both IEC 61131 programming standards and the Navy’s MIL-PRF-32006 programmable control standards. For analytics, including diagnostics and operational cycles, the HMI provides graphics and trends of system history. This design incorporates non-developmental equipment configured to provide harmonic mitigation, overall power quality to MIL-STD-1399, and deliver repeatable, higher speed deflector movement. Control system analytics reduce maintenance time and costs since the equipment conditions can be monitored continuously, and deviations from nominal operating ranges are detected early before leading to a part failure or other downtime event.

To understand how all these benefits are derived, we must start with the Programmable Automation Controller. PACs, which have evolved from PLC based products, are tremendous at accomplishing discrete logic, high speed computations, and repeatable activities accurately and consistently. PAC control system technology is widespread and universal throughout many industries; much of which is due to their ease of programming and high reliability, so hardware is widely available and proven. There is tremendous flexibility in modifying the PAC’s program functions and configuring the system’s output performance is unmatched requiring far lower engineering efforts and costs to accomplish as compared with special one-of-a-kind, developmental based control systems. Programs and subroutines are quickly

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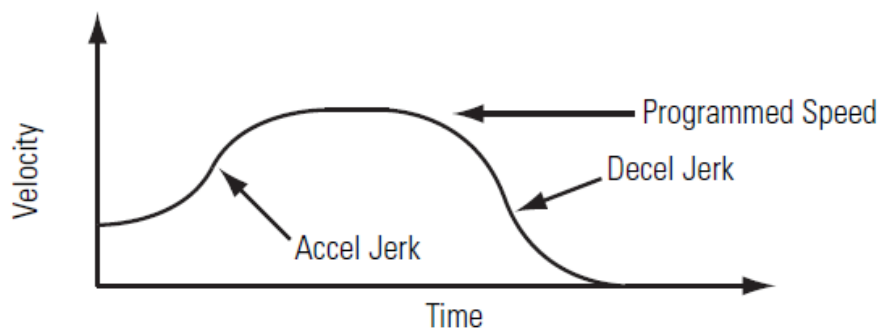


created in the ladder logic programming language that has instructions which resemble the traditional electrical wiring of relays and contactors familiar to many skilled trades, electricians, and engineers. Edits and additional subroutines are quick and easy to create in a standard, commercial software GUI editor where rungs of logic connect the power flow between the two depicted power rails that look like a typical control schematic diagram. Such a presentation doesn't remove details or obscure the program's logical flow and operations, which can happen with typical computer machine language programming, providing a system that is much easier to follow and troubleshoot.

In this application, the configured PAC with variable frequency drives and EMAs provide greater speed and motion performance than hydraulics by controlling the EMA actuator's acceleration and velocity throughout the entire travel stroke of each EMA actuator. Resolver-based sensors on the electromechanical actuators provide feedback to the variable frequency drives to continuously adjust voltage and current provided to each EMA to closely match actual velocity to commanded velocity given to the EMA. Hydraulic systems produce single speed control that is rough and jerky during an actuator's start and stop sequence and this is tough on all the mechanical components which reduces their expected service life. With the PAC/EMA system, the actuators' motion profile can be adjusted to smoothly transition from stop to start, vice versa, and other velocity steps within the EMA actuator's stroke range, see Figure 1. All of this is configurable through the setting of parameters from an operator's panel. The six JBD deflector panels move quickly and smoothly at a higher controlled speed than hydraulics thereby reducing the cycle time to raise and lower the deflectors. This flexibility also allows for fine tuning of speed and position to account for the typical variation between the various deflector panels and their specific mechanical orientation on the ship due to tolerances and installation variations.

This precise, position control has another advantage from the PAC/EMA based system because it utilizes this feedback to synchronize both actuators that raise and lower the Integrated Catapult Control Station without it becoming skewed while in transit to the full up and locked position. For hydraulics, in such a situation, the Integrated Catapult Control Station is stuck and cannot be properly used.

Figure 1: VFD Configurable Speed Profile





The PAC's permissive and interlocks ensure safe operation of the pair of EMAs and Variable Frequency Drives assigned for each deflector by monitoring overcurrent, overvoltage, and over temperature conditions of the VFDs and will safely turn the VFD off before damaging the actuator, mechanical linkages, and the VFD itself. Hydraulics are more limited in offering such diagnostics to stop a hydraulic actuator when something in the drivetrain is mechanically seized or binding between components. Many more hours have been spent to repair a hydraulic system due to such events.

Variable Frequency Drive (VFD) technology

A VFD's parameters of acceleration time, deceleration time, speed control, Flux Vector control, and many others are set from the PAC logic, and the variable frequency drive translates those parameters' settings into control algorithms which determine the drive's semiconductor-based gate switching methodology that transform the voltage and current sinusoidal waveforms to the electromechanical actuator. Since VFDs are universally employed throughout the world, industry continues to push for advances in semiconductors that have led to highly efficient power switching controls, resulting in the maximum torque output per amperage supplied to the motor. The switch gates for a VFD's Active Front End are typically Insulated-Gate Bipolar Transistors (IGBTs) which take the DC voltage on the VFD's DC Bridge and invert it into approximate sinusoidal-like voltage and current waveforms. Figure 2 shows an example VFD convertor and inverter schematic.

The VFD's control algorithms determine the optimum pulse width modulation (PWM) of the Active Front End's gates for switching on and off at certain durations and frequencies necessary for both immediate dynamic responses and instant energy transitions from one energy state to another for the motor with little time delay. Much of this is governed by the Flux Vector control principles derived from electrical engineering to control the interactions between a motor's stator and rotor magnetic and electric fields.

Starting an electromechanical actuator with a VFD leads to near 100% torque at initial speed and a dynamic response to changing load conditions. The electromechanical actuator's torque feedback is another parameter into the VFD's control algorithm used to rapidly adjust the motor field winding's voltage output and induced stator magnetic field orientation toward the rotor's magnetic field. Compared to the hydraulics system, this superior torque and speed control results in deflector operational cycle times that are much faster and smoother than typical with hydraulic approaches.

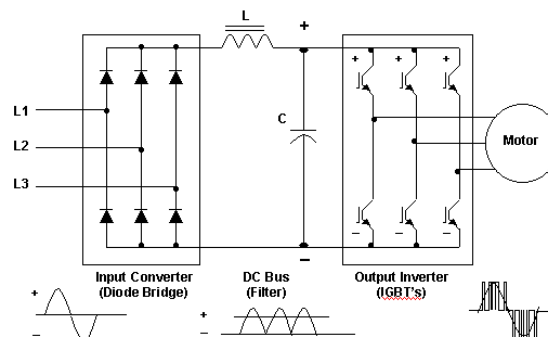


Figure 1 - TYPICAL VFD BLOCK DIAGRAM



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These VFDs comprise Active Front End IGBT arrangements on both the inverter, load side, and converter, line side, sections. As such, this VFD design effectively reduces harmonic distortions on the voltage and current waveforms to the electrical distribution system to levels far below 5% per individual harmonic and 3% overall harmonics, thereby meeting the power quality requirements of MIL-STD-1399.

Because of this feature with the VFDs, an isolation transformer is not needed for the electrical distribution system, thus saving on weight and space as well as producing less generated heat for system operations. These are important advantages versus the earlier hydraulic systems which moved the deflectors slower and where the hydraulic system's pumps consumed power to such a degree they generate significant heat even when the deflectors are not operating.

Additional Benefits and Maintenance Improvements:

Simplified Integration

Increased EMA use can reduce installation cost, specifically in new ship builds, by eliminating integration of hydraulic conveyance (plumbing and piping) within or integral to the ship's structure. Electrical power distribution is performed with commercially available VFDs and other command and control components. These types of installations are typically more flexible and less intrusive than the use of fluid power distribution systems. Distributed power and localized power systems in support of EMA applications can further reduce costs and add flexibility.

The scalability and simplified installation of EMAs also makes modular systems and decoupled payload support more feasible. Interconnection of sub-systems developed by multiple suppliers and/or delivered over different periods of ship construction is less intensive to integrate and support than coordinating installation of hydraulically powered alternatives and mitigating potential cross contamination of shared hydraulic powered systems. Furthermore, hydraulic systems require long and extensive flushing requirements during ship construction which means many maintenance hours spent to perform that work. Although new ship designs see greater benefit, retrofit and modernization of existing ships that incorporated significant levels of hydraulic systems could also benefit from this EMA and PAC approach., For example, consideration of incremental EMA adoption can provide a means for affordable relevance by allowing additional or differing capabilities to the ship while minimizing impacts to the ship's basic design and structure.

Energy Efficiency and Environmental Benefits

A significant advantage of EMAs are their inherent efficiencies, in both converting and using power, to perform their function. As modern ships and retrofits to existing ships add new capabilities and more advanced command and control systems, weapon systems and radars, utilizing electrical power efficiently is not just a matter of cost savings but one of mission capability and priority. To that end, this PAC/VFD/EMA system consumes less energy versus the energy consumed by the hydraulic system's fluid pumps, reservoir cooling pumps, and its other auxiliaries. It achieves this because the aggregate electrical kilowatt-hour requirements to operate are less for all the electrical

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subsystems combined in a PAC/VFD/EMA design since they draw power only when loads are in motion whereas the hydraulic system has various electric loads which draw power continuously.

Environmental sustainability is another concern for modern navies. This is broader than just being “green” and minimizing the impact to the environment, although these are noble objectives. Reducing the use of hydraulic fluid and its potential exposure to personnel can be a matter of safety and health. Hydraulic systems have greater complexity than EMAs because of numerous fittings and hoses which are prone to routine leaks where each time a leak occurs, it represents a hazard material activity to ship’s personnel. Cost to mitigate a hydraulic leak or potential collateral damage from hydraulic contamination is extensive. Furthermore, system flushing after repairs or installation is long and costly. The storage and recycling of spent hydraulic fluid, particularly when compared to the use of electric power already available on most modern ships, is an avoidable expense when using EMAs. Furthermore, with the PAC and electromechanical actuator system, these hoses and fittings are unnecessary. As such, they represent a 3-fold savings in overall space and 2-fold reduction in weight for the entire system. All maintenance hours involved for the fluid handling system are eliminated. Hazardous waste and contamination to the environment are nonexistent. All of these factors translate to a system which has easier serviceability, many less maintenance hours, and greater availability.

As modern navies incorporate more unmanned and autonomous platforms to work in conjunction with more traditional manned platforms, the energy efficiency and reduction in environmental impact for EMAs make them a suitable alternative to hydraulic options.

Diagnostics, Availability, and Commonality of Components

The PAC/VFD/EMA system provides status, alarms, diagnostics, and performance history by means of an HMI display. Each actuator is monitored for over temperature and resolver error; each VFD is checked for over temperature, inverter de-saturation, feedback out-of-bounds, communications errors, overcurrent per phase, DC bus overvoltage and overcurrent; and the deflector’s seawater supply system is checked for high temperature and pressure. In totality these represent a full, comprehensive health status of the PAC/VFD/EMA actuator system that ensures greater availability than the original hydraulic system which didn’t announce faults and hardware status. Ship’s personnel gain greater insights into the system’s performance to exploit knowledge of a problem before it happens. Maintenance hours and troubleshooting efforts are reduced because maintenance can be proactive and predictive. Eventually, this data and history could show that periodic maintenance intervals can be fewer or the length of time between them increased for a greater number of flight operations. Time to troubleshoot is much less and problems are resolved much quicker due to these diagnostics which help to understand what component is out of tolerance and, if it fails, the cause of its failure. The simplified topology of PAC/VFD/EMA systems reduces the maintenance, both scheduled and unscheduled, as well as provides faster Mean Time to Repair (MTTR) when maintenance is required. Higher reliability and more commonality in components can reduce the maintenance staff and their costs.

Taking advantage of the scalability and modularity of EMAs can support future adaptation and change out of payloads and systems and incorporating more automated approaches with electronic controls

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can provide both less demand for operational staff and more flexibility in “re-programming” the systems capability over traditional hardwired or dedicated systems. Commonality of components is another way EMAs and COTS-based automation architectures can support higher operating efficiency and lowering Total Cost of Ownership by reducing on-board or depot spares and supporting common training of maintenance and operations personnel. This is becoming a more important focus area for the US Navy, and although not exclusive to EMAs, the ability to size and configure an EMA to cover a broad range of applications is often easier than sizing a hydraulic system and all its associated components to do the same.

Overcoming Obstacles to Deploy EMA Technology:

On the FORD class, since hydraulic approaches had greatly been reduced as part of the overall ship’s design, and because of the power available to support other systems such as EMAs, the use of Electromechanical Actuators (EMAs) in place of the traditional hydraulic systems made sense. However, the historic use of hydraulic actuation would prove to be difficult to replace. As discussed, the most demanding, highest force actuation had long been reserved for hydraulic actuation, even with all their constraints and support issues.

EMAs commonly use what’s known as an L10 life calculation, commonly used in systems with mechanical interfaces (gearboxes, bearings, etc). L10 is, simply, a calculation showing the life that 90% of the force bearing surfaces will survive. For linear actuation, that life is calculated in inches of travel. Inches of travel, then, are used to calculate the expected number of cycles (inches out + inches back). This calculation is handy for sizing and selecting the proper EMA for a given application. It is, however, more difficult to measure the life of actuation in a harsh environment with forces varying greatly based upon sea state and weather. While MIL standard testing can provide evidence of survival in the various environmental operating conditions, the question of lifecycle and reliability, particularly when matched against the long-standing use of hydraulic actuation, would, necessarily, become the key proving ground for EMAs.

Life Testing the EMA Technology

The EMAs designed to lift and lower the FORD’s jet blast deflectors use planetary roller screw technology for driving the load. This technology has been proven in commercial and industrial applications where high duty cycles are common for 24/7/365 use in factory automation and machine control (presses, weld guns, etc). However, both a bias for existing technology along with some skepticism based on previous experience of early experimentation demanded more than calculations and commercial evidence of success to satisfy both the Navy and shipbuilder.

Both sortie rates and sea state are, of course, wholly unpredictable. In addition, it was discovered that the JBD cycle counts specified in the ship specifications included additional cycles accounting for the older hydraulic systems lack predictability and therefore overstating the requirement. With that, developing a formula for testing the life of an actuator was difficult. However, with the use of variable speed servo drives (VFDs) programmed to mimic the force profile of the lift and lowering forces of the



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jet blast deflectors, the actuators were tested to full specified ship life using the assumed highest forces seen at the highest sea states in which they would be operated.

The surrogate jet blast deflector test fixture designed and built for the life test utilized the ship's tactical linkage between the actuator and the jet blast deflector and replicated the tactical kinematics of the operation on the ship itself. With the force profile and the expected linear speed of the actuators programmed into the VFDs, the test was designed to test the life of the EMA versus the expected cycle rate of the jet blast deflectors during the ship's 50-year life.



Two life tests were performed. The first test showed that the roller screw mechanism would last through, but likely needed replacing, at the mid-life Refueling and Complex Overhaul (RCOH). The second test, using an additional system for the lubricating oil that circulated within the housing to protect the roller screw mechanism, extended the life of the roller screw by up to 50%. In both cases, no other Lowest Replaceable Unit for the EMA-based JBD system showed wear that would constitute a need for replacement. Proving availability and reliability through the RCOH cycle crossed an important hurdle for the use of EMAs in this demanding and critically important operation.

Conclusions:

Benefits of EMAs together with PAC and VFD technologies include higher availability of operations due to reduced complexity of the system's design, improved comprehensive diagnostics, less Mean-Time-To-Repair, commonality of parts, and reduced personnel training. Improved performance of the Jet Blast Deflectors to cycle up and down more quickly and, because of smooth transitions, leads to much less wear and tear of mechanical equipment. Maintenance hours are less and the environmental impact is lower. Overall, Total Cost of Ownership is reduced.

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