Journal of Mechanical Science and Technology 21 (2007) 950~954

Journal of
Mechanical Science and Technology

Technology Transfer of Aircraft Actuation to Marine and Propulsion

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(Manuscript Received November 16, 2006; Revised January 8, 2007)

Abstract

The most fundamental concept in designing multi-lane smart electromechanical actuation systems, besides meeting performance requirements, is the realization of high integrity. The main aim of this paper is to discuss fundamental consolidation designs and monitoring schemes in different architectures and to address threshold settings methodologies, inherent randomness, lane equalization, and control strategy. The analysis is based on a 4-lane actuation system capable of driving aerodynamic and inertial loads (with 2 lanes failed) of an aileron control surface similar to that of the Sea Harrier.

Keywords: Multi-lane electromechanical actuator

1. List of symbols

A_{TWi}, B_{TWi}, …	Control parameters in ANOVA.
$Cost_{00}$	Cost of accepting hypothesis $\Re_0$ when hypothesis $\Re_0$ is true
$Cost_{11}$	Cost of accepting hypothesis $\Re_1$ when hypothesis $\Re_1$ is true
$Cost_{01}$	Cost of accepting hypothesis $\Re_0$ when hypothesis $\Re_1$ is true.
$Cost_{10}$	Cost of accepting hypothesis $\Re_1$ when hypothesis $\Re_0$ is true
K_A, K_B, …	Number of levels in the control factors A_{TWi}, B_{TWi}, …
K_c	Number of interactions between A_{TWi}, B_{Twi}
K_1 & K_2	Constants to be evaluated
L_{ATWi}	Levels of control parameter A_{TWLi}
L_{BTWi}	Levels of control parameter B_{TWLi}
M	Mach Number
N_{ATWi}	Number of simulation tests for control parameter A_{TWi}
N_{BTWi}	Number of simulation tests for control parameter B_{TWi}
N_{obs}	Total number of observations
$P\Re_0$	Priori probability that hypothesis $\Re_0$ will occur
$P\Re_1$	Priori probability that hypothesis $\Re_1$ will occur
S	Sample size (to be determined) with certain confidence level
SS_A	Variation due to control parameter A_{TWi}
SS_{AxB}	Variation due to interaction between A_{TWi} and B_{TWi}
SS_B	Variation due to control parameter B_{TWi}
SS_e	Error sums of squares
SS_T	Sums of squares
T_{obs}	Sum of all observations
$\overline{\mathbf{T}}_{obs}$	Average of all observations $=T_{obs}/N_{obs}$, global mean
Z_T	Threshold value
$\boldsymbol{\delta}_a = 18^o\|_{M=0.2}$	18^o Aileron deflection at Mach Number 0.2.
$\aleph$	Expected Bays Risk value

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2. System under consideration

The study is based around a multi-lane (4 lanes) actuator, which has the capability of driving aerodynamic and inertial loads of a combat aircraft fighter aileron control surface, even with 2 lanes failed. Each lane contains its own dedicated micro-processor/s to perform control and comprehensive monitoring tasks. In this particular application, a failure will introduce a failure transient that will result in an aircraft roll rate response and hence a change in bank angle. Hence, based on a small aircraft type and conforming to good practice in design and various MIL-STD specifications in the Mil-F-83300 (1970), Mil-C -18244 (1970), two types of architectures were taken into account, velocity and torques summing.

3. Architecture consolidation

This section discusses briefly, torque and velocity summing architectures, failure logic and actions that follow failure detections. In both architectures, logic ensures that failures in any of the feedback sensors would result in their isolation and feedback signals in the control system will always have the average value of the remaining active sensors. Detailed description may be found in (Annaz, 2005), however, here are some of the main key points that should be taken into account:

Torque Summing: It is unlike velocity summing, where potentiometers and tachometers placement is not considered to be crucial, since all individual and common output shafts are locked together. Here, the use of the motors' built-in tachometers could result in the loss of its reading after lane isolation. However, a better signal is produced if the motors' built-in

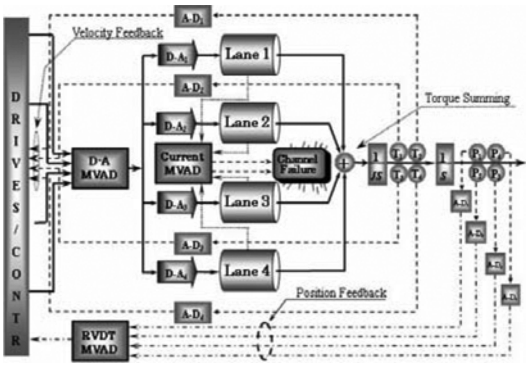

Fig. 1. Torque Summing Architecture.

tachometers are used due to the higher shaft speed. A lane failure will result in the isolation of the entire affected lane by initially isolating the power supply and then activating a clutch in the path of the failed lane (to prevent back driving the motor). In this architecture, Lane equalization is crucial to minimize force fight between lanes.

Velocity Summing: In this architecture, to provide actuator angular displacement and speed measurements, RVDTs and tachometers should be placed at the output shaft. Their placement before the summing differential gearbox would result in individual lane angular feedback measurements, which will result in immediate loss of a reading after lane isolation (due to chip or motor failure). A Lane failure will result in the isolation of the entire affected lane by isolating the power supply and then activating a brake to avoid speed compensation by other lanes. Here, lane equalization is not crucial, but can also be provided to eliminate lanes speed runaway.

4. Fault detection and fault isolation, FDI

(Patton *et al.,* 1989) explained that the effectiveness of any FDI system could be assessed by examining promptness of detection, sensitivity to incipient faults, missed fault detection, the rate of false alarms and incorrect fault identification. In the multi-lane actuator, the FDI system has the basic function of registering an alarm when an abnormal condition is developed. It is the inclusion of this system that makes the actuator 'smart'. A component or a lane failure will introduce failure transients that will result in an aircraft roll rate response and hence a change in the bank angle. To minimize the roll disturbance, promptness in failure detection, identification and isolation are essential. These are closely related to the rate of false alarms and are functions of the thresholds on the Monitoring-Voting-Averaging Devices, included in the FDI system.

5. Inherent randomness

It is practically impossible to use identical components in repeated hardware, however, it is possible to match repeated components with some degree of certainty. The degree of matching is subject to the effect components' deviation has on the system behaviour. Components with low tolerance may be selected at the expense of the cost of the system. The presence of the inherent disparities dictates that the thresholds should be set so that acceptable failure transients are produced with minimum, preferably zero, false alarm rate. The inherent deviations in lane disparities are functions of the magnitudes of the input command signals, generated by the pilot or the onboard computers, and the aircraft speed.

6. Possible Threshold Setting Methodologies

Although different methodologies will be presented here, it is worth mentioning early in this discussion that a Simulation Graphical Monte Carlo (SGMC) method was found to be the most suitable threshold setting technique. The historical development of Monte Carlo Methods and the mathematical background were discussed in details by (Hammersley et al., 1964 ; Kalos et al., 1986 ; Rubinstein, 1981 ; Snell, 1988). Further theoretical background may be found in (Abramowitz et al., 1956 ; Chambers et *al.,* 1983 ; Ermakov, 1976 ; Sage, 1971). All these discussions were summarized by (Annaz, 1996). As a threshold setting technique, SGMC is more accurate and much simpler to apply when compared to other techniques such as Decision Theory and Analysis of Variance. Unlike these two methods, it requires a small sample of simulation tests (or hardware runs) to calculate threshold levels with false alarm rates, as low as 10^{-4}. To elaborate on the advantages this method has over Decision Theory (Hypothesis Testing) and Analysis of Variance, the methods will briefly be described in the next sections.

Decision Theory: The probability of a single observation $z=\alpha$ to be under priori probabilities $\Re o$ or $\Re 1$ distributions may be expressed by:

$$\Re_o{:}P_Z(\alpha)=P_{Z\,|\,\Re}\,(\alpha\,|\,\Re_o)\text{ and}$$
$$\Re_1{:}P_Z(\alpha)=P_{Z\,|\,\Re}\,(\alpha\,|\,\Re_1) \tag{1}$$

The idea here is to accept one of the two above functions as being "most representative" of the density of a given sample. If $\alpha=Z_T$ is the threshold, it follows that if a single observation $\mathbf{z=\alpha_1}$ is greater than $\mathbf{Z}_T$, $\mathbf{\Re_1}$ is accepted and if it is less than $\mathbf{Z}_T$, then $\mathbf{\Re_o}$ is accepted. In fact, the Bays Risk " $\aleph$ " representing the expected value of the cost for the four alternatives is as given in (2). Minimizing "$\aleph$" in (2), (Ross, 1989) expressed the threshold by the expression in (3).

$$\aleph = \mathrm{Cost}_{00}P(\text{accept }\Re_o,\Re_o\text{ true}) + \mathrm{Cost}_{01}P(\text{accept }\Re_o,\Re_1\text{ true}) + \mathrm{Cost}_{10}P(\text{accept }\Re_1,\Re_o\text{ true}) + \mathrm{Cost}_{11}P(\text{accept }\Re_1,\Re_1\text{ true}) \tag{2}$$

$$T_{hresh} = \frac{P_{\Re_o}\left(\mathrm{Cost}_{10} - \mathrm{Cost}_{00}\right)}{P_{\Re_1}\left(\mathrm{Cost}_{01} - \mathrm{Cost}_{11}\right)} \tag{3}$$

It is clear that in order to utilize this method the following is required:

- Knowledge of observations distributions, in the presence or absence of failures.
- Knowledge of prior probabilities, in the presence and absence of failures.
- Knowledge of cost functions for correct and incorrect decisions.

Analysis of Variance, ANOVA: Problems treated with this method could be set up in different forms depending on the number of control parameters, Spiegel (1961). Higher forms of ANOVA may be conducted depending on the number of control parameters. In the multi-lane actuator, the control parameters could be reduced to aileron deflections at specific aircraft speeds ($\mathbf{A}_{TW_i}$ and $\mathbf{B}_{TW_i}$). Assuming equal number of levels in each control parameter and if only three levels were assumed (for analysis purpose), it follows: The levels in $\mathbf{A}_{TW_i}$ & $\mathbf{B}_{TW_i}$ are $\mathbf{L}_{A_{TW_i}}\Big|_{i=1,2,3}$ & $\mathbf{L}_{B_{TW_i}}\Big|_{i=1,2,3}$. Hence, computed data, ys, could be divided into three groups, one per level. Assuming that $\mathbf{N}_{A_{TW_i}}$ and $\mathbf{N}_{B_{TW_i}}$ are the number of simulation tests for control parameter $\mathbf{A}_{TW_i}$ and $\mathbf{B}_{TW_i}$ for a particular level.

Let $\mathbf{N}_{obs} = \sum_{i=1}^{K_A} \mathbf{N}_{A_{TW_i}} + \sum_{i=1}^{K_B} \mathbf{N}_{B_{TW_i}}$ be the total number of observations

The Two-Way ANOVA total variation, $\mathbf{SS_T}$ in (4) is composed of variation due to the control parameters $\mathbf{SS_A}\big|_{A_{TW_i}}$, $\mathbf{SS_B}\big|_{B_{TW_i}}$, $\mathbf{SS_{AxB}}\big|_{A_{TW_i},B_{TW_i}}$ and $\mathbf{SS_e}$.

$$\mathbf{SS_T = SS_A + SS_B + SS_{AxB} + SS_e} \tag{4}$$

Where, $\mathbf{SS_T} = \left[\sum_{s=1}^{N_{obs}} y_s^{\,2}\right] - \frac{T_{obs}^{\;2}}{N_{obs}}$,

$$\mathbf{SS_A} = \left[\sum_{i=1}^{K_A}\left(\frac{A_{TW_i}}{N_{A_{TW_i}}}\right)\right] - \frac{T_{obs}^{\;2}}{N_{obs}},$$

$$SS_B = \left[\sum_{i=1}^{K_B} \left(\frac{B_{TW_i}}{N_{B_{TW_i}}} \right) \right] - \frac{T_{obs}^{\;2}}{N_{obs}},$$

$$SS_{AxB} = \left[\sum_{i=1}^{K_c} \left(\frac{(AxB)_i^{\;2}}{N_{AxB_i}} \right) \right] - \frac{T_{obs}^{\;2}}{N_{obs}} - SS_A - SS_B, \text{ and}$$

$A_1B_1 = (AxB)_1$, $A_2B_1 = (AxB)_2$, $A_1B_2 = (AxB)_3$, $A_2B_2 = (AxB)_4$, …, etc.

The "**x**" between A_{TW_i} and B_{TW_i} represents the value due to interaction of a particular "A_{TW_i} **state**" with a particular "B_{TW_i} **state**". SS_{AxB} may be expressed by (5).

$$SS_{AxB} = \left[\frac{A_1B_1}{K_C} + \frac{A_1B_2}{K_C} + ... + \frac{A_2B_1}{K_C} + \frac{A_2B_2}{K_C} + ... + \frac{A_{KA}B_{KB}}{K_C} \right] - \frac{T_{obs}^{\;2}}{N_{obs}} - SS_A - SS_B \quad (5)$$

The error in (4) will be used to evaluate inherent disparities between the lanes, with the false alarm rate being dependant on the confidence level used in the above calculation. Regardless of the form of ANOVA used, the method has the following limitations:

- The confidence level is dependent on the confidence level at which the data were obtained. This could be improved by increasing the sample size.
- The complexity of this method is directly related to the number of control parameters associated with the problem.

The Simulation Graphical Monte Carlo: The advantages of this method lie in the fact that it does not suffer from any of the above disadvantages and that it has the following additional advantages:

- Although the "Monte Carlo" method will be utilized with tolerance distributions for selected system components that are essentially Gaussian, it can be used with the same ease of application to any finite region. The effect of the combinations of "multi-dimensional variously-shaped distri-butions" could easily be handled by this method. In such distributions, the domain of the independent variables is represented by "stratified unit d-dimensional square" distributions, (Kalos et al., 1986).
- A purely simulation-based approach is inefficient, since simulation time is governed by the desired rate of false alarms and not the sample size.

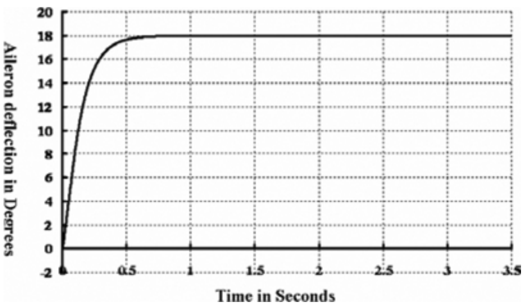

Fig. 2. 18° aileron Response.

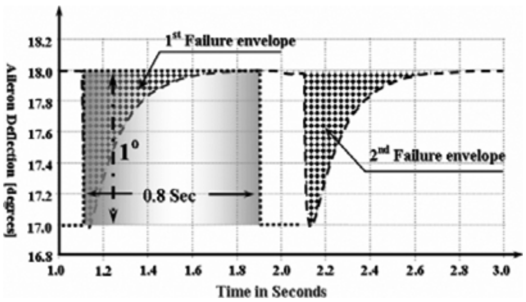

Fig. 3. Typical failure transient envelope following lane isolation.

7. Control system consideration

As far as the control system design is concerned, (Annaz, 1996) showed that there was little shift in the open loop poles due to the high gearbox ratio. It was also found that it is essential to include velocity feedback to cater for any nonlinearity due to the aerodynamic load. Therefore, the open loop poles were modified to pass through dominant complex poles, so that the undamped natural frequency remained unchanged. Forcing the locus to pass through these poles resulted in a zero introduction and a slight drop in the damping factor, ζ. In terms of steady state error, this increased when the actuator experienced the steady component of the aerodynamic load. Hence, it was essential to include a lag filter (which had little effect on the general response) in the forward path. (Annaz, 2005) showed that a reduction in the driving force has little effect on the general system characteristics, showing small change in the natural frequency, the damping, and the speed response. Figure 2 is the step response to a maximum authority limit of $\delta = 18^{\circ}|_{M=0.2}$ (without failures). With the current design, typical failure envelopes that follow a lane isolation is as shown in Fig. 3, which was simulated as a disturbance pulse to test for trends in aircraft response. The effect of the control system design may also be seen by examining the response in Fig. 3, as the actuator recovered from two successive failures. Furthermore, the output of this controller acted as a common control input signal to the 3-phase nodes of each motor (via transistors that activated them sequentially, depending on the switching state), provided that this input signal value is within the permitted range. If the common control output signal falls outside this range, then the transistors will be driven into their "off" or "saturation" modes. In simulation tests, either lumped or 3-phase models may be employed. In the lumped model, the input voltage will simply be the Signum function of the controller output. However, in the 3-phase model, the switching of transistors and the corresponding switching states should be included in the algorithm, to simulate the real system. Common control input signals to the phase nodes were essential for lanes equalization, particularly in the torque summing architecture.

Conclusion

The presented work was based around a 4-lane actuation system designed to drive an aileron control surface similar to that of the Sea Harrier. The paper touched on general fundamentals that are necessary in designing multi-lane smart electromechanical actuation systems. The paper addressed lanes consolidation and touched on sensory integration and monitoring schemes in different architectures. The superiority and ease of a Simulation-Graphical Monte Carlo was also compared to other threshold setting techniques. Finally, control strategy and its effectiveness in lanes equalization, was also described.

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