Proposal of Prognostic Parametric Method Applied to an Electrohydraulic Servomechanism Affected by Multiple Failures

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Abstract: Prognostics could employ several approaches with the aim to detect incipient failures due to a progressive wear of a primary flight command electro hydraulic actuator (EHA); the efficacy shown in failure detection drives the choice of the best ones, since not all the algorithms might be useful for the intended purpose. This happens because some of them could be suitable only for specific applications while giving bad results for others. The development of a fault detection algorithm is thus beneficial for anticipating the incoming failure and alerting the maintenance crew so as to properly schedule the servomechanism replacement; such algorithm should be able to identify the precursors of the above mentioned EHA failure and its degradation pattern. This paper presents a research focused on the development of a prognostic methodology, able to identify symptoms alerting that an EHA component is degrading and will eventually exhibit an anomalous behavior; in detail, six different types of progressive failures have been considered (dry friction acting of servovalve spool or mechanical actuator, radial clearance between spool and sleeve, shape of the corners of the spool lands, torque sensitivity of the first stage torque motor, contamination of the first stage filter). To achieve such objectives, an innovative model based fault detection technique has been developed merging together the information achieved by FFT analysis and proper "failure precursors" (calculated comparing the actual EHA responses with the expected ones), relying upon a set of failure maps. The robustness of the proposed technique has been assessed through a simulation test environment, built on the purpose. Such simulation has demonstrated that the methodology has adequate robustness; also, the ability to early identify an eventual malfunctioning has been proved with low risk of missed failures or false positives.

Key-Words: - electrohydraulic actuator, primary flight control, multiple failures, numerical modelling, position servomechanism, prognostics

1 Introduction

Prognostics are a discipline that aims to predict the moment in which a specific component fails and loses the capability to achieve its duties at the desired levels. It is based on knowledge and analysis of the possible failure modalities of the considered item and on the capability to individuate the initial symptoms of aging or wear; additionally, this discipline has the objective to assess the magnitude of the damage experienced by the considered item (ensuring, on the whole, an analysis for the identification/evaluation of the considered failures). A proper failure propagation model uses therefore these pieces of information to evaluate any possible malfunction and its impact. Applying prognostics to aeronautics could be useful to reduce maintenance costs and inspection time. The discipline known as Prognostics and Health Management (PHM) was conceived to optimize these different needs. PHS is intended to provide real-time information on the current status of the monitored item and to assess the Remaining Useful Life (RUL) before a fault occurs or a component loses the capability to maintain an adequate level of performance. The advantages gained applying PHM methodologies can be verified comparing the life performances of a system conceived according to this discipline with those of a classical design.

The primary flight controls are a critical feature of the aircraft system and are therefore designed with a conservative safe-life approach; this criterion imposes to replace any element to which it is applied after a predetermined amount of flight hours (or operating cycles). Such approach is applied irrespective of the effective status of the items and the ability to continue to operate correctly, as such conditions are not evaluated and the maintenance activity is performed anyway.

Safe-life approach is unable to cope with any initial flaw (occurred during manufacturing) that could cause a sudden fault, compromising the safety of the aircraft; it is also unable to individuate are the components that really failed and to limit on them the maintenance intervention (with the related inefficiencies and additional costs). On the opposite, a system designed with an approach based on PHM strategies is able to better manage failures, resulting into several benefits: lower operating costs, less maintenance interventions, lower number of redundancies to be installed on board, improved aircraft safety and reliability, possibility to plan maintenance activities optimizing the necessary actions (limiting downtime and related costs and allowing a more effective organization of the maintenance and management of spare parts warehouses) and limiting the logistical difficulties resulting from the manifestation of the fault.

This paper is referred to the considerations reported by Jacazio et al. in [1], and proposes new findings as the outcome of further research, focused on the development of a fault detection/evaluation method able to identify failure precursors (alerting that the system is degrading) and to assess the extent of the damage; it could be noteworthy to know that a progressive degradation of a component, even if not resulting (at least at the early stages) into an unacceptable behavior, often results in a reduction in efficiency, as the performances of that component are impaired, compromising the normal actuation system operation. In order to develop the above mentioned research, A typical aircraft primary command electrohydraulic (EH) actuator has been modelled in the MATLAB Simulink® simulation environment to be considered as a case study; several sets of conditions (nominal or with various failures) have been simulated.

2 Aims of Work

The aims of this work are:

1. to propose a numerical algorithm able to perform the simulations of the dynamic behavior of a typical EHA considering the effects due to six different types of progressive failures (dry friction acting of servovalve spool or mechanical actuator, radial clearance between spool and sleeve, shape of the corners of the spool lands, torque sensitivity of the first stage torque motor, contamination of the first stage filter);
2. to introduce an innovative fault detection and evaluation method able to detect the EHA failure precursors and assess the resulting failure that is going to occur.

An appropriate simulation test environment was developed to evaluate the robustness of the proposed techniques; this has been aimed to the assessment of the effects deriving from the six mentioned failures on the EHA behavior, with different simulations performed combining several failure configurations. A monitoring model has been used as a reference to compare the simulation results, so to determine the related differences and define a correlation with the corresponding failures. By means of proper algorithms, the simulation results are used to timely identify the failures and evaluate their magnitudes. To fulfill the intended objective, an innovative model-based prognostic methodology has been developed merging together several information achieved by means of Fast Fourier Transform (FFT) analysis and proper "failure precursors" (calculated by comparing the actual EHA responses with the expected ones).

The results so obtained showed an adequate robustness and confidence was gained in the ability to early identify the malfunctioning with low risk of false alarms or missed failures.

3 Considered Actuation System

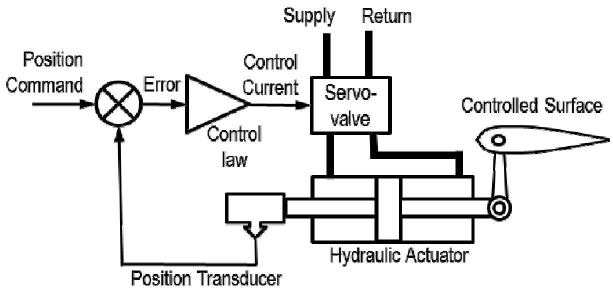

Fig. 1: Concept schematic of the EHA actuator

The examined electrohydraulic actuation system is shown in Fig. 1; it consists of three subsystems:

1. *controller subsystem*: it is made of a control electronics and a servoamplifier (SA); the control electronics may be a computer, microprocessor or guidance system and creates a command input signal; the SA provides a low power electrical actuating signal which is the difference between the command input signal and the feedback signal generated by the feedback transducer. The SA usually implements an embedded PID control logic (proportional-integral-derivative); sometimes it could only use a proportional-integral (PI) or a proportional-derivative (PD) logic, or a further simplified proportional logic with a velocity loop; the present work refers exactly to a pure proportional control logic;

2. *electrohydraulic two stage servovalve*: it responds to the low power electrical signal generated by the controller subsystem and manages the high power flow of hydraulic fluid to the actuation element;
3. *hydraulic piston*: it is a symmetrical double acting linear cylinder subject to Coulomb friction, provided by a position transducer, which positions the device being controlled.

The description of the electrohydraulic actuator employed in the present work and its mathematical model are shown in [2]; the logic that represents the considered servomechanism is shown as a block diagram in Fig. 2.

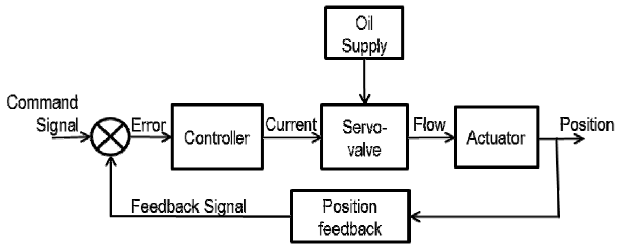

Fig. 2: Block diagram of a position control logic EHA.

The aforesaid servomechanism belongs to the fly-by-wire paradigm: the pilot's command is read by transducers that reflect the pilot gestures with an electric or a digital reference signal; such signal is continuously compared via a feedback loop with the actual position of the control surface generating the instantaneous position error as input to the control law. The error is processed and transformed into an electric current operating the electrohydraulic servovalve; this valve drives an actuator that moves the control surface continuously pursuing, by a proper control law, the reduction of the error between pilot's commanded position and flight surface actual position. The considered servovalve is a high performance two-stage valve (Fig. 3).

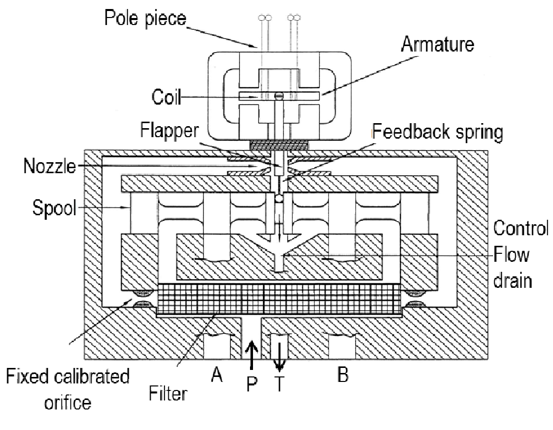

Fig. 3: Flapper – nozzle servovalve.

The output stage is a closed center, four-way sliding spool, while the pilot stage is a symmetrical double nozzle and flapper, driven by a torque motor. Only its orifices resistive effects have been considered, as its natural frequency is supposed to be orders of magnitude higher than the desired closed loop bandwidth of the whole position servomechanism; on the basis of this consideration, the behavior of the servovalve (SV) can be represented with a lumped parameters second order electro-mechanical model for the pilot stage (first stage) and a second order for the sliding spool (second stage) and the related feedback spring. The second-stage dynamic model considers the effects due to the Coulomb friction forces acting on the spool, according to the numerical model proposed in [3]. A feedback from the second stage toward the first one, a saturation of the second stage output differential pressure and the effect of working flow and leakage on the differential pressure itself are considered; the model considers the effect of time dependent supply pressure. A double acting symmetrical hydraulic linear actuator has been considered; its model, as shown in [4], includes inertia, Coulomb and viscous friction and leakage effects through the piston seals developing a not working flow; the model takes into account the effects due to its interactions with the possible mechanical ends of travel as well as the external load acting on the flight surface.

This type of simulation algorithm is also able to evaluate the dry friction force, taking into account its dependency on mechanical actuator efficiencies and also on external loads (opposing or aiding) acting on the EHA. Additional details concerning this topic are provided in [5].

4 Analytical Model of the EHA

The considered electrohydraulic actuator has been modelled by means of a Simulink numerical model representing the block diagram shown in Fig. 4.

The position error (Err), coming from the comparison of the instantaneous value of commanded position (Com) with the actual one (XJ), is processed by means of a PID logic giving the suitable current input (Cor) acting on the servovalve first stage torque generator; the engine torque (expressed as a function of Cor through the torque gain GM), reduced by the feedback effect due to the second stage position (XS), acts on the first stage second order dynamic model giving the corresponding flapper position (XF) (limited by double translational hard stops).

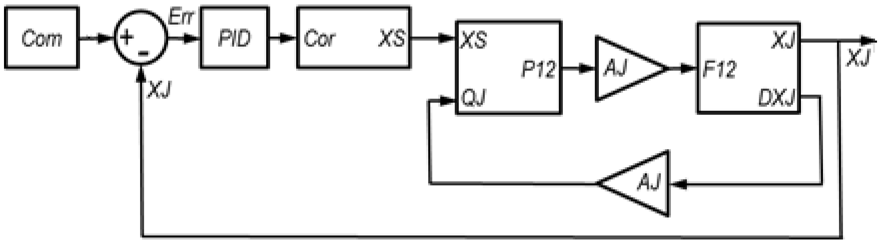

Fig. 4: Simulink block diagram of the considered EHA.

The flapper position results in a consequent spool velocity and, by time-integrating, originates the displacement XS (limited by double translational hard stops ±XSM); it must be noted that the second stage dynamics is modelled by means of a second order numerical model able to take into account the dry friction forces acting on the spool. From XS, the differential pressure P12 (pressure gain GP taking into account the saturation effects) effectively acting on the piston is obtained by the flows through the hydraulic motors QJ (valve flow gain GQ). The differential pressure P12, through the piston active area (AJ) and the equivalent total inertia of the surface-motor assembly (MJ), taking into account the total load (FR), the viscous (coefficient CJ) and dry friction force (FF), gives the assembly acceleration (D2XJ); its integration gives the velocity (DXJ), affecting the viscous and dry frictions and the linear actuator working flow QJ that, summed to the leakage one, gives the above mentioned pressure losses through the valve passageways. The velocity integration gives the actual jack position (XJ) which returns as a feedback on the command comparison element.

Effects due to conversion from analogic to digital of the feedback signals (ADC), electrical noise acting on the signal lines and position transducers affected by electrical offset are also covered by the proposed numerical simulation model.

5 Considered EHA Degradations

The electrohydraulic actuators and, in particular, the servovalves, regulating the hydraulic power, are complex devices that can fail in several ways: as above said, in the present work the authors highlight some typical failures affecting only the servovalve. It should be noted that some servovalve failures have a quasi-random occurrence. Usually, they are: the interruption of the electrical coils, the breaking of the internal feedback spring, the nozzle or the jet-pipe clogging by oil contamination, and finally the spool seizure resulting from a large metallic chip stuck in the radial clearance between spool and sleeve.

All these failures are unpredictable events leading to a servovalve lack of operation, or uncontrolled movement: they could be recognized by a dedicated monitoring logic that cuts off the hydraulic power supply to the servovalve and inhibits any further operation[1]. However, there are many other cases where a progressive degradation of the SV occurs, with an initial imperceptible, but increasing, performance reduction that leads to a condition in which the servovalve, and hence the whole EHA functions are impaired.

In this work the servovalve progressive degradations considered are the following:

1. Obstruction of the first stage filter. As dirt and debris accumulate in the first stage filter, power losses increase with a consequent reduction of the supply pressure available at the first stage and hence the differential pressure applicable to the spool: this causes a slower response of the servovalve, with increased phase lag and reduced EHA stability margin.
2. Reduction of the torque sensitivity of the first stage torque motor. This can be caused by a) the shorting of some adjacent coils of the torque motor windings due to the presence of metallic debris, or b) the degradation of the materials properties of the magnetic core. As for the above case, a progressively slower response of the servovalve results and, consequently, the system dynamic behavior degrades.
3. Increase of the friction force between spool and sleeve. This is due to a silting effect associated either to debris entrained by the hydraulic fluid or to the decay of the hydraulic fluid additives which tend to polymerize when the fluid is subjected to large shear stresses as they occur in the flows through small clearances: in this case, the progressive reduction of the spool positioning accuracy generates a corresponding decrease of the system stability margin.

1 In general, servovalves are provided with an LVDT position transducer sensing the spool position; the lack of response or an uncontrolled movement is detected by the comparison of the servovalve current with the spool position.

4. Increase of the radial clearance between spool and sleeve and change of the shape of the corners of the spool lands due to wear between these two moving parts and to the oil debris scraping.

In addition to the above mentioned progressive degradations of the servovalve, the authors have also considered the effects of the friction force increase acting on the linear hydraulic actuator. This dissipative force, caused by the cylinder sealing and guiding elements, has been considered because of its influence on dynamic behavior of the actuation system that induces a reduction of the EHA position accuracy and breakaway resolution, and, eventually, generates stick-slip conditions.

It should be noted that the proposed numerical model is also able to simulate the effects of the backlash growth at the mechanical interface between the internal feedback spring and the second stage spool[2], of the conversion from analogic to digital (ADC) of the feedback signal, of the electrical noise acting on the signal lines, and, finally, of the electrical offset of the position transducers. Obviously, the real EHA system may also suffer electrical or electronic problems (EMC noise, sensors degradation, etc..) not less important than the others; as their evolution is usually very fast (if not instantaneous) and the corresponding failure precursors are often difficult to identify and evaluate they will not be considered in this work even if it is the intention of the authors to study these types of failure in a future work.

6 EHA Monitoring Model

The proposed EHA Simulink model, as explained in the previous paragraphs, deals with the dynamic behavior of an actual EHA taking into account the effects of typical command inputs, different environmental boundary conditions, and several faults and degradations. This model allows the simulation, even though with proper limitations, of the dynamic response of the real system in order to evaluate the effects of different faults and degradations. Moreover, the model permits the design and the effectiveness verification of different diagnostic and prognostic monitoring strategies. In order to conceive a “parametric” system able to identify and evaluate the progressive degradation effects, it is necessary to compare its dynamic behaviors with those provided by an ideal system operating in nominal conditions: with this intention, a new reference model dedicated to monitoring operations has been developed. As shown in Fig. 5, this model represents a simplified version of the detailed EHA numerical model with the same logical and functional structure; in this way it is possible to get similar performance, although less detailed, requiring less computational effort and reduced computational time.

The symbols definition is the following Table:

Symbol	Definition
Com	Position command
Cor	Servovalve current
Err	Position error
F12	Actuator force
FV	Actuator viscous force
P12	Actuator pressure differential
QJ	Actuator flow
s	Laplace variable
Tact	Net torque on flapper
TM	Servovalve motor torque
XF	Flapper position
XJ	Actuator position
DXJ	Actuator speed
D2XJ	Actuator acceleration
XS	Spool position
DXS	Spool speed
AJ	Actuator area
ASV	Spool end area
CJ	Actuator viscous resistance coefficient
GP	Servovalve pressure gain
GQ	Servovalve flow gain
GQFm	1^{st} stage flow gain
GAP	Control law proportional gain
GM	Torque motor gain
KFt	1^{st} stage mechanical gain (spring stiffness)
KSFm	Servovalve feedback spring stiffness
PSR	Maximum pressure differential
MJ	Actuator mass
XFM	Flapper max. displacement (half stroke)
XSM	Spool max. displacement (half stroke)
XJM	Actuator max. displacement (half stroke)

2 This is the result of wear due to the relative movement between these two parts and gives rise to an increasing hysteresis in the servovalve response which leads to an instability of the whole hydraulic servo-loop.

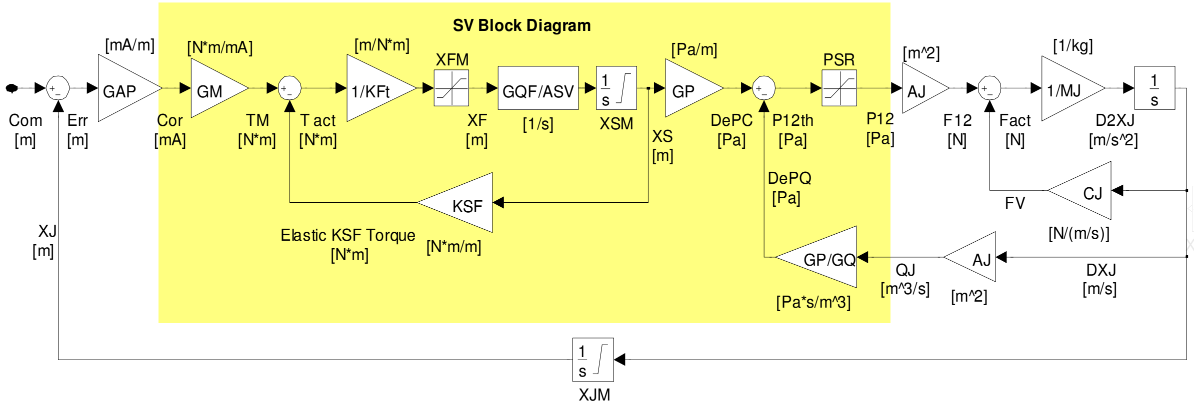

Fig. 5: Block diagram of the EHA simplified model used for the prognostic algorithm

For example, in Fig. 6 the dynamic behaviors produced by the numerical model of the EHA in response to a step position command (respectively jack XJt and spool XSt positions) are compared with the corresponding monitoring system ones (XJm and XSm). While considering nominal conditions, it is possible to observe a certain discrepancy between the behaviors of EHA and monitoring system: this is due to the simplifications characterizing the simplified model of the monitoring system (in particular, the dry or viscous friction forces acting on the SV spool, which introduce a certain response delay, and some EHA nonlinearities are neglected).

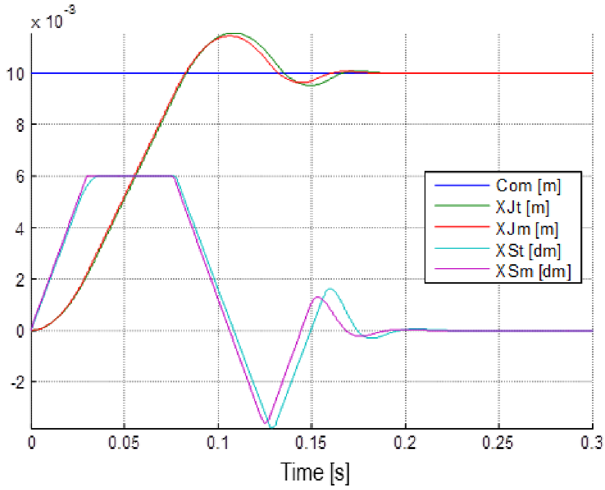

Fig. 6: Dynamic responses of detailed and simplified monitoring EHA models - step command.

7 Progressive Degradation Effects

A simulation campaign has been conducted in order to recognize the effects produced by the servovalve degradation on the dynamic behavior of the actuation system: the dynamic responses generated under degraded conditions are compared with those in nominal conditions.

The proposed EHA model has been tested with several simulations in Nominal Conditions[3] (NC): the compliance between the actual behaviors of a real EHA and the corresponding simulated results has been evaluated by many types of input commands (Com). Successively, these results have been compared with the system behavior in degraded conditions.

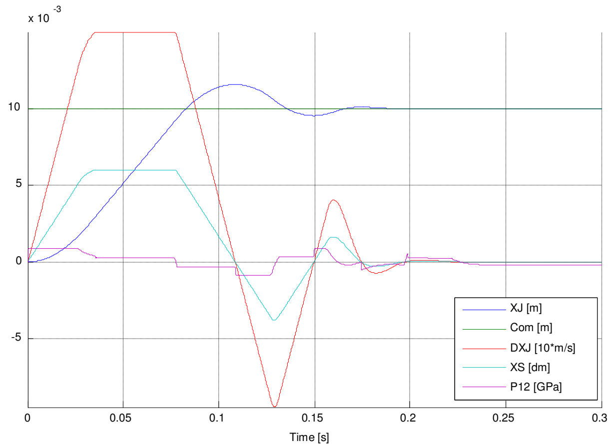

Fig. 7: Example of system dynamic behavior with the step position command.

A step command input (Fig. 7) generates a dynamical response that, in NC, puts in evidence the system stability margin, the non-linear effects (due to saturations), and the position errors (due to friction). In particular, the presented model integrates the dry friction algorithm into a dynamic system and takes into account also the hard stops effect, and their mutual interactions. in this way it is possible to discern between static and dynamic friction conditions and evaluate their effects on the system.

3 It should be noted that, in Nominal Conditions, the values of the above mentioned progressive failures are consistent with those reported in literature in the case of an actuator in optimal conditions.

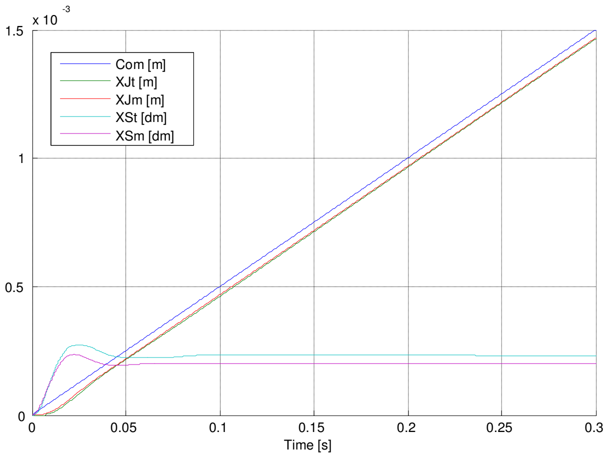

Fig. 8: Example of system dynamic behavior with the ramp command.

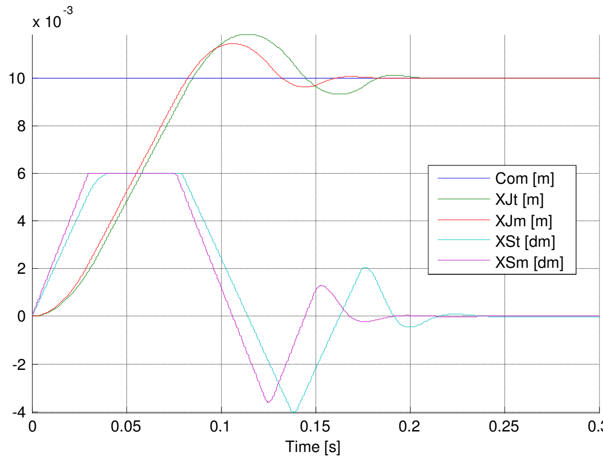

Fig. 9: Example of system dynamic response in case of increased contamination of the first stage filter.

The ramp response analysis (Fig. 8) reveals that the proposed model is able to simulate both a high-slope ramp response and a stick-slip phenomenon; the first case underlines the limits of the actuator in terms of maximum speed, while the second case shows what occur when the ramp slope is lower enough to emphasize the frictional effects. Furthermore, the model allows evaluating the incipient motion resolution of the servomechanism, i.e. the smallest command value producing an actuator's response. Obviously, this value becomes higher as the frictional contribution is more significant (eg when the EHA undergoes an increasing wear). In the same way, several periodic inputs have been examined confirming the model ability to simulate the behavior of the real actuation system and its sensitivity to nonlinear effects, command inputs (dynamic response related to sine wave input) and external loads. After the validation of the proposed numerical model in NC, several analyses have been performed evaluating the effects of the considered degradations. It should be noted that the results obtained from these simulations broadly confirm what described in the paragraph 5, as shown in the following figures where some typical cases underline the ability of the proposed EHA detailed numerical model to simulate the effects of these faults. In order to highlight the effects produced by these faults on the EHA behavior, its dynamic response has been compared to the monitoring model one (representing the NC).

Fig. 9 shows the dynamic response of the system to a position step command in case of increased contamination of the first stage filter: this degradation, slowing the spool speed of response, reduces the EHA stability margin and, thus, increases the dynamic oscillatory transient and the corresponding actuation time.

Fig. 10 shows the dynamic response of the system to a position step command in case of reduction of the torque sensitivity of the SV first-stage torque motor: this progressive deterioration, limiting the mechanical torque developed, increases the damping action on the entire servomechanism and, thus, increases its stability margin and produces reduced overshoots.

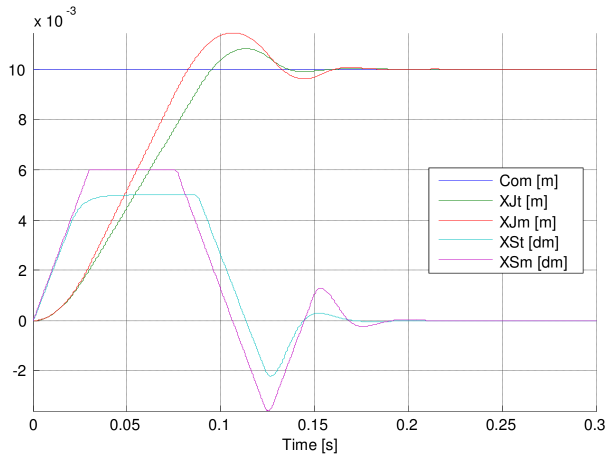

Fig. 10: Example of system dynamic response in case of reduced SV torque motor sensitivity.

Fig. 11 shows the dynamic response of the system to a position ramp command in case of increase of the friction force acting between spool and sleeve: as previously mentioned, the progressive reduction of the spool positioning accuracy generates a corresponding reduction of the system stability margin of the detailed model (failure sensing). It should be noted that a similar behavior may be obtained in case of step position command: in this case, the actuator does not reach a stationary position, but its instantaneous position manifests a triangular limit cycle around the commanded one.

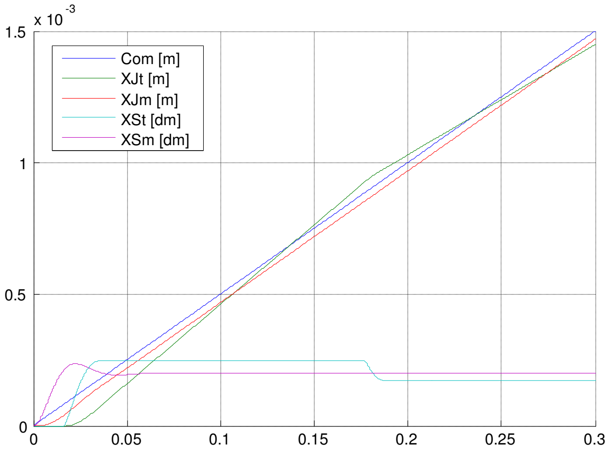

Fig. 11: Example of system dynamic response in case of increased spool friction force.

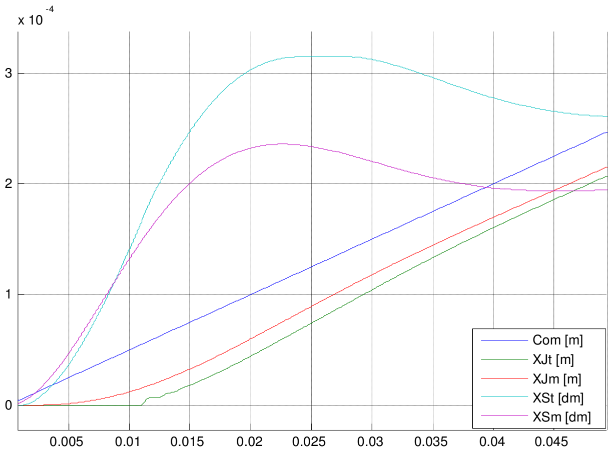

Fig. 12: Example of system dynamic response in case of increased jack friction force.

Finally, Fig. 12 shows the dynamic response of the system to a position ramp command in case of increase of the friction force acting on the linear actuator: as previously mentioned, the detailed model (failure sensing), with respect to ideal conditions (monitor), shows an increased breakaway resolution error.

8 Failure Precursors

As already said, prognostics is an engineering discipline whose purpose is to predict an incipient failure of a certain component, allowing possible interventions before the initial flaw propagates; the purpose of the prognostic model is to use the available information, without using additional sensors, to identify system degradations leading to a performance outside the acceptable range and eventually to abnormal operating conditions. The aforesaid failure detection/evaluation function could be achieved by means of a proper algorithm (typically applied to a numerical model) able to detect the failures and predict their evolution. This fact underlines a limit of prognostics: it could predict only failures which present a gradual growth and it is not able to detect sudden faults. Prognostics algorithms can have several complexity levels, from the simplest based on heuristic criteria to the most complex involving physical failure models. Developing a prognostic algorithm able to identify the precursors of an EHA failure and its degradation pattern is thus beneficial for anticipating the incoming failure and alerting the maintenance crew such to properly schedule the EHA replacement. This avoids a servomechanism failure in service, thereby ensuring improved equipment availability and minimizing the impacts onto the logistic line.

To this purpose, a proper model based failure detection/evaluation method was developed: this algorithm fuses various information obtained by comparing actual with expected responses of the EHA to recognize a degradation and estimate the remaining useful life. The choice of the best algorithms able to detect and evaluate a particular kind of incipient failure is driven by their ability to detect the failure itself, so proper tests are needed. In particular, the proposed prognostic algorithm is based upon three different checks, with each check defining a characteristic parameter; the aforesaid checks are performed in preflight when the servoactuator is unloaded.These checks, described hereunder, are based upon the results gained by three different failure precursors:

1. Fourier spectral analysis (by means of FFT);
2. Correlation coefficient C;
3. Correlation function E(τ).

The Fourier Transform (FT) is a mathematical instrument, based upon the theory of Fourier series, which has many applications in physics and engineering [6]-[7]. Fourier Transform of a function f(t) is often calculated by means of the Discrete Fourier Transform (called DFT). Unlike the typical FT, the DFT requires as input a discrete function; this restrains the DFT to the analysis of a function on a limited and discrete domain. It must be noted that the input values of DFT are finite sequences of real or complex numbers, feature that makes it ideal for data processing on electronic calculators; this method is employed to analyze the frequencies composing a certain numerical signal by means of proper algorithms constituting the Fast Fourier Transform (FFT) [8]-[10]. In order to achieve the spectral analysis of the dynamic response of the actuation system to a given command, a dedicated numerical algorithm (based upon FFT MATLAB implementation) has been conceived.

This method processes the dynamic response generated by the real actuation system (as a result of appropriate command inputs) calculating the FFT and, then, it compares the so obtained results with the corresponding ones obtained by ideal system (NC) and by corresponding monitoring model. For example, Fig. 13 shows the spectral analysis performed evaluating the dynamic response of the EHA in response to a step position command (Com = 5 [mm], null external load and NC system).

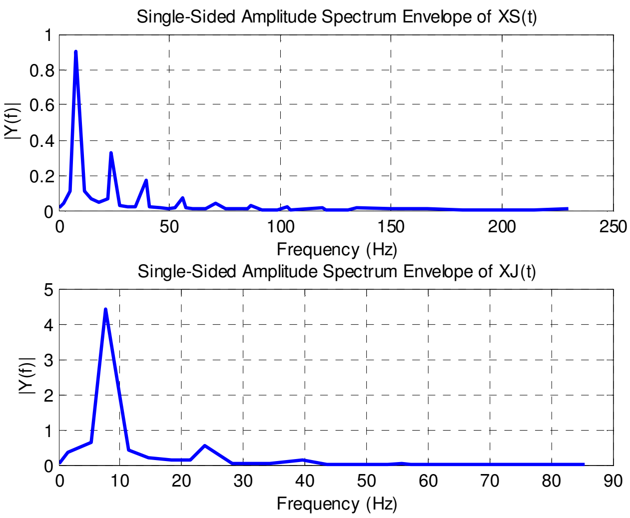

Fig. 13: Example of FFT spectral analysis achieved on the dynamic response of spool (XS) and jack (XJ).

As mentioned earlier, the second instrument used to detect incipient failures or wear conditions is the correlation coefficient C.

This coefficient, as shown in [11], is defined as:

$$C = \frac{\int_0^T x_T \, x_M \, dt}{\int_0^T x_T^2 \, dt} \qquad (1)$$

where x_T is the set of observed data and x_M is the theoretical data: in this work, they are respectively the results of the model that simulates the actual system and the data from the monitoring model. The data considered in the two vectors, depending on the case, could concern positions, velocities or other physical magnitudes of the system. The data representing the dynamic response of the actual system (fault sensitive) are compared with the results provided by the monitoring system (that simulates ideal conditions, since no progressive failures are considered): the more the failure is considerable, the more the results obtained from the simulated actual system differ from the theoretical data. This difference, in order to be useful for prognostic analysis, should have a monotonic trend related to the corresponding failure increase.

In order to allow a direct correlation between the growth of a defined failure and the corresponding value of the correlation coefficient, it is necessary to identify a physical magnitude (sensitive to the said failures) that, with increasing failure itself, generates a monotonic and easily detectable trend of C.

The two checks defined above can detect most of the servovalve degradations, but fail to identify a possible variation of the radial clearance between spool and sleeve, and a change of the corner radius of the spool lands as a result of wear of spool and sleeve. Variations of these parameters could only be detected in normal operating conditions (closed loop) by looking at the pressure/flow characteristics of the servovalve around the hydraulic null condition. A direct measurement of the pressures at the servovalve control ports would require two pressure transducers and a direct measurement of the flow rate would be a very difficult task.

Therefore, the prognostics algorithm evaluates the servoactuator behavior by performing a correlation between the servovalve spool position and the actuator position when a sinusoidal input current is generated in an open-loop mode. As for the evaluation of the correlation coefficient, this check is performed in preflight when the actuator is unloaded and is based on the following rationale. For an unloaded actuator, its speed is a function of the spool position. If the spool position is sufficiently away from the hydraulic null, actuator speed (while unloaded) and spool position are almost proportional. If a sinusoidal command is given to the servovalve spool, the relationship between actuator speed and spool position holds as long as the input frequency is sufficiently lower than the cutoff frequency of the EHA. The actuator speed is not known, but the measurement of the actuator position is available, which is lagging of a 90° phase with respect to its speed in response to a sinusoidal command. A sinusoidal input current is thus generated during this preflight check while the EHA is operated in an open-loop mode in order not to get the effect of the position feedback on the current.

The input current frequency and amplitude must be defined according to the specific application; however, since the purpose of this check is to detect the effects of wear on the servovalve characteristics around the hydraulic null, a sinusoidal amplitude from 3 to 5% of maximum current at a frequency of a few Hertz should in general be a suitable input.

The correlation function E(τ) is defined as:

$$E(\tau) = \frac{1}{T}\int_0^T x_T(t+\tau)\,y(t)\,\mathrm{d}t \qquad (2)$$

where $\tau = \pi/2\omega$ is the time delay corresponding to a phase angle of 90°, x_T is the true spool position measured by the spool LVDT, y is the actuator position measured by its own position transducer, t is the time and T the time interval over which the correlation function is evaluated. This time can correspond to a few oscillation cycles. This check is run at a few different frequencies, corresponding to different values of τ. Starting from a new servovalve, if wear causes a variation of the radial clearance or a change of the shape of the corner radius of the spool lands, a change of the correlation function is observed and if a definite trend is recognized an alert signal of a SV degradation is generated. It must be noted that a possible error of this check is that the variation of the correlation function is not determined by a change of the servovalve characteristics, but by a change of the friction force of the actuator seals. This is a legitimate possibility and thus a steady variation of the correlation function should actually indicate either a spool wear or an anomalous friction between the actuator piston and cylinder. However, as it was shown by the simulations, a greater effect is determined by the variation of the servovalve spool characteristics, which will be the most likely cause of the variation of the correlation function.

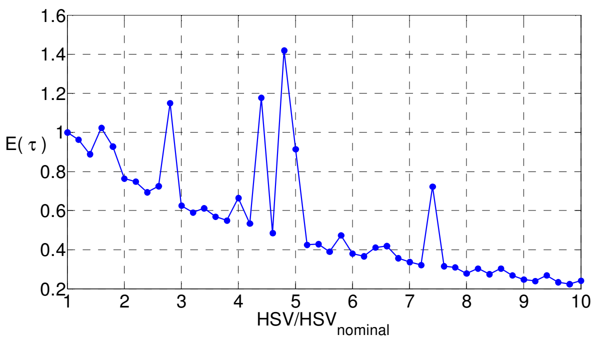

Fig. 14: Evolution of the correlation function $E(\tau)$ as a function of the spool radial clearance HSV.

For instance, Fig. 14 shows the evolution of the correlation coefficient $E(\tau)$ as a function of the spool radial clearance HSV (normalized with respect to the corresponding nominal value $HSV_{nominal}$).

9 Fault Detection/Evaluation Method

The effects of servomechanism degradations on the three characteristic parameters of the prognostic algorithm were first assessed separately, then simultaneous degradations were simulated and their effects were evaluated. The authors' work focuses on the effects due to the simultaneous presence of different kinds of failures acting on the system. With the purpose to achieve a timely identification and evaluation of these failures, the authors developed in [12] a new faults detection technique based on failure maps (FMs). A Failure Map constitutes the graphical representation of how a system-representative parameter varies as a function of two different types of failures. More exactly, a failure map displays the first failure G_1 on x-axis and the representative parameter P_1 on y-axis.

Each map represents a set of curves $P_1=f(G_1)$ which are parameterized with the second failure G_2. A proper choice of P_1 is crucial in order to obtain a useful failure map. Firstly, this parameter should be a function of both $G_1$and G_2. It is preferable a parameter which is highly sensitive to changes in failure levels. In particular, its dependence from the two kinds of failure should be monotonic, i.e. the curves plotted on the maps should not intersect.

This feature is the most important, since it allows to detect a specific area on the map containing all the possible failure levels. The proposed prognostic technique, in order to identify system conditions with high enough accuracy, requires more than one of these maps for a specific couple of failures. When several maps are employed, it is important that they be independent from each other. Independent maps can be obtained when the actuator undergoes different command inputs: in this way, the parameter represented on each map is a magnitude that is not related to the others. By using three independent maps, i.e. representing three different parameters P_1, P_2 and P_3, an accurate area containing the possible failures is identified. By using the results found during the single failure analysis to find the most suitable parameter for the map drawing, all the possible failure combinations have been studied. It must be noted that, in many cases, the FMs were not suitable for prognostics; for few couples there were not enough independent maps (as for the couple friction acting on the linear hydraulic actuator – increase of the radial clearance between spool and sleeve, with only two employable maps). A couple on which the method has been successfully tested was the friction acting on the spool (FSS_{spool}) – increased contamination of the first stage filter (K_{intas}) couple, allowing to obtain more independent maps. Among these, three were chosen to apply the FMs method (G_1= spool friction, G_2= filter contamination).

The first FM (Fig. 15) concerns the spectral analysis performed evaluating the dynamic response of the EHA in response to a step position command (Com = 5 [mm], null external load and NC system): in this case the parameter P_1 thus refers to the dynamic response of the spool position XS.

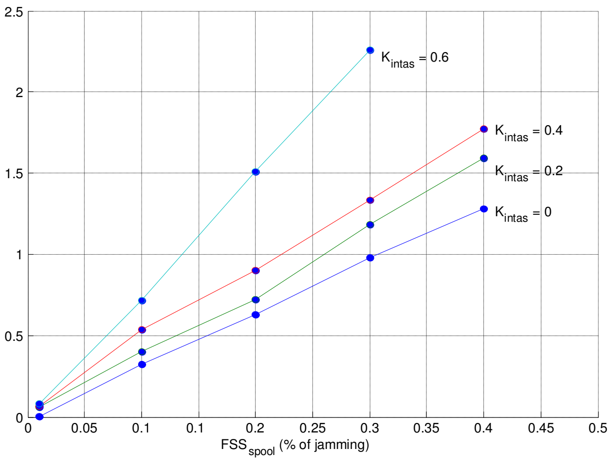

Fig. 15: Spectral analysis failure map related to spool position – Step position input.

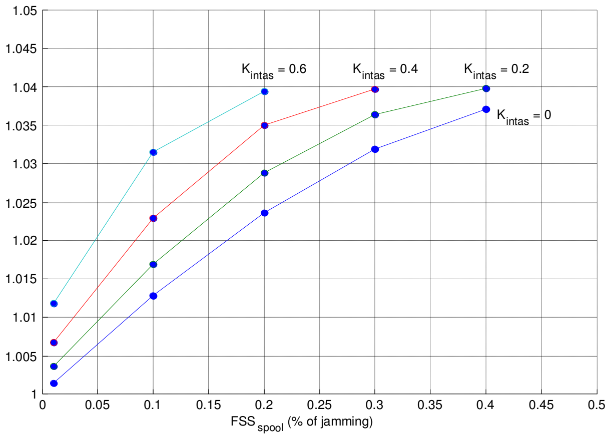

Fig. 16: Correlation coefficient C failure map related to spool position – OL current input.

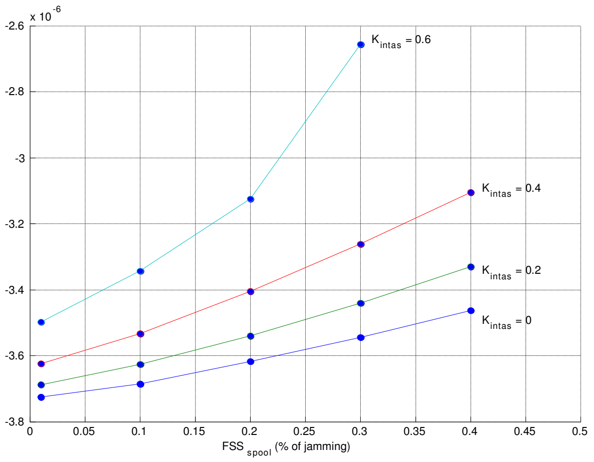

Fig. 17: Correlation function E(τ) failure map – OL current input.

Fig. 16 shows the second FM that represents the correlation coefficient C for the spool position XS (representative parameter P_2), when a step current input Cor is applied to the actuation system operating in open-loop (OL) conditions.

Finally, the last map (Fig. 17) is related to the correlation function E(τ) obtained with a sinusoidal current input Cor (5 mA of amplitude at 5 Hz of frequency) applied to the open-loop system (P_3). After the maps have been obtained, they can be employed for the proposed procedure, which is now explained in detail. Firstly, the numerical model is simulated as affected by a known level of both friction and coil failure ratio, considering the three different command inputs: this step provides the parameters P_1, P_2 and P_3. As these values will employed on the failure maps, a certain statistical dispersion, equal to a defined % of the maximum variation between the curves of each map is taken into account. Then, the first map is employed with the entering value of P_1 and an initial large area containing the possible failure levels for G_1 and G_2 is obtained. These two intervals are inserted on the second map, which requires also the value P_2: their intersection provides narrower intervals of the two kinds of failure. The procedure applied on the third map (on which P_3 is considered) is the same seen for the second one. This method has been employed on a number of combinations of progressive failures, always resulting on an enough accurate detection of the failure levels acting on the actuator.

10 Conclusions

The prognostic concepts, because of the variety of applications and the huge impact that they generate, have aroused great interest in the scientific and technological world and, especially in recent years, have been the subject of extensive development and dissemination in the scientific literature;therefore, the realization of an exhaustive comparison between the proposed method and the state of the art can be rather complex and articulated. Very often these contributions, despite being extremely innovative and significant, result too theoretical or specific and tend to overlook a more comprehensive approach (i.e. systemistic vision), dwelling on well-defined and circumscribed aspects of the considered problem. In this paper the authors propose a more systemistic and multidisciplinary approach, in which the different aspects of the considered problem, concerning the electrical, hydraulic and mechanical characteristics of the actuator and its relevant failure modes, have been analyzed and modelled together in the same multi-domain numerical model: in particular, it must be noted that this research proposes a fault detection/evaluation technique able to detect both single and multiple failures, identifying their precursors and evaluating the corresponding damage levels.

Moreover, to ensure the feasibility of the application on the proposed prognostic method, real-time inflight analysis is not implemented: this technique specifically refers only to preflight/postflight or ordinary maintenance procedures, when the data can be analyzed by an external computer without affecting the normal inflight operations. These algorithms can be easily integrated in an automatic system check process, which can be performed by the maintenance staff. Lastly, in order to avoid the introduction of new sensors or additional components, the proposed algorithms use only information gathered from transducers that already equip the considered system or that are derived from virtual sensors which post-process the actual raw measurements. This work focuses on the research of system-representative parameters which are suitable for prognostic activities and on the development of a technique, allowing a prompt detection of gradually-increasing failures on aircraft actuators. The study has been performed on a numeric test bench (simulating the behavior of a real EHA actuator) that implements six kinds of failure: dry friction acting of servovalve spool or mechanical actuator, radial clearance between spool and sleeve, shape of the corners of the spool lands, torque sensitivity of the first stage torque motor, contamination of the first stage filter. By means of proper simplifications, the aforesaid numerical model was then reduced obtaining the monitoring model. The proposed failure detection/evaluation algorithm has been developed mixing together the information derived from the spectral analysis of signals (performed by means of the FFT algorithm), from direct comparison between EHA and monitoring model (through the correlation coefficient C) and from the analysis of the actuator dynamic response (using the correlation function $E(\tau)$); by means of these tools suitable fault precursors, useful for early recognition and quantification of the damage, have been identified. Finally, proper failure maps have been drawn to perform the analysis of combined failures. This method has been successfully applied to many different combinations of considered failures, guaranteeing always an enough accurate detection / estimation of their levels.

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