Health Management System for the Hydraulic Servoactuators of Fly-by-wire Primary Flight Control Systems

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ABSTRACT

Aircraft maintenance is one of the most important cost items faced by the operators of air fleets and is a major contributor to the aircraft life cycle cost. An aircraft fly-by-wire flight control system has a total of primary flight control actuators ranging from 10 to 20 depending on the aircraft type, with a failure rate of 1/1000 flight-hours; therefore, a health monitoring system for primary flight control actuators, able to recognize an actuator degradation in its early stage could greatly contribute to optimize the maintenance operations, reduce the airplane downtime and prevent missions interruptions.

This note presents the initial part of an ongoing research project aimed at developing a prognostic and health management system for fly-by-wire primary flight control actuators. A key feature of the project is to develop a PHM system for these actuators suitable for the flight control actuators of legacy airplanes, which are poised to operate for still a long time, and not only for those of new aircraft. The primary flight control actuators of fly-by-wire flight control systems of existing aircraft are electrohydraulic servoactuators with a typical configuration and complement of transducers, and there is no practical possibility of introducing additional sensors. For this reason, the research activity was directed towards the study of algorithms able to identify faults only by using the already available information of the servoactuators state variables.

The implemented algorithms are a combination of mathematical and neural network based ones, and the identification of degradations was performed by the analysis of the response of the servoactuators to a sequence of selected stimuli provided in preflight or postflight. The servovalve current and the feedback position are processed by dedicated algorithms in order to obtain significant indicators of the servocatuator health condition. The values of the indicators obtained during the sequence of stimuli are analyzed in combination with those obtained in the past. This is performed by the neural network part of the algorithm which allows a reliable identification of presence and of type of a degradation.

The results obtained from the initial part of the research activity are interesting and encouraging. Individual degradations of the servoactuator parameters have so far been addressed and the algorithms for identifying them have been developed. All that makes up the foundations of the future research activity which will be focused on analyzing the effects of simultaneous multiple degradations and to the estimation of the remaining useful life.

1. INTRODUCTION

The development of a PHM system suitable for flight control actuators of legacy airplanes presents numerous problems related mainly to the impossibility to increase the number of sensors, and consequently of information, useful to recognize the appearance of a degradation. Comes the need to best combine the information already acquired not only for control of the servosystems but also the normal control operation, as the hydraulic oil temperature. In addition, the inability to detect the external loads acting on the wing surface makes it necessary to think of prognostic systems capable of working when the aircraft is pre/post-flight condition. Injection of selected stimuli during ground test offers the possibility to recognize all possible degradations of servovalve; however the detection of actuator degradations is not possible by the reason of absence of external load. (Borello, Dalla Vedova, Jacazio and Sorli 2009).

The research conducted to date has focused on the analysis of major degradation of the servovalve: toque motor degradation, spool friction increase, growth of radial clearance between spool and sleeve, feedback spring degradation and progressive clogging of a nozzle.

2. MATHEMATICAL MODEL

Studies of the effect of different degradations on the behavior of the servo actuator were carried out using a high-fidelity mathematical model especially implemented in Matlab-Simulink. In the realization of the mathematical model all the typical nonlinearity that characterizes the behavior of electrohydraulic servoactuators have been taken into consideration.

The servovalve torque motor model is implemented with equations presented by E. Urata (2007) which express the magnetic flux as a function of the armature position and dielectric constant of air-gap and also give the possibility to set an unequal air-gap thickness. In the dynamic equations of servovalve flapper and spool the influence of feedback spring force, coulomb and viscous friction and structural stiffness and damping, have been considered, furthermore each parameter can be modified in order to simulate a degradation of the components. The servovalve control flows resulting, for each port, from the difference of the contributions coming from supply and direct to return. Each contribution is a function of: spool position, pressure drop, radial clearance and discharge coefficient; the last term, in turn, depends on the port opening, Reynold number and on the ratio between corner radius and port opening.

The hydraulic actuator is describe by a 3-DOF model: the first two are the rod and the surface position, the last concerns the deformation of the attachment point of the actuator with the fixed structure. Special attention has been committed to modelling the actuator coulomb friction, which is function of dynamic condition of the rod and as well as of geometrical and physical data of the seal and of pressures in the actuator chambers.

The model also includes the electronic part of the servosystem, the LVDT demodulator, the analog-to-digital converters, the data refresh rate and the computation time of the fly-control-computer are implemented. In the purpose of increasing the fidelity of mathematical model electrical noise in A/D converter and the noise that corrupts the servovalve current command are taking in to account.

2.1. Environmental condition

The dynamic response of a servoactuator is also a function of the external loads and environmental conditions, such influence, in particular severe conditions, can become particularly significant and to vary heavily indices of health considered in the PHM system.

Being the prognostic test carried out in pre/post-fight the aerodynamic force is due exclusively from atmospheric wind, this has been modeled as the sum of three distinct components:

- Velocity of atmospheric wind, obtained by a normally distributed random number.
- Wind gust, whose amplitude and duration are determined by a random number generator. Gusts occur in a random pattern.
- Turbulence, whose characteristics are calculated using the Dryden model.

The airstream velocity thus obtained is used with atmospheric density and drag coefficient to obtain the aerodynamic force.

The environmental conditions, in particular the temperature, influence also the oil properties, hence the mathematical model includes a set of equations that updates the values of density, viscosity and bulk modulus.

2.2. Mathematical model validation

The mathematical model has been validating using a set of experimental data consisting of frequency responses for different command amplitude and step response. As shown in Figure 1 the behavior of the model and the experimental data are particularly close.

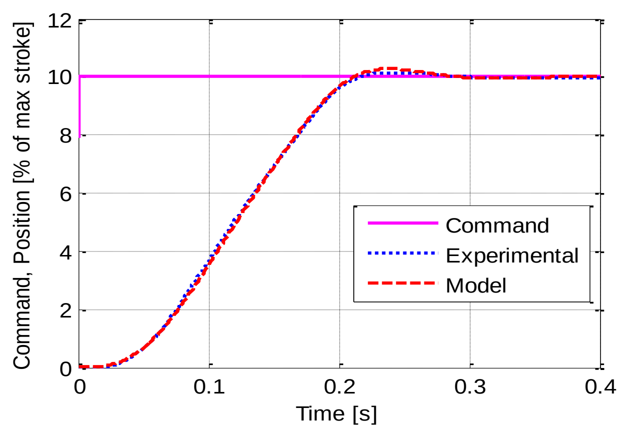

Figure 1: Step response model validation

The absence of experimental data concerning degrade servosystems did not allow to validate the mathematical model in fail to failure condition, however the physical-based nature of the model affords to hypothesize a good fidelity of the model even in case of those parameters that allow to introduce degradations.

3. INDICATORS OF HEALTH CONDITION

The PHM system developed is based on the observation, both punctual and the trend, of significant indicators of the servocatuator health condition. The indices are obtained by the processing of servovalve current and feedback position get as response of servoactuators to a sequence of selected stimuli provided in preflight or postflight.

The command set is designed to maximize the number of health index obtainable, it is 1.8 s long and it is the combination of four different input kinds (Figure 2):

- Sinusoidal command: amplitude equal to 5% of half stroke at 5 Hz frequency.
- Step command: amplitude equal to 10% of half stroke.

- Constant command: amplitude equal to 10% of half stroke.
- Ramp command: ratio equal to 22 mm/s.

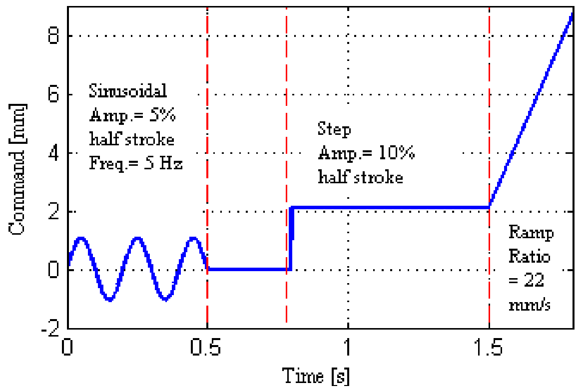

Figure 2: PHM command

The analysis of the servosystem response, both in terms of feedback position and servovalve current, to the different stimuli allows to obtain eleven different indices, five from the position and six from the current. The indexes are presented in Table 1 divided by type of command.

Table 1: Indicators of health condition

Command	Position Index	Current index
Sinusoidal	Gain	Min current
	Phase	Max current
		Mean current
Step	Rise time	Decries time
Constant	Limit cycle	Limit cycle
Ramp command	Rate error	Rate current

The tests were carried out to identify the influence of each degradation on the health index had put in evidence that is possible correlate univocally the trends of the indices to deterioration, since any deterioration involves a unique set of variation of the indices. In addition, tests have revealed a greater sensitivity of the indices of the current with the degradations, but at the same time also a greater sensitivity to noise and environmental conditions. Therefore it was decided to combine the two types of indices: those of the current for an early identification of the degradation and the position indices to have a reliable estimate of the condition of the servosystem.

3.1. Nominal variation range

The indicators of health condition, exactly as the response of the servo system in its entirety, are strongly influenced by environmental conditions, by the aerodynamic loads and noise. The value of the index is also dependent on the geometric tolerances provided for in the design phase, thus making impossible to define a nominal values of the index valid for a family of servoactuators. Several tests carried out in order to define a range of variation of the indexes in the absence of degradation. The simulations have been conduct combining different environmental conditions and changing flow and pressure gain of the servovalve, in accordance with technical specification. The limits so defined have been multiplied by a safety factor in order to avoid false alarms. This procedure has allowed to identify a range, function of the oil temperature, in which the variation of the health index taken into consideration does not involve the presence of a degradation.

4. PHM ALGORITHM

The developed PHM algorithm is composed of three different subroutines, which work jointly to detect and identify degradations. The first subroutine is dedicated to the processing of the current and position recorded during the pre/post-flight test and it is also designated to detecting the appearance of the degradations. The algorithm, after obtaining the value of the health indices, compares these with the range of nominal variation relative to the oil temperature. If an index comes out from these limits for three consecutive times, the algorithm indicates the presence of a degradation and activate the second subroutine that identifies the type of degradation. In case the first degradation has already been identified, the first subroutine will begin to analyze the historical trend of indices in order to identify the occurrence of further failure. The appearance of a new degradation induces a variation of the rate of the trend indices, which entails a peak in the second derivative curves of all of the indexes in the same instant. Due to of the derivatives performed, and the identification of the necessary filtering of the indices takes place with about twenty acquisitions delay. The detection of a second failure involves the start of the third subroutine.

The second subroutine includes in its interior a double layer neural network, which receives in input the values of the eleven indices normalized and limit between -1 and 1; 1 corresponds to the upper limit of nominal band exceeded by the index, -1 the lower limit exceeded. The output of the neural network is the indication of the type of degradation. The neural network has been subjected to a learning process in order to optimize its operation, the training function adopted working in according with Levenberg-Marquardt optimization (Levenberg 1944 and Marquardt 1963). During the process of learning 1366 set of indices taken at random from the simulation results has been provided to the neural network.

The third subroutine is composed of a double layer neural network with eighteen inputs and seven outputs. The first seven inputs are the indication of the previous degradation, 1 indicates that the degradation was detected previously otherwise the corresponding value is zero; the other eleven inputs correspond to the signs of the peaks of second derivative of the indexes trend detected from the first subroutine. Using the supplied input the neural network provides to classify the new degradation. The neural network has been trained using the same learning function used for the second subroutine; in this case ten different multiple degradations were provided in input.

5. RESULTS

The algorithms have been tested using data generated by a large number of simulations, in which the environmental and operative conditions were changed in order to test all the possible operative scenarios.

In the following sections the results of validation algorithms tests are present divided in single degradation and multiple degradations case. In both cases the algorithms were proved robust and the nominal variation ranges were reveled very useful for the purpose of avoid false alarms due to fluctuations of the indices caused by changes of environmental conditions.

5.1. Single degradation detection

The classification of a single degradation carried out by the second subroutine provides very interesting results. The neural network has been verified with a large numbers of set indices, 13631, the classification was successful except that in 42 cases, corresponding to an error less than 0.31%. The classification errors appear mainly in the presence of high degradations level, where all the degradations affect in a similar way all the indices. The test results are shown in the Figure 3. In Table 2 are shows the average values for each failure in which occurs the recognition and classification.

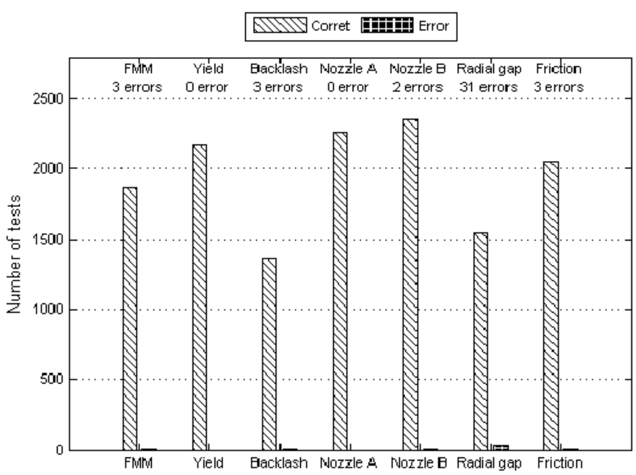

Figure 3: Single degradation classification

Table 2: Value of recognition

Degradation	**Value**
FMM degradation	6.2 %
Feedback spring yield	10.3 %
Feedback spring backlash	13.4 µm
Clogging nozzle	2.5 %
Spool radial gap	8.8 µm
Spool friction	5.0 N

5.2. Multiple degradation detection

The recognition of multiple degradations present greater difficulties than in the single case, since the recognition of the peaks of the second derivative is particularly complex because of the fluctuations in the indices due to disturbances and noise.

The verification of the algorithms has been made by providing twenty different combinations of degradations as input to the neural network. In seventeen cases the classification of the second degradation was successful, in two cases there were errors of classification, while in one case the second degradation was not recognized.

Failure to recognize the degradation has occurred in the case of a reduction of the magnetic force and friction, the main cause of the error is the small amplitude of the peeks as a consequence of the low influence of friction on the health indices.

6. CONCLUSION

The research carried out has proved particularly interesting and can provide an excellent starting point for a prognostic algorithm able to estimate the RUL. The algorithms developed are particularly robust and do not require a priori knowledge of the fail to failure mechanisms, since all strategies identified to recognize and classify the degradations are based on the analysis of certain data acquired during normal operation of the actuator.

An improvement in the quality of research will be to validate the algorithms by using experimental data, in addition the reliability of algorithms could increase exploiting the data from an entire fleet of aircraft, thus optimizing both the neural networks and nominal range of indices variation.

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