TECHNOLOGY DEVELOPMENT FOR STEERING AND STABILIZERS

BY

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ABSTRACT

As part of a continuing programme into the All Electric Ship concept, the Marine Engineering Development Programme element managed within the Warship Support Agency of the UK MoD is investigating two separate areas of technology development for steering and stabilizers. The Electrical Actuation of Hydrodynamic Control Surfaces (ELAHCS) Project is presently examining the replacement of traditional hydraulic systems for steering and stabilizers with novel electric actuation methods. The principal potential benefits of these new solutions are reduced life cycle costs, simpler installation and maintenance, improved survivability, cleaner systems, elimination of hydraulic systems from ships and hence the associated support and training.

The studies are investigating technologies that could yield benefits in the future but are not sufficiently mature to be demonstrated. These include the high power applications such as stabilizer and steering gear actuators for carrier size vessels together with the unique requirement for submarine applications. The study is investigating internal and external to the hull actuators, together with emerging technologies. The system demonstrator is a programme designed to demonstrate the operation of an escort sized naval platforms stabilizer system using a Type 23 frigate as host platform. The programme uses commercial technology in a novel application and aims to provide additional evidence that electric actuators are suitable and cost effective for this application.

ELAHCS is now a year into the Demonstration Phase and within this phase, work packages have been designed to de-risk solutions for future Royal Navy vessels such as Future Surface Combatant, T45 and Sub-sea platforms. These work packages include a mix of studies and a system demonstrator.

This article describes the development of the ELAHCS project and the progress to date of the System Demonstrator Program.

Introduction

Background

The UK MOD is currently pursuing a programme of technology demonstration projects, which are designed to de-risk those technologies identified as enablers for the concept of an All-Electric Ship. In addition to the main motor and prime mover technologies, there are also a considerable number of auxiliary systems that need to be considered. One of these is the method of actuating control surfaces, both for surface ship rudders and stabilizers as well as submarine control surfaces. The Marine Auxiliary Systems Integrated Project Team (MXS IPT) has been tasked with investigating the potential for replacing the current hydraulic technology that is used for such appliances with electric actuation systems. This investigation is being conducted through the Electric Actuation of Hydrodynamic Control Surfaces (ELAHCS) Project.

Aims

It will be shown that ELAHCS is both technically feasible and cost effective to drive surface ship and submarine hydrodynamic control surfaces. The article will briefly explain previous work and the various phases that are currently underway, in particular the System Demonstrator Program (SDP) and discuss the design and integration of the SDP, highlighting some of the more technically challenging areas of the project.

Previous Work

In 1997, the Warship Support Agency (WSA) and BAE SYSTEMS embarked on an investigation into the use of electric actuators to replace hydraulic and pneumatic actuators in auxiliary systems. The ELAHCS Project was created to specifically examine the issues associated with actuating hydrodynamic control surfaces. With the potential to reduce whole life costs, weight and space in future platforms and is funded through the Marine Engineering Development Programme (MEDP). The project is divided in to 3 separate phases:

- Concept.
- Assessment.
- Demonstration.

This can be related to the CAMID Cycle of the UK MoD's SMART Acquisition Process.

Phase 1, the Concept phase is now completed, this phase identified the requirement as well as conducting a market survey to identify all potential electric actuation solutions, in particular focusing on those technologies that were either in production or in the latter stages of development.

The UK MoD currently specifies its functional requirements in terms of operational capability as opposed to detailed technical specifications. Therefore, it was necessary to establish what the requirement for future vessels would be with regard to hydrodynamic control surfaces and an appropriate engineered solution. The results of these studies were summarized in a previous paper, which was presented at INEC 2000.[1]

Phases 2 and 3, the Assessment and Demonstration phases were combined, as sufficient evidence from phase 1 indicated that the technology considered for the Future Surface Combatant (FSC) was sufficiently mature to merit combining the Assessment and Demonstration Phases for this application. The combined Assessment and Demonstration Phase is being undertaken through a System Demonstration Program (SDP) along with a number of paper studies to complement the work.

These paper studies consider three very separate applications for this technology, namely the Future Aircraft Carrier (CVF), the Future Surface Combatant (FSC) and a future Sub-sea Platform. Actuators are only currently suitable for steering and stabilizer applications in a frigate sized vessels. There are none that can meet the requirements of a large aircraft carrier or a submarine. Potential solutions are on the horizon, but there are many technical issues that will need to be addressed before they can be realized and detailed work is currently underway to examine these matters. In submarine applications, actuators are required for the forward and after hydroplanes as well as the upper and lower rudders, which are mechanically coupled in pairs. The requirement was established for different control surface configurations (cruciform, x-form etc.) and with the use of smaller actuation surfaces such as trim tabs.

The SDP, the electrically actuated stabilizer system for a Type 23 frigate is now well underway and the prototype will be ready for platform integration in October 2004 in preparation for six-month sea trials. HMS *St. Albans* has been identified as the preferred platform to test the equipment in an operational environment

Why Electrical Actuation?

Electro-Mechanical (EM) actuation is not appropriate for all applications, however as technologies mature industry is looking to exploit these developments and EM applications will increase.

EM actuation is especially appropriate for marine applications where the key design drivers are cost of ownership, safety and low risk. Independent trade studies show a reduction in initial purchase price of between 5-20% and a 50% reduced yearly cost of ownership when comparing electrically powered systems in comparison to hydraulically powered for a marine application.[2]

For a ship-based system such as stabilizers, rudders or hull valves an EM approach can yield significant benefits:

(*a*) Improved reliability.

(*b*) No high pressure seals - no leaks.

(*c*) No pumps and drive couplings.

(*d*) No hoses, fittings, filters, reservoirs, accumulators or valves.

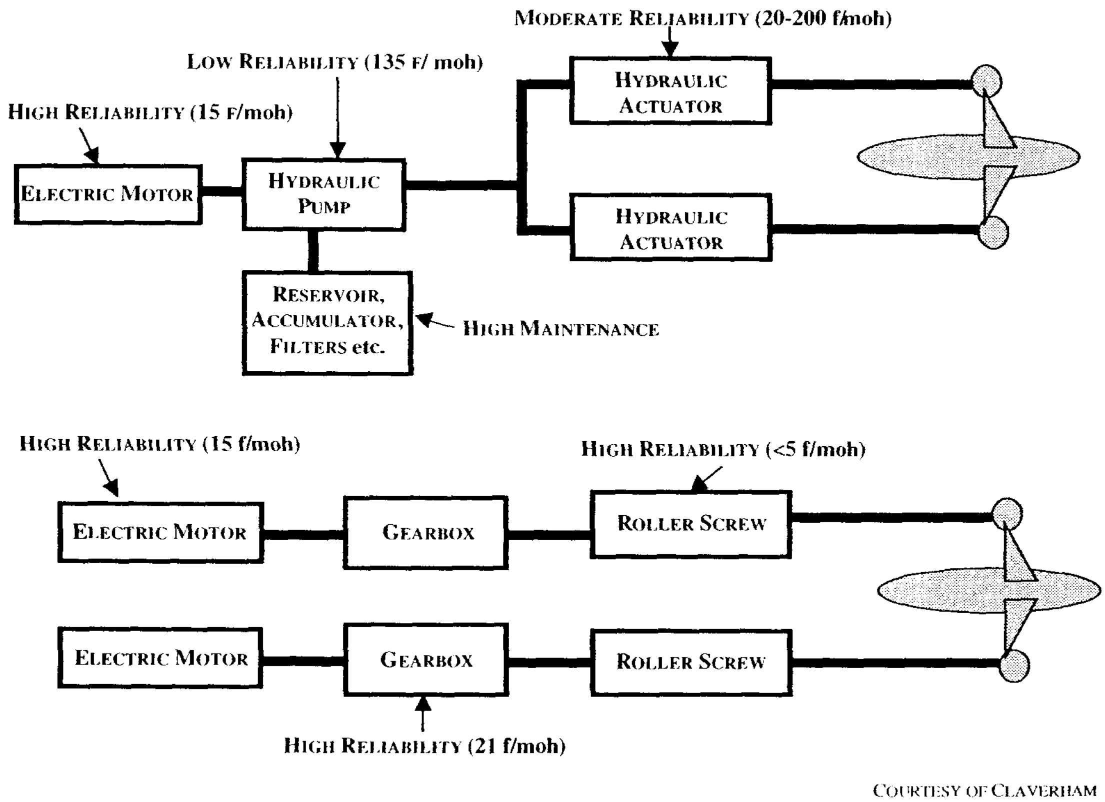

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FIG.1 – (TOP DIAGRAM) TOP LEVEL BLOCK DIAGRAM OF A T23 STABILIZER SYSTEM (ONE SIDE)[3]
(BOTTOM DIAGRAM) TOP LEVEL BLOCK DIAGRAM OF AN ELAHCS STABILIZER SYSTEM (ONE SIDE)[4]

A simple comparison of both hydraulic and electrically actuated systems from a reliability viewpoint is demonstrated at (FIG.1). The simple top level diagram effectively illustrates the Availability, Reliability and Maintainability (ARM) of the two different actuation systems. Further details on the ELAHCS RAM will be covered later in this article.

Electrical Actuation – SDP

The SDP is concerned with the design, manufacture, test and installation of an electric actuation system for a Type 23 frigate steering and stabilizer system, by replacing the steering gear and stabilizer hydraulic actuators. The ELAHCS system is designed to control an externally mounted single stabilizer and will replace the two existing hydraulic actuators mounted on the Port side of the ship.

In order to ensure a better understanding of the exact requirements of the electric actuators for the SDP, it was necessary to carry out a 'Requirements Capture'. The aim was to collate data on the characteristics and performance requirements of the existing Type 23 steering gear and stabilizers.[5] Part of this process is to investigate the loads seen by the actuators and the associated operating profile. The loads, torque and powers estimated for existing steering and stabilizers systems are calculated using hydrodynamic empirical formula. Although the resultant equipment has proven to be reliable and robust, it is not clear what peak loads are seen in service. Gaining a better understanding of these actual loads is crucial in specifying realistic equipment for the SDP.

The operating profile for the stabilizer actuators on the Type 23 was not well understood, although this is not critical for the hydraulic actuators, it becomes more important when selecting appropriate alternative electrical actuators. By understanding the loading and the power requirements for each actuator, the prime sub-contractor (Claverham) has been able to select the most appropriate equipment and rating. The peak loads and load duration seen by the equipment when undertaking a number of set manoeuvres information was gained during the Requirements Capture Trial and this is very briefly summarized at Table 1. This information was then used to establish the boundary and limits of operation of the equipment. The highest load seen and measured was 118kN and 54kN at the maximum slew rate of 41°/s respectively during the sea trials, using these values plus a 20% load margin to accommodate any measured errors and provided an acceptable margin.

TABLE.1 – *Summary of Data from Requirements Capture Trial*

DESCRIPTION	MEASURED LOAD (KN)	MEASURED CROSSHEAD TORQUE (KNM)	LOAD WITH 20% MARGIN (KN)	MEASURED CROSSHEAD TORQUE WITH 20% MARGIN (KNM)	FIN RATE (DEG/SEC)	TIME HELD AT LOAD/ RATE (SECS)
Maximum load measured during sea trial (Equalized)[1]	**118**	106	142	128	0	120
Maximum load at maximum rate (41deg/s)[2]	**54**	49	65	58	41	-
Maximum stall load of incumbent hydraulic actuator[3]	159	143	-	-	-	10

1. Maximum load measured during HMS *Northumberland* Sea Trial – Zero rate.
2. Maximum load measured during HMS *Northumberland* Sea Trail – Maximum rate.
3. Maximum stall capability of incumbent hydraulic actuator in the extend direction.

The data bolded in Table 1 is the maximum load actually measured during the manoeuvres, however these loads are below that of the stall capability of the hydraulic actuators. Therefore, in order to ensure that the new ELAHCS electromechanical actuators can at least match the capability of the incumbent hydraulic system, the electric actuators have been designed to match the maximum possible stall load of the jack.

In order to ensure that the worst case is considered, the piston side of the jack is assumed to be exposed to maximum pressure whilst the annulus side is assumed to be at atmospheric pressure. This is obviously the most extreme case and this load would only be maintained for a very short period of time (i.e. 10 seconds). This maximum load calculated is 159 kN.

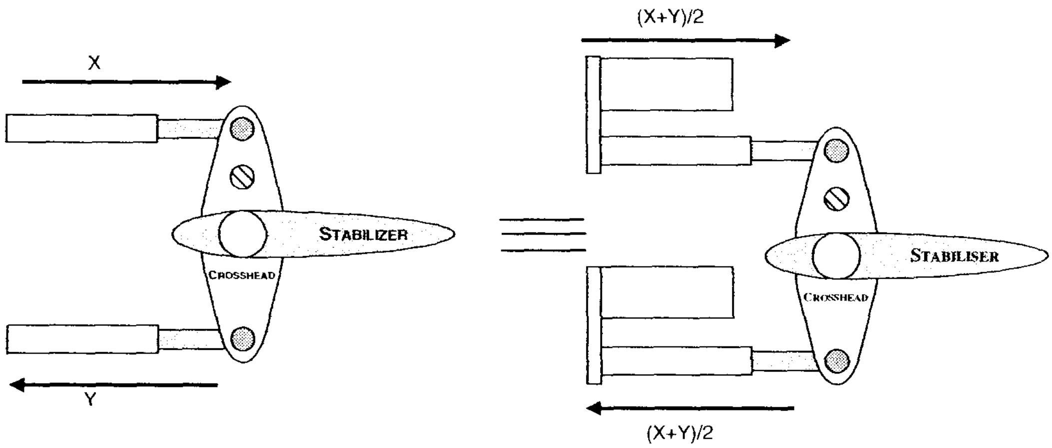

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FIG.2 – LOAD DERIVATION

The load derivations of both the hydraulic and electromechanical systems can be best explained at (FIG.2). The hydraulic system shown illustrates how both rams operate to move the stabilizer, as the ram extends (x) the opposite ram retracts (y) this system is dynamically unbalanced. The force exerted by the extend ram (x) is 2.1 times greater than that of the extend (y) ram. The ELAHCS system is balanced with both electromagnetic actuators working together i.e. as one actuator is driven to extend the other is counter driven to retract the opposite ram, providing a more power efficient and torque effective system than the current incumbent set up.

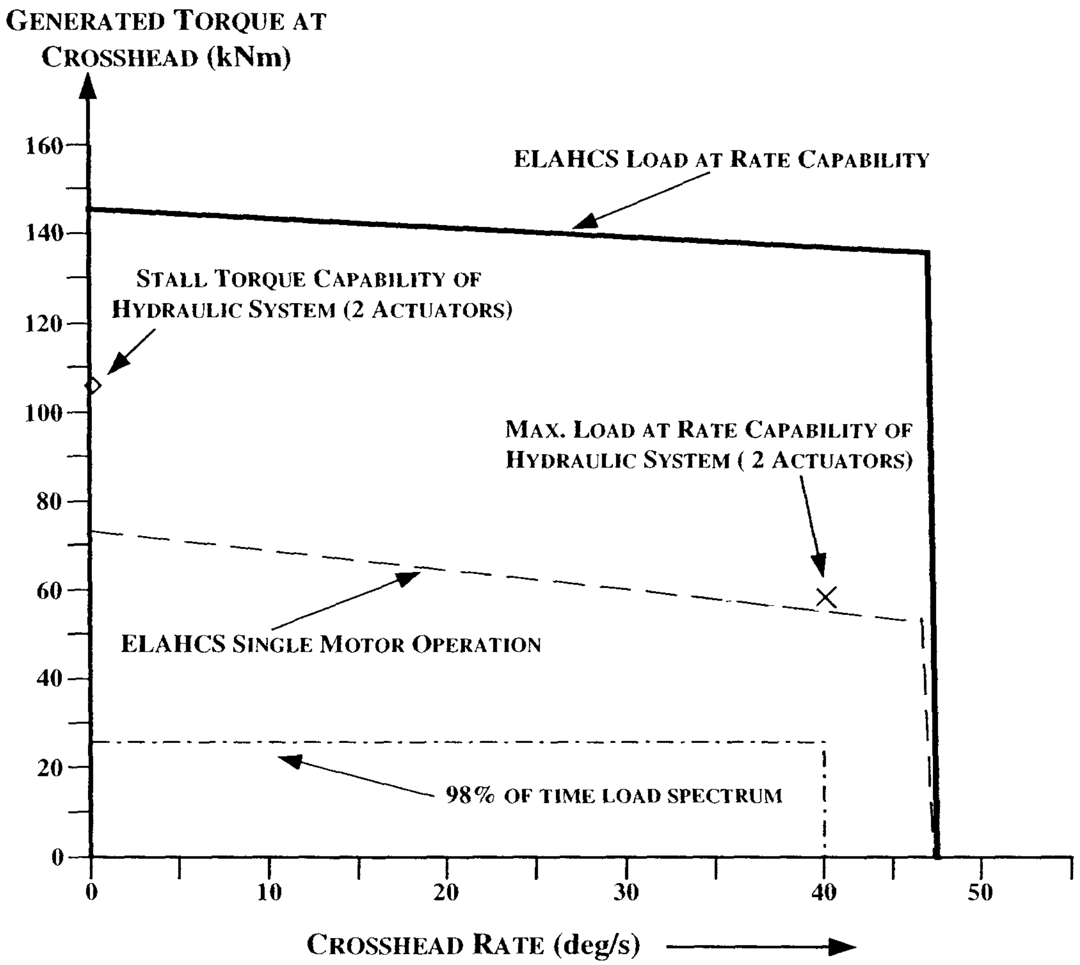

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FIG.3 - GRAPH TO SHOW LOAD OPERATING PROFILE

From (FIG.3) it can be seen that the hydraulic actuators operate at 20% of their capacity for 98% of their operational time.[3] The load derivation figures plotted at FIG.3 are the maximum measured load at rate capability of hydraulic system that was extracted from the HMS *Northumberland* trial data. It should be noted that the graph, FIG.3, shows the crosshead toque against crosshead rate.

The solid line depicts the operating envelope of the System Demonstrator when both motors and actuators are functioning normally. The dash line depicts operation if one side of the system fails i.e. it has sided operation, single motor operation. From the graph it can be seen that in single motor operation the system will still operate well within the normal operating parameters. The black cross, as marked identifies the maximum torque at the maximum slew rate of the hydraulic system; consequently the auxiliary mode can deal with all but the most arduous requirements of the installed current hydraulic system, therefore providing an auxiliary mode.

ELAHCS Design

The design of the ELAHCS SDP has several added benefits:

1. Multiple Redundancy (auxiliary mode).
2. Intelligent system diagnostics.
3. Zero maintenance throughout trial.
4. Integrated manual reversion capability.
5. High availability.
6. Commercial off the shelf (COTS).
7. Higher torque output capacity.
8. Efficient power use.

ELAHCS will fit the same mechanical interfaces and be controlled using electronics driven from the original stabilizer control signal. The major assemblies are two Electro-Mechanical Actuators (EMA) with a single manual input drive that can be fitted to either EMA, the Electronic Control Unit (ECU) and Motor Control Unit (MCU) that are both housed in a common enclosure with a data logger. The interconnecting cable harness provides power to supply the system and signal data transfer to the data logger. A pictorial representation can be seen of the electrical actuators at (FIG.4). The system is generally in one or two conditions; ACTIVE, when the system is in operation, and STAND-BY when the control system is powered but the motors are isolated.

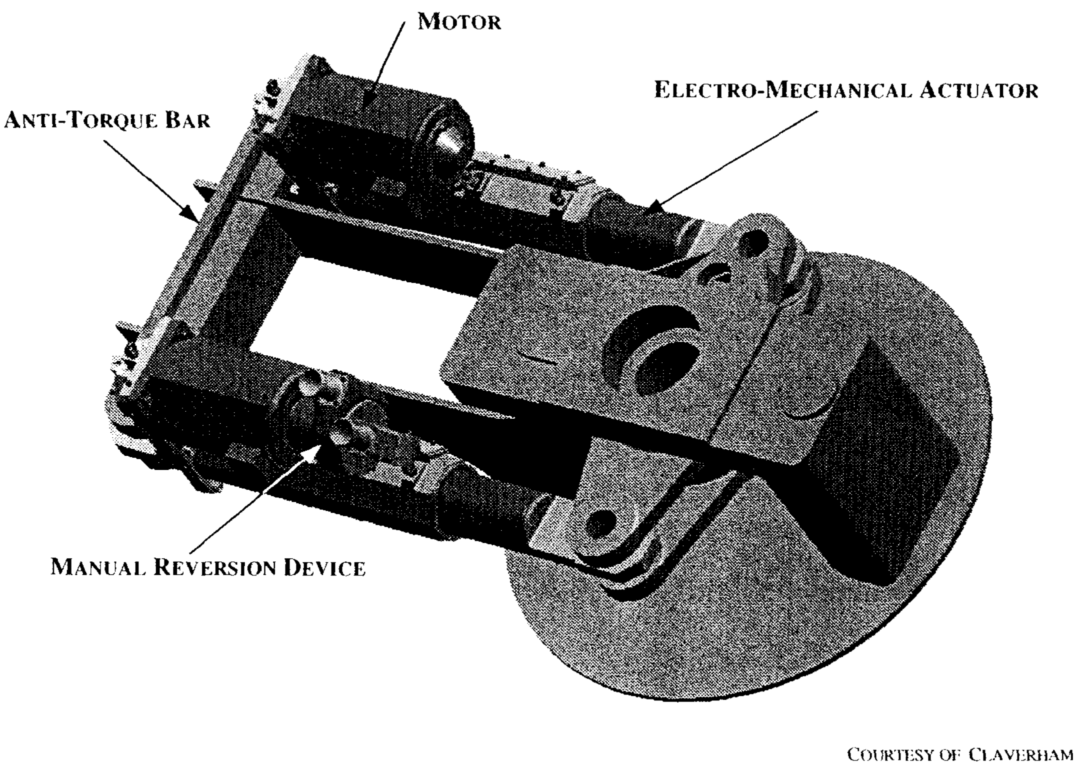

FIG. 4 – ELAHCS ELECTRICAL ACTUATOR – A PICTORIAL REPRESENTATION[6]

The EMAs are pin-mounted actuators, designed to fit within the existing mounting frame and crosshead arrangement. Each actuator comprises a single DC motor that drives through a transfer spur gear train (1:1 ratio gearbox that is incorporated due to the space envelope restrictions). The gearbox is lubricated and sealed for the duration of the proposed trial fit programme. The gear train drives into a planetary roller screw and by earthing the roller screw nut assembly the rotational energy is transferred into linear force acting on the output rod.

Electro Mechanical Actuator (EMA)

The individual EMAs comprise a:

- Moog DC brushless motor.
- 1:1 ratio spur gear drive.
- Thrust bearing assembly.
- Planetary roller screw.
- Runaway protection spring-box.

The EMA attaches to the ships structure at two locations use in forced lubricated spherical bearings. The output from the motor, which operates at 600v DC (rectified from the ships 440v supply), is taken by the gearbox assembly and transmitted to the end of the screw. The screw is supported in a thrust pack, which comprises a pair of angular contact bearings; sized to carry the output thrust of the jack plus the gear separation loads. The planetary roller nut is clamped to an internal piston arrangement, which is prevented from rotating by a track roller bearing that runs in a pair of guides, mounted in the jack body.

By preventing the nut from rotating the planetary rollers within the nut are forced to progress along the rotating shaft thus providing the rotary to linear translation. This motion is transferred to the output rod through the runaway protection spring boxes. A representation of the EMA and its major components can be seen at (FIG.5).

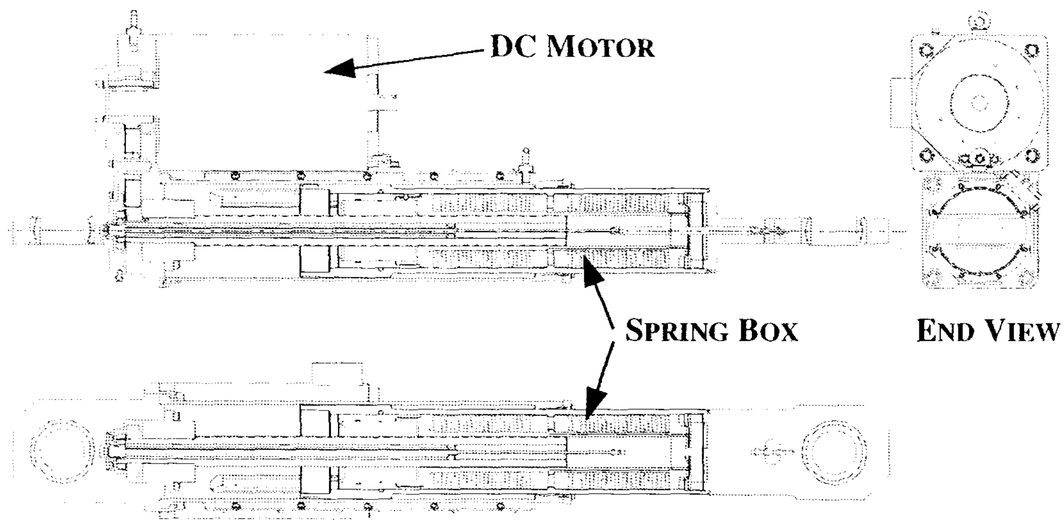

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FIG.5 – ELECTRO-MECHANICAL ACTUATOR

Mechanical Components

Manual Reversion Device

The manual input device has been designed to allow the stabilizer fin to be either moved to the desired position or retained in the current position when the electrical supply to the motors has been removed. This condition would occur in the event of a complete ships power failure or should the ELAHCS go into standby mode. In the event of an emergency, it must be possible to manually operate the system and return it to its mid position.

The device is fitted onto one of the EMA's, see FIG.4. If it is necessary to move the actuator manually a special tool is inserted in the drive socket and rotated. A cam action drives a cone clutch into engagement. Rotation of the drive in a second socket will be transmitted by a worm and wheel arrangement through the clutch and hence into the gear assembly. The output rod can now be positioned with infinite resolution.

The 'special to type' input device is used for sequential engagement and position adjustment operations. The design ensures that an incorrect operation sequence will not present hazard to the operator or damage the equipment. At no time is the operator exposed to any hydrodynamic loads. An electrical interlock isolates the equipment during engagement and prevents accidental start-up of the system whilst the manual reversion device is engaged.

Roller Screw Assembly

The function of the planetary roller screw within its actuator converts the rotary action of the motor to linear stroke whilst also gearing down the motor speed to achieve the optimum range of torque output in conjunction with the associated torque arm.

When meeting the safety, life and mass requirements engineering specialists are able to offer either ball or roller technologies, they consistently suggest a roller-screw. There are considerable advantages of roller-screw over roller-ball for a given size:

1. Higher load rating (40mm screw) 5x dynamic and 3.5x static rating.
2. Higher rotational speeds and acceleration rates (x1.5).
3. Significantly longer life (x160 factor).
4. Greater ability to survive shock loads.
5. Greater ability to withstand fatigue.

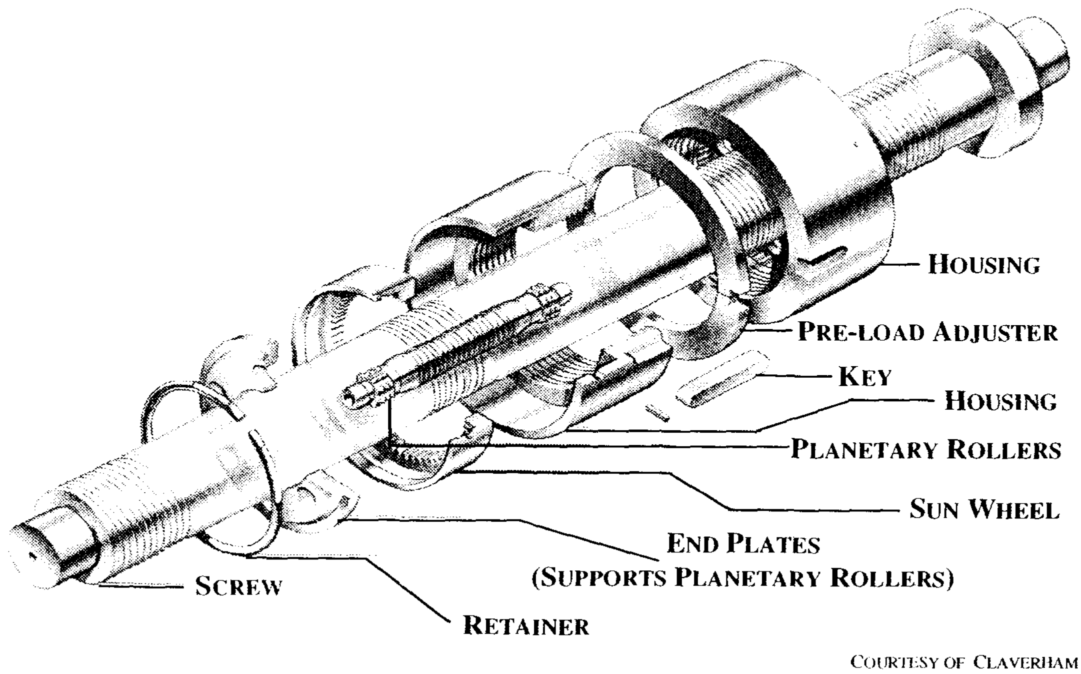

FIG.6 – A TYPICAL ROLLER-SCREW MECHANISM

The penalty for these benefits is a slightly reduced efficiency (-6%). Roller-screws are extensively used in the aerospace industries and applications include trailing edge flaps, leading edge flaps, engine air control flaps for various platforms that include JAGUAR, MIRAGE F1 and F3, DASSAULT FALCON and CONCORDE. An example of a roller-screw can be seen at (FIG.6).

Spring-Boxes

The runaway protection spring-boxes are pre-loaded spring configurations that act as a stiff strut within the actuator. Within the normal operating loads (up to stall effort) the runaway protection spring-boxes act as stiff structural element with no compliance. Hence they have no effect on the output performance of the actuator. However, should a runaway condition occur there would be significant energy present within the rotating elements of the design (motor, gearbox and screw). When motion of the output rod is brought to a sudden halt the spring absorbs that energy by compressing from their in-situ length and damping the load spike. The peak load induced is calculated to be 265 kN, compared to a 159 kN peak operating load.

Each spring-box has 8 sets in series of parallel discs (total 24); the spring-box is preloaded to 159kN by displacing 12.4mm from the unloaded condition. In order to take 1781 joules the spring-box deflects to a total of 21mm (a further 8.6mm from preloaded).* The maximum load achieved in the spring-box at this 21mm deflection is 265kN; this assumes that all the kinetic energy has been perfectly converted into strain energy. A single spring failure will not lead to appreciable degradation in performance. A diagram of the spring box arrangement can be seen at FIG.5.

Electrical

Electronics Enclosure

The electronics are housed within a single enclosure. The principle modules are:

- Digital Signal Processing cards (DSP's).
- Power Supply Units (PSU).
- Two Motor Control Units (MCU's).
- Data logger.
- Maintenance control panel.
- Operators control panel.

The ECU translates the position demand from the Central Control Unit (CCU) to command the fin to the demanded position. All input signals are derived from the existing ship's signals for the operation of the hydraulic system in service at present. The CCU drives the stabilizer servo unit in response to the ship's gyro and log, and mode selections from the Operator Control Panel. Its operation and functionality will remain unchanged. The test signals indicating ship's roll and fin angle are used by the data logging system.

The function of the Digital Signal Processor (DSP) is to translate the position demand from the ship to command the fin to the demand position. This is achieved by driving the master motor controller with an analogue signal that corresponds to motor velocity. The DSP closes the loop by interpreting the signal from the position sensor within the roller screw and has the capability to perform BIT on itself and its interfaces; the operator control panel to report system health and interpret operator controls.

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* Data supplied courtesy of Claverham – Critical Design Review Presentation

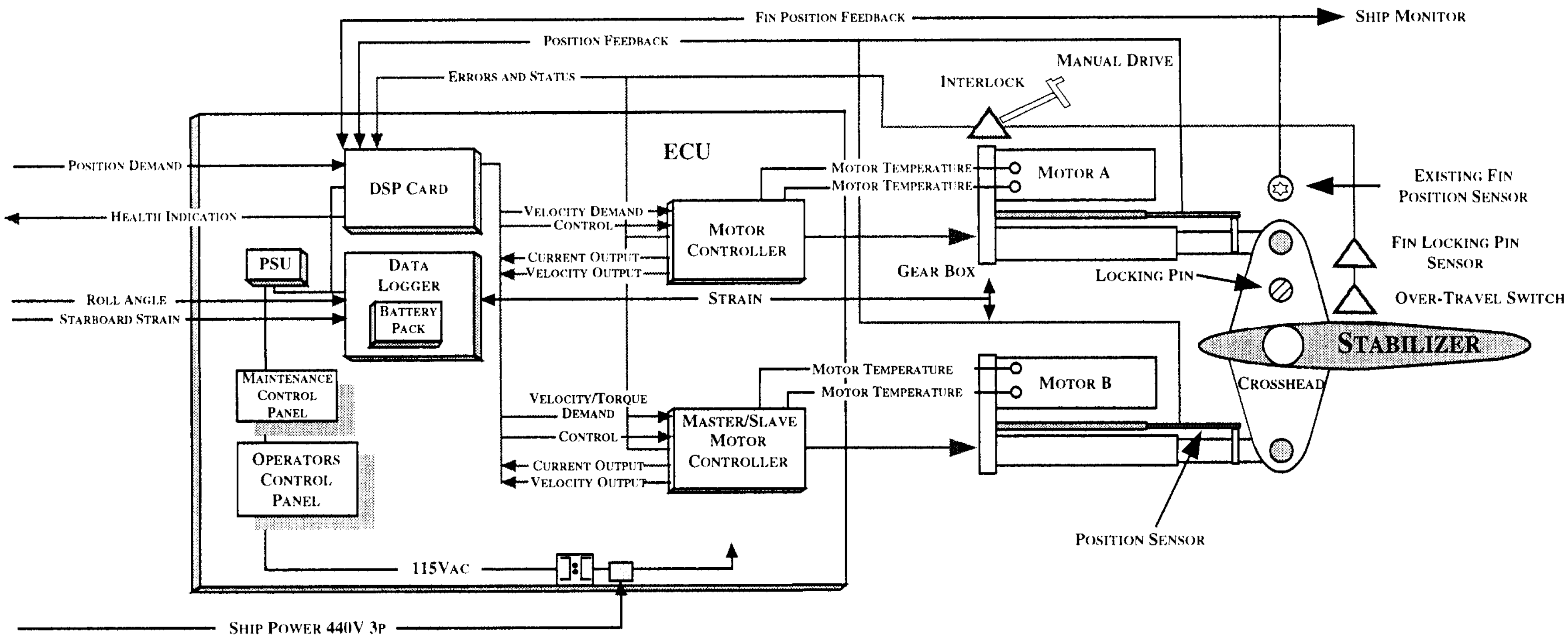

Fig.7 – Stabilizer Electrical Schematic

A Data logger system is also mounted within the ECU to record the performance of the system during installation and set to work, and for the duration of the 6-month trials on board the vessel. The Data logger is an intelligent system with the capability of changing sample rates and logging functionality. The file structure is designed to cope with power loss or logging system failure. The logging equipment will have the capability of displaying the dynamic data readings of the system to the crew, if required. An electrical schematic of the control system can be seen at (Fig.7).

Motors

The motor is also key part of the system for which its prime purpose is to provide the motive force for the actuators. There are two motors in total, arranged as one motor per actuator driving into a 1:1 gearbox, which connects, to a roller screw actuator. The motor chosen for this project is the FAS T4 V3 020 made by Moog Industries, it is a Commercial Off The Shelf (COTS) servomotors that is used extensively in industrial automation applications. FAST servomotors provide high dynamic performance characteristics and offer brushless motor performance advantages and traditional dc servo system economy.

Motor Controllers

Each of the MCUs controls a single motor in the system they are connected as a master/slave so that the load is equally shared across both motors. The MCU has an internal processor and accurately controls the connected motor using the integral resolver from the motor. Both MCU's has a discrete dc$\pm$ 10v output that tracks motor current. The master outputs the motor current that is then fed to the slave MCU input. The slave is configured in torque mode. This configuration equalises loads across the motors and minimizes offsets and inaccuracies. If a motor or MCU fault is detected the auxiliary mode can be activated whereby the MCU's and/or motors on the actuator side that has the fault are disabled and the other side continues to operate at reduced capacity. Each motor controller is a proprietary industrial device and capable of performing built in test of its own.

Interlocks

Sensor devices are fitted to the ELAHCS system to protect the system.

1. Manual Drive Interlock.
2. Fin Locking pin Interlock.
3. +30 and −30 degrees Fin Over Travel Limit Switches.

If any of these interlocks are active, i.e. indicating a hazardous condition then the drive power to the motors is disabled and the system will change into the Standby mode.

The system is also protected with health monitoring equipment including:

1. Motor overspeed.
2. Motor overcurrent.
3. Motor Temperature.
4. ECU Temperature.
5. Feedback device comparator.

Type 23 Frigate System Control

The T23 stabilizer system is designed to operate at ship's speeds between 6.5 and 18 knots allowing unrestricted fin angles of ± 28 degrees. At ship's speed above 18 knots the fin angles are reduced proportionally by the ships control system. When control of the hull sound acoustic is required the system can operate in 'quiet' mode whereby fin angles are further reduced from normal values.

When going astern or at speeds less than 6.5 knots the CCU will demand the fins to centralize automatically. If the astern manoeuvre is in excess of 6.5 knots or manoeuvres last for long periods the fins are to be manually locked in the central position with fin locking pins inserted and the motors disabled. The general operational efficiency of the stabilizer system is reduced when towing or being towed. However, the system will remain operational if the ship is proceeding at a speed greater than 6.5 knots.

Position Feedback Sensors

The system has three position feedback devices; two Variable Reluctance Vector Transducers (VRVT), one in each EMA and a single rotary sensor that is part of the existing system. Housed co-axially within the screw is the position feedback device the VRVT's are connected to measure the extension of the actuator arms with respect to the gearbox, this signal is then used by the ECU. One of the VRVT's is used as a backup device in case of failure of the primary device.

The sensor incorporates proven contact-less position measurement to achieve high resolution and high linearity. This is a Penny and Giles supplied VRVT assembly, which offers the envelope benefits of a potentiometer with the contact-less benefits of a Linear Variable Differential Transformer. The body is retained within the earth fitting and the rod is anchored within the output eye-end.

The ECU provides power for the existing ship's sensor (Fin Angle Transmitter), which feeds back its signal directly to the ships electronics via the ECU. This signal is logged and compared with the signal from the sensor on the starboard stabilizer.

Structural Design Drivers

Shock

The data derived from the Requirements Capture was fundamental in the structural design drivers in particular the duty cycle of the currently installed system.[4] In addition, the MoD shock requirements for ship stabilizers are extremely rigorous and have considerably impacted upon the design and decision processes. A full shock analysis has been completed and the results of this analysis showed that the equipment could remain captive when subjected to accelerations up to $1844 m/s^2$ and operational up to $1033 m/s^2$. The system will be subjected to a shock testing programme on completion of the sea trials.

The Type 23 has been designed to its own very rigid shock policy. The ELAHCS equipment is a low risk option and the new equipment is well understood, and further testing will ultimately justify our confidence and provide the Fleet with the necessary belief that our system is extremely robust.

The structural strength of the system is based upon the maximum stall load of the incumbent system with an appropriate margin. The key reserve factors based on this load are shown at Table 2. These are key either because the reserve factor is less than 2 or the location is on a component in main load path. A reserve factor of 1.30, for instance, indicates a 30% margin over and above the design load.

TABLE 2 - *Reserve Factors*

DESCRIPTION	RESERVE FACTOR (RF)
Bush Bearing Radial Strength (ultimate)	1.18
Bush Bearing Radial Axial Strength (ultimate)	5.16 Headed Bush
Stabilizer Bar Ultimate Tensile Load	1.64
Ultimate Bending Load	1.91
Ultimate Pin Shear	1.79
Ultimate Lug Tensile Strength Torque Link Bar	1.53
Ultimate Bending of Lug Root	2.26
Ultimate Lug Tensile Strength (Gear Box Cover)	3.87

Analysis indicates that the stresses are below the material fatigue endurance limit and therefore infinite life achieved. The amount of margin before fatigue damage accumulates cannot be extracted from this data.

In summary, none of the components show a reserve factor less than 1.0 and no components exhibit fatigue damage. Vibration, acceleration and thermal effects are insignificant and the fatigue duty cycle is low, however at the maximum slew rate bottoming out is a key load case. The spring box as previously described will accommodate this loading.

Torque Link Arrangements

To augment the current design proposal, an additional torque link has been developed. This was necessary after a series of calculations were undertaken to ascertain loading on the spherical bearing bushes. Due to the angle at which the stabilizer is canted to fit within the ships structure, the added weight of the electric motors results in extra stresses at the bearing surfaces which would certainly result in wear. Calculations using Finite Element Analysis were completed to determine the maximum local peak stresses.

As a result of these calculations a torque link arrangement has been fitted to distribute the peak stresses, further calculations have shown that the peak stresses are now well below a threshold that may induce wear. The Torque Link arrangement can be seen at (FIG.8).