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Smart Multi-Lane Electromechanical Actuators

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Abstract

Recent development in brushless dc motors and their drives provided the technology to build electromechanically actuated primary controls, hence they were proposed for ground, aerospace and (recently) mercantile applications. This paper addresses the transfer of single type summing architectures (namely, velocity, Torque and electromagnetic summing) to marine technology. The paper will highlight the drawbacks in such architectures and will propose (as an alternative) a novel Electromagnetic Torque Summing technique and will address the possible application of a vibration control method to this type of architecture. The previously proposed Fault detection and Fault Isolation system (in the all-electric aircraft) will be recommended and description of suitable threshold setting techniques on the imbedded Monitoring Devices will be given. The paper will also show how stringent space and response requirements in aircraft actuation systems could be relaxed when actuation technology is transferred to propel marine systems.

Keywords: Brushless DC motor; Marine actuation and propulsion

1. List of symbols

E	Error
F_D	Disturbance
F_{eq}	Maximum gain
F_{Lev}	Levitation Force
F_{max}	Maximum gain
I	Coil current
K_d	Mass displacement from the electromagnet surface
K_i	Electromagnet coil constant
K	Spring constant
m	Levitated particle mass
x	Particle displacement from the magnet surface
x_N	N^{th} Particle displacement
X_{Ref}	Altitude to a set input

2. In the beginning

Generally speaking, both aircraft and marine technologies share many common aspects in the way their control surfaces underwent development over the years. In both, early control systems were totally manually operated, so that, forces had to be generated by the pilot or the captain and transmitted (by cables/rods/shafts or gears) to the control surfaces. As frames were developed and higher speeds were attained, the number of control surfaces, their size and the loads acting on them increased too, which demanded an increase in power. In order to provide this extra required power, hydraulic technology was introduced. The other major advance in both technologies was the introduction of computers, which also evolved from being simple and slow to complex and fast, eventually leading to the fly/sail-by-wire concepts. To date, the common element in the development of control surfaces has mainly been restricted to hydraulic technology for its proven

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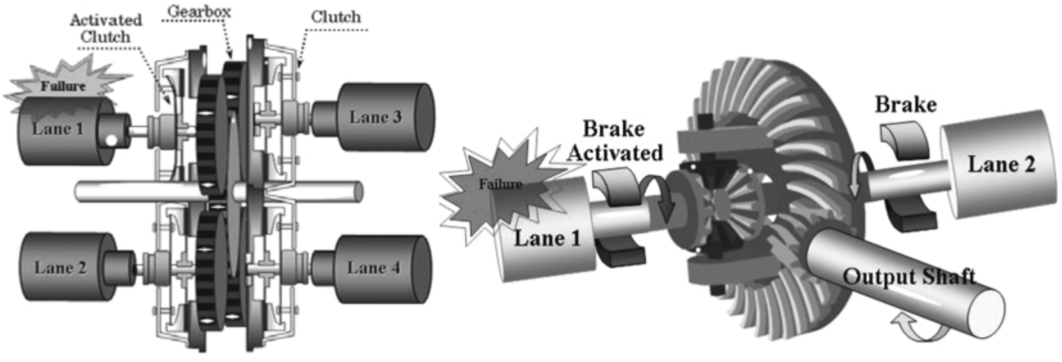

Torque Summing

Velocity Summing

Fig. 1. Electromechanical architectures.

reliability, as well as, the lack of any other alternatives.

It was until 1964 when brushless dc motors were developed by NASA and the technology to build electromechanically actuated primary control systems was made possible, Murugesan (1981). The attraction in this new all-electric technology lies in the consolidation concept of all secondary power systems into electric power, improving maintainability, dispatch readiness and use of energy, Hair (1983).

3. Hardware redundancy

Hardware redundancy is associated with the inclusion of repeated key hardware components that are likely to fail during operation. In the case of aircrafts, powered flying controls are fitted with at least two independent hydraulic power supplies driving a tandem hydraulic ram. Fly-by-wire systems were designed for failure survival, hence the corresponding designs of surface actuators are commonly found to have up to four lanes of parallel 'first stage' hydraulic actuation driving a duplicate or triplicate hydraulic secondary "power stage", Leonard (1983). A purely all-electric system had to match the current performance and redundancy specifications.

3.1 Electromechanical summing, ES, system

Annaz (2005) described how electromechanical hardware redundancy could be achieved through torque summing, velocity summing, or a combination of the two architectures, if more than two lanes are summed. Velocity summing architecture resembles that of the torque summing architecture, except that the differential gearboxes have to be replaced by torque summing gearboxes, Fig. 1. However, it should be noted that the gearbox assembly in these architectures reduces the overall system reliability to that of the gearbox itself.

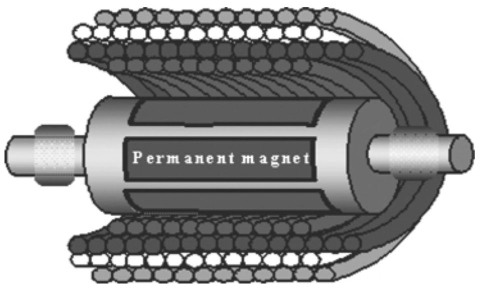

Fig. 2. ES architecture.

3.2 Electromagnetic summing system

Pond and Wyllie (1983) described the electromagnetic summing design in Fig. 2 as an attempt to remove the gearbox assembly to increase the system reliability. This summing technique comprised of a rare earth permanent magnet brushless motor utilising magnetic torque summing of quad redundant windings driving a ballscrew output assembly. The authors reported to have persistent test performance problems stemmed from developmental immaturity in motor control circuits and power transistors as well as stray circuit noise.

3.3 Shaft spread electromagnetic torque summing, SSETS

In aircraft systems, compact architectures are essential, however, since housing constraints are more relaxed in marine systems, it is proposed here that the

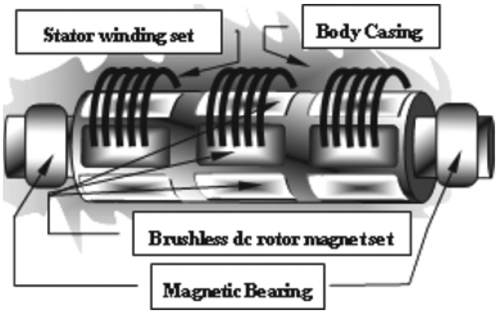

Fig. 3. The SSETS.

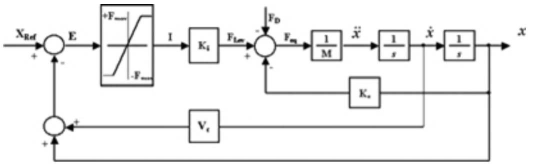

Fig. 4. Levitation control system.

electromagnetic summing idea could be extended by spreading the permanent magnets and their windings assembly along the length of the shaft, Fig. 3. It is believed that this will eliminate electromagnetic noise and interference as well as allow for effective cooling and implementation of superconductive windings approach to enhance the system's efficiency. However, long shafted architectures could suffer from vibrations and flexure modes, which could be tackled through vibration control and shaft structural modifications, respectively, Annaz (2000).

Although the forgoing discussion emphasised on redundancy in drives and their power conditioners only, it should be stressed that further redundancy in power sources, feedback sensors as well as on board computers should be included too. Previous studies showed that loss in torque generators or their power conditioners resulted in the highest failure transient disturbances, when compared to feedback sensors failures. Therefore, system recovery tests should be limited to power (lane) loss only, however, designers should account for appropriate threshold settings for all redundant components, including feedback sensors.

4. Fault detection and fault isolation system, FDI

Patton *et al.* (1989) described that the effectiveness of the FDI system is assessed by its promptness in detection, sensitivity, rate of missed fault detection, rate of false alarms and rate of incorrect fault identification. These terms are closely related and depend on the FDI system's threshold values.

Feedback sensors usually operate simultaneously, therefore, the control system should receive the average reading of healthy sensors only. In case of lane failures (and depending on the design); backup systems should come on line immediately, if lanes were designed to operate alternatively; or assisting lanes should increase their output power, if the lanes were operating simultaneously. Sensor failures result in failed sensor isolation, however, a motor or a power conditioner failure should result in the isolation of the whole lane. The FDI system could also be utilised to provide lane equalization to reduce any possible force fight between torque-summed lanes or gradual speed runaway between velocity-summed lanes. In the SSETS system case, it is important to equalise as well as synchronise coils excitations to prevent/minimize torsion effects.

5. Wave control

Annaz (2000) presented a wave-absorbing control strategy to suppress transient free vibrations in a single levitated particle application. The wave control was comprised of two control actions aiding each other simultaneously. The first control action is provided by some type of controller to achieve the desired levitation, Fig. 4. The second type of control is achieved by creating a chain of virtual spring-mass components (Fig. 5) to seep out any trapped waves.

Components in the virtual chain were linear mathematical equivalents of the real single levitated particle. The equations of motion for a homogeneous system comprising of a single levitated particle linked to a virtual chain of "N" components are as stated in (1) and (2).

$$\mathbf{F_{Lev} = m\ddot{x} = k_d x + k_i I} \tag{1}$$

$$\left.\begin{aligned}
&\mathbf{m_0\ddot{x}_0 + 2kx_0 - kx_1 = F_{lev}}\\
&\mathbf{m\ddot{x}_1 + 2kx_N - kx_{N+1} - kx_{N-1} = 0}\Big|_{(N=1)}\\
&\mathbf{m\ddot{x}_N + 2kx_N - kx_{N+1} - kx_{N-1} = 0}\Big|_{(N=2\sim N-1)}\\
&\mathbf{m\ddot{x}_N + 2kx_N - kx_{N-1} = 0}\Big|_{(N=N)}
\end{aligned}\right\} \tag{2}$$

In this configuration, and regardless of the chain's length, propagating waves will eventually reflect back into the system as shown in Fig. 6. Annaz (1998) showed that with a moderate chain length, efficient

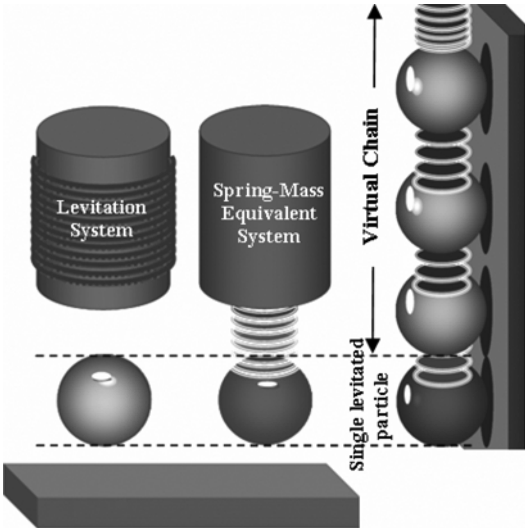

Fig. 5. Single levitated particle chain.

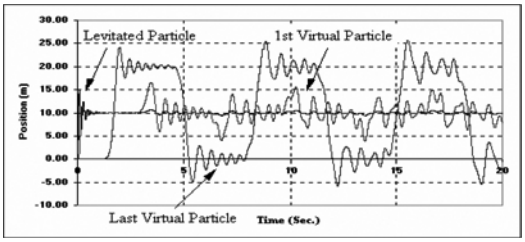

Fig. 6. Wave propagation in levitated particle and Chain.

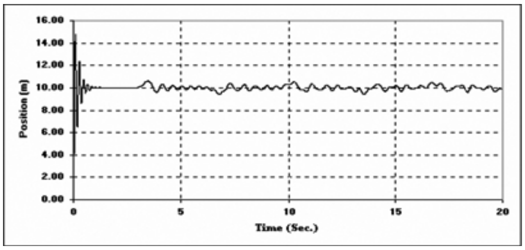

Fig. 7. Wave control without initialization.

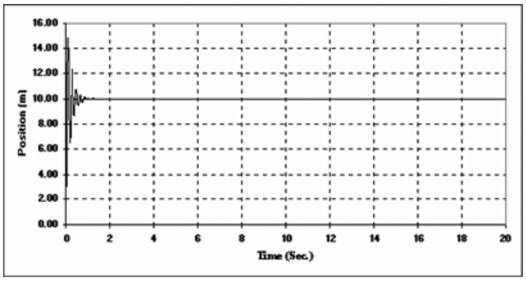

Fig. 8. Wave control with initialization.

on-line control was possible only with appropriate initialization to reset the positions of the virtual components as waves reach the end of the chain, Figs. 7 and 8.

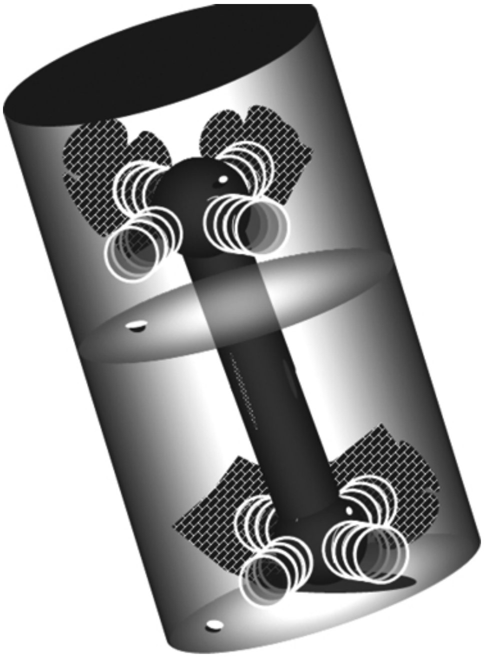

Fig. 9. Wave control in the SSETS system.

In the SSETS system, a similar trapped vibration effects might take place when the active magnetic bearings take over in supporting the shaft, after a failure. It is proposed that 2-D virtual chains should be implemented to seep out any vibrations, as shown in Fig. 9.

6. Threshold setting methodologies

Detailed description of threshold setting techniques were given by Annaz (1998) and Annaz (2005), this section will briefly compare the efficiency and superiority of the Simulation-Graphical Monte Carlo (SGMC) to decision theory, analysis of variance, and a purely simulation Monte Carlo.

6.1 Decision theory

Sage and Melsa (1971) described how decision theory requires knowledge of observations and prior probabilities in the presence and absence of failures, as well as knowledge of cost functions for correct and incorrect decisions. Such requirements disqualify this method as a suitable threshold setting technique.

6.2 Analysis of variance

This method is known as the ANOVA and it is inaccurate, requires large samples and could be very complex, depending on the form used, Ross (1989). In fact, its complexity depends on the number of control parameters for a given set of random variants. For example, in the aircraft system, the problem could be reduced to a two-way ANOVA if the control parameters were limited to aileron deflection and aircraft speed for a given servos parameters and feedback sensors.

6.3 A Simulation graphical monte carlo

The SGMC does not suffer from any of the above disadvantages, can be used with the same ease of application to any finite region and requires smaller sample of simulation or experimental tests, hence it is more efficient, Kalos and Whitlock (1986). This method, accounts for random inherent disparities in redundant components, reducing the nuisance disconnects probability to 10^{-4}. Unlike aircrafts, marine systems not only have the luxury of larger housing spaces and larger recovery time. The latter relaxes threshold setting design requirements in the FDI system.

To close this brief discussion on monitoring and monitoring techniques, the following two points should be noted:

- Regardless of the monitoring technique implementted, correct setting of thresholds remains of great importance, since high threshold values could result in unnoticed failures progress, which could lead to a serious damage. However, low thresholds could result in high false alarm rates, i.e. reoccurrring nuisance disconnects.
- It is also important to cater for online monitoring for certain components to eliminate dormant failures. A constant output for specific number of computing cycles could indicate that a driving chip (for example) has actually failed. Dormant failures are highly unlikely events in aircraft applications as its unlikely for a system to maintain constant output for a long time. However, in Marine systems and due to the relatively larger time constants, it is possible for such failures to develop and remain unnoticed until a large sudden change in the output takes place.

7. Conclusions

This paper tried to address two fundamental issues in all electric actuators, namely, systems architecture and fault detection and fault isolation related concepts. On one hand, this paper promoted ideas which have already been used in designing electromechanical control surfaces in aircraft systems and on the other hand proposed alternative technology concepts. The increase in installing compartments and the much larger time response marine systems enjoy over aircraft systems permits to:

- Move away from the classical electromechanical architectures and even allow for the implementtation of backup systems, instead of parallel operation.
- Allow for new architectures such as the proposed SSETS system.
- Relax the rules over high system performance restoration after a failure.

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