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Proposal of a Fast Model-Based Prognostic Paradigm for Electrohydraulic Actuators affected by Multiple Failures

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Abstract: - The electrohydraulic actuator (EHA), and in particular the servovalves (SVs) regulating their hydraulic power are complex devices and can fail in several ways. Developing a fault detection algorithm able to identify the precursors of the above mentioned EHA failure and its degradation pattern is thus beneficial for anticipating the incoming failure and alerting the maintenance crew so as to properly schedule the servomechanism replacement. To this purpose, authors propose a new model-based fault detection and identification (FDI) technique able to perform an early detection of two of the most common types of SV progressive failures (dry friction acting on servovalve spool and contamination of the first stage filter).

1 Introduction

Prognostics is a discipline whose purpose is to predict the moment in which a certain component loses its functionality and is not further able to meet desired performances. It is based on analysis and knowledge of its possible failure modalities and on the capability to individuate the first signs of aging or wear and, then, evaluate the magnitude of such damage (i.e. fault detection and identification FDI). The aforesaid data will be then used as input of a proper failure propagation model. Vachtsevanos et al [1] put in evidence as the use of this discipline in aeronautics, as in many other technological fields, could be very useful if applied to maintenance, since it lowers both costs and inspection time. In order to optimize these advantages, the discipline known as Prognostics and Health Management (PHM) originated: its purpose, as reported by Byington, Watson, Edwards, and Stoelting [2], is to provide real-time data on the current status of the system and to calculate the Remaining Useful Life (RUL) before a fault occurs or a component becomes unable to perform its functionalities at a desired level. The research presented in the paper, referring to the considerations reported by Borello, Dalla Vedova, Jacazio and Sorli in [3] and by Maggiore et al. in [4], is focused on the development of a fault detection/identification (FDI) method able to identify failure precursors (alerting that the system is degrading) and to evaluate the damage entity.

Indeed, a progressive degradation of a system component, which does not initially create an unacceptable behavior, often leads to a condition in which the efficiency of such component is impaired and hence the whole actuation system operation could be compromised. In order to develop the above mentioned research, a typical aircraft primary command electrohydraulic actuator (EHA) has been modelled in the MATLAB Simulink® environment and several sets of simulations (in nominal conditions or with various failures) have been run.

2 Aims of Work

The aims of the work are:

1. the proposal of a detailed numerical model able to simulate the dynamic behaviour of EHAs taking into account the effects due to two different types of progressive failures (dry friction acting on servovalve spool and contamination of the first stage filter);
2. the proposal of an innovative fault detection and evaluation method able to detect the EHA failure precursors and estimate the failures entity.

To assess the robustness of the proposed techniques, a dedicated simulation test environment has been developed; in particular, in order to evaluate the effects due to the abovementioned failures on the EHA behavior, several simulations (related to different combinations of damages as well as different entity) have been performed.

The results obtained from each simulation have been compared with the ones provided by a monitoring model (a simplified model that works in nominal conditions) in order to evaluate the differences and, consequently, define an association with the corresponding failures.

3 EHA Reference Model

The studied actuation system (schematically shown in Fig. 1), is a typical electrohydraulic position servomechanism (SM) widely used both in primary and secondary aircraft flight controls.
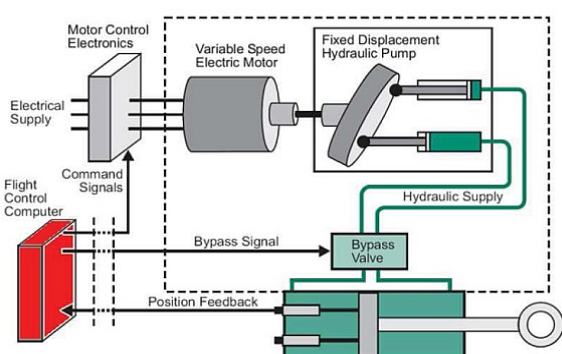

Fig. 1: Schematic concept of EHA actuator

As shown in [5-7], this servomechanism consists of three main subsystems, listed below:

1. Controller subsystem: the control electronics may be a computer, microprocessor or guidance system and creates a command input signal; the servo-amplifier (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); it must be noted that, in several applications, it is possible to implement more simplified control logics. The present work is referred to simple proportional control logic.
2. Electrohydraulic two stage servovalve (SV): responds to the SA low power electrical signal and controls the high pressure hydraulic fluid [8].
3. Hydraulic piston (symmetrical double acting linear cylinder subject to Coulomb friction): actuates the flight control surface closing the position feedback loop by means of a network of integrated position transducers.

Wider descriptions of the servomechanism employed in this work and of its mathematical model are shown by Maggiore et al. in [9]; the scheme of the above said logic is shown in Fig. 2.
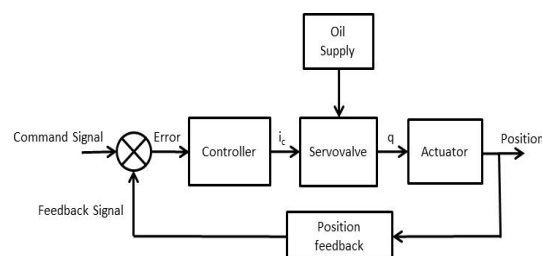

Fig. 2: Schematic concept of EHA actuator

The aforesaid servomechanism belongs to the fly-by-wire paradigm: the pilot's command depends upon transducers that express the pilot wishes by an electric or a digital reference signal; this 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. So, the error is processed and transformed into an electric current operating the electrohydraulic servovalve. The servovalve drives an actuator that moves the control surface continuously pursuing the reduction of the error between pilot's commanded position and flight surface actual position.
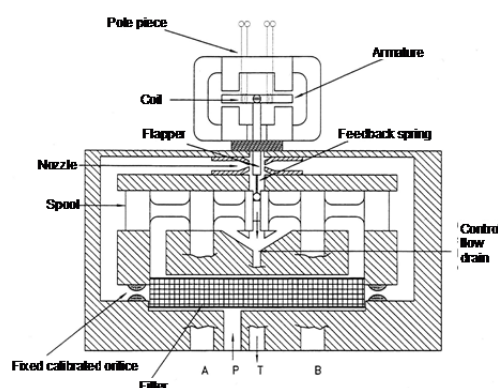

Fig. 3: Schematic of the flapper-nozzle servovalve

The servovalve is a high performance two-stage valve (Fig. 3); its second 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. Since its natural frequency is supposed to be orders of magnitude higher than the desired closed loop bandwidth of the whole servomechanism, only its orifices resistive effects were taken into account. The hydraulic linear actuator considered in the present paper is a double acting symmetrical one. It has been modelled considering inertia, dry friction (according to [10]), viscous friction and leakage effects through the piston seals developing a not working flow; it is also able to take in account the effects due to its interactions with the mechanical ends of travel as well as the external (aerodynamic) loads acting on the flight surface.
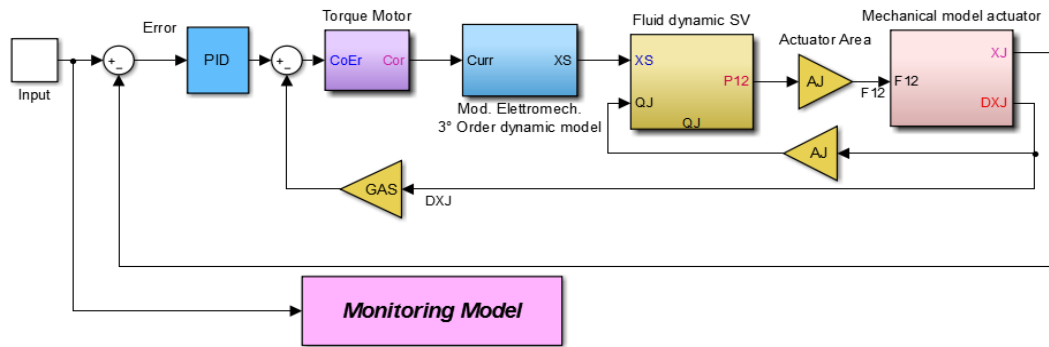
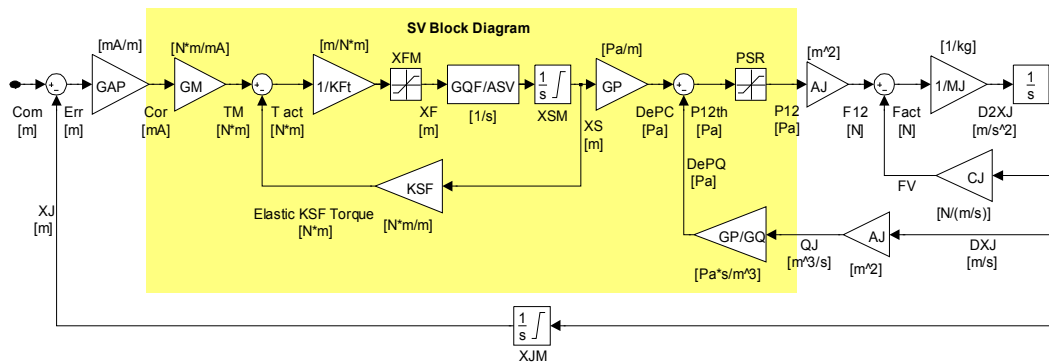Fig. 4: Simulink block diagram of the considered EHA

Fig. 5: Block diagram of the EHA monitoring model

In order to develop the abovementioned research, a typical aircraft primary command EHA has been modelled (according to considerations previously reported and widely explained in [9]) and subsequently, implemented in MATLAB Simulink® simulation environment; this model has been used to simulate the dynamic behavior of a real actuator allowing to perform several sets of simulations (in nominal conditions or under several failures level). Its Simulink block diagram is shown in Fig. 4.

4 EHA Monitoring Model

The proposed detailed EHA Simulink model, as explained in the previous paragraphs, is able to simulate the dynamic behavior of an actual electro-hydraulic servomechanism taking into account the effects due to command inputs, environmental boundary conditions and several failures; therefore, it allows simulating the dynamic response of the real system evaluating the effects of different faults and testing new diagnostic and prognostic strategies.

In order to conceive a smart system able to identify and evaluate the progressive failures, the authors propose a new method able to identify the health condition of the real EHA by comparing its dynamic response with the corresponding one provided by a simpler monitoring model properly designed:

Practically, the proposed FDI algorithm compares the two dynamic responses (EHA detailed model vs. monitoring, calculated for the same command inputs and equal boundary conditions) identifying the value of appropriate coefficients of the monitoring model that minimize the quadratic error and, subsequently, correlates them with the actual amount of the corresponding damages. To this purpose, on the basis of the algorithm shown in [9], a new monitoring model has been developed.

As shown in Fig. 5, the monitor represents a simplified version of the detailed EHA numerical model having the same logical and functional structure; such a model, with respect to the detailed one, is able to give similar performance (although less detailed) requiring less computational effort and more reduced computational time.

5 Progressive Failures Effects

The electrohydraulic actuator, and in particular the servovalves regulating their hydraulic power are complex devices and can fail in several ways: according to the above considerations, in this work authors focused on some of the typical faults that affect the servovalve. It must be noted that a few servovalves failures are a sudden occurrence and there is at present no conceivable way of predicting them.

Failures of this type are the interruption of the electrical coils, the breaking of the internal feedback spring, the clogging of a nozzle or of the jet-pipe due to large size debris in the oil, or a spool seizure resulting from a large metallic chip stuck in the radial clearance between spool and sleeve of the SV. However, as shown in [3,9], there are several other scenarios in which a progressive degradation of a servovalve occurs that does not initially create an unacceptable behavior; if undetected, these faults may lead to conditions in which the servovalve, and hence the whole EHA operation is impaired. As previously reported, the progressive SV faults considered in this work are the contamination of the first stage filter and the dry friction acting on servovalve spool.

5.1 Contamination of First Stage Filter

As dirt and debris accumulate in the SV first stage filter, its hydraulic resistance increases with a consequent reduction of the supply pressure available at the first stage and hence the pressure differential applicable to the spool: this progressive damage results in a slower response of the servovalve, with increased phase lag and reduction of the EHA stability margin (as show in Fig. 6).
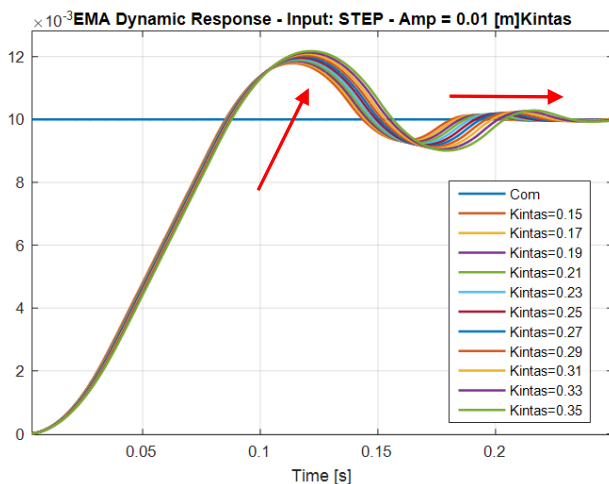

Fig. 6: EHA step position response in case of increasing first stage filter contamination

5.2 Dry Friction Acting on SV Spool

This growth of the dry friction force acting between spool and sleeve 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 high temperatures or large shear stresses - as they occur in the flows through the small clearances of SV):

in this case, the progressive reduction of the spool positioning accuracy generates a corresponding decrease of the system stability margin while about jack fault, the effects due to an increase of the friction force 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: this results in a reduction of the EHA position accuracy and breakaway resolution and could generates stick-slip conditions (Fig. 7).
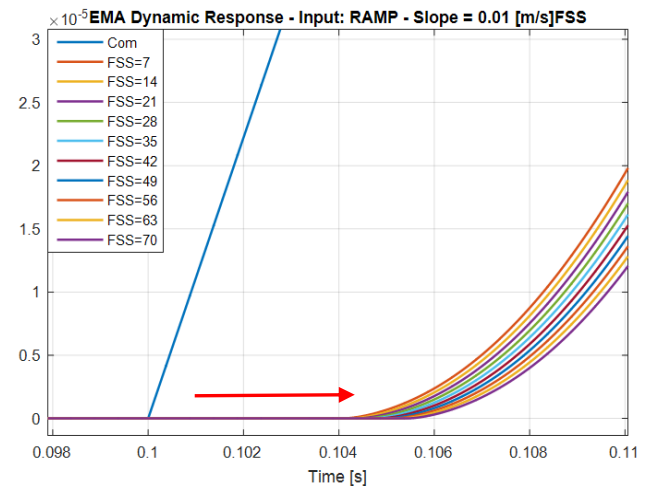

Fig. 7: EHA ramp position response in case of increasing SV spool friction

For completeness, it should be noted that, in addition to these faults, the considered EHA system may also suffer electrical or electronic problems. Electrical and sensor failures are not less important than the others but, generally, their evolutions are usually very fast (if not instantaneous); then, the corresponding failure precursors are often difficult to identify and evaluate reasonably in advance on the onset of the corresponding fault.

6 Failure Precursors

The proposed approach performs the fault detection and identification (FDI) analysis by means of an algorithm (based upon comparison between real system and its monitoring model) able to detect the progressive failures and predict their evolution[1]. The health conditions of the real EHA are identified by comparing its dynamic response with the corresponding one provided by a simpler monitoring model properly designed.

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1 This fact underlines a limit of prognostics: indeed, it could predict only failures which present a gradual growth and it is not able to detect sudden faults (or progressive faults having too rapid growth).

Operatively speaking, the proposed algorithm compares the two dynamic responses (generated by detailed model and by monitor, under the same command inputs and boundary conditions) in order to identify the value of appropriate coefficients of the monitoring model that minimize the quadratic error and, subsequently, to correlate them with the actual amount of the corresponding damages. It must be noted that, in order to limit costs, logistic problems and the reliability implications related to introduction of new components into the sensors network, this approach identifies degradations without requiring any additional transducer.

In conclusion, the proposed prognostic algorithm is based upon the detections of the precursor of degradations identified during the simulations: then now we are going to briefly explain what kind of result we have found during our analysis.

In case of increased contamination of the first stage filter, we have observed a high correlation between this fault and the following parameters:
- Amplitude of the first overshoot.
- Time required for complete adjustment.

In Fig. 6 it is possible to evaluate how the EHA dynamic response changes even with a small increasing of the filter contamination (simulated by a chocking factor called Kintas), generating a measurable reduction of the stability margin of the whole system. Indeed, in case of greater filter contamination (shown by red arrows in Fig. 6) the EHA puts in evidence a damping reduction (with broader overshoots and longer settling times).

As regards the increasing of the friction force acting between spool and sleeve, the authors found some difficulties in discern the effects attributable to static friction and dynamic one. Indeed, especially in the considered application, these two phenomena tend to be hardly discernible each other.
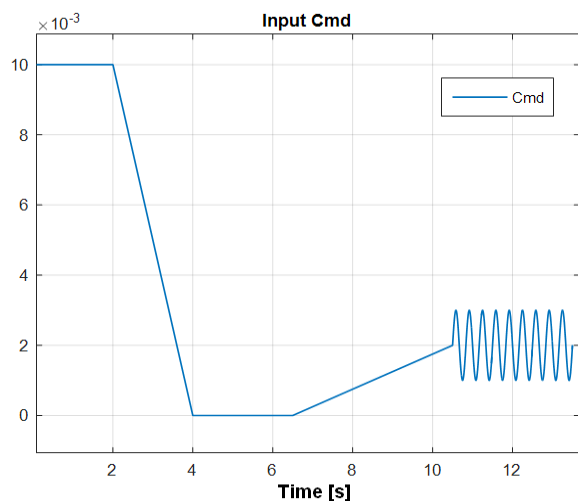

Fig. 8: Command input used to perform the FDI analysis

About the dynamic friction acting on SV spool, three parameters have been considered (Fig. 7):
- Breakaway resolution.
- Average position error during slope actuation.
- Frequency and amplitude of eventual stick-slip.

In order to identify increasing of dry friction, the most effective was the slope command input that could easily identify the previous three parameters. To ensure a better prognostic level of the incipient failure, several evaluation parameters about time response and steady-state have been introduced.

7 Fault Detection and Identification

The effects of the progressive faults on the characteristic parameters of the prognostic model have been firstly assessed separately, by considering the degradation of the single parameters, and then simultaneous degradations have been simulated to evaluate their effects. With the purpose to achieve a timely identification and evaluation of these failures, the authors have analyzed how the previous parameters evolve during the degradations of system: many scenarios were evaluated and the know-how acquired has made it possible the identification of a sequence of command inputs (shown in Fig. 8) useful to perform with satisfactory accuracy the FDI of these progressive faults.

This FDI procedure could be performed during the preflight checks (or the daily maintenance): the dynamic response produced by the real actuator as a consequence of the proposed command input will be acquired and, then, analyzed with a post-processing software in which, by means of the comparison with the monitor, the EHA health status is esteemed.

In the first part of this paragraph we are going to consider degradation of just one parameter. In order to perform a faster and more precise identification of the level of damage of the valve, the authors have considered responses within some predetermined band (as shown in Fig. 9, 10 and 11). This simple approach allows establishing if the actual performances of the servovalve are still acceptable and, moreover, in this way it is possible to have a first identification of the failure level.

The bands identification algorithm analyzes specific parts of the command input (shown in Fig.8) in order to use the most suitable command to identify the contamination of the first stage filter or the increasing of dry friction action on SV spool. In particular, as reported in paragraph 5.1 and 5.2, step position command input performs best in identification of first stage contamination; on the contrary, small amplitude slope ramp is best to identify dry friction.
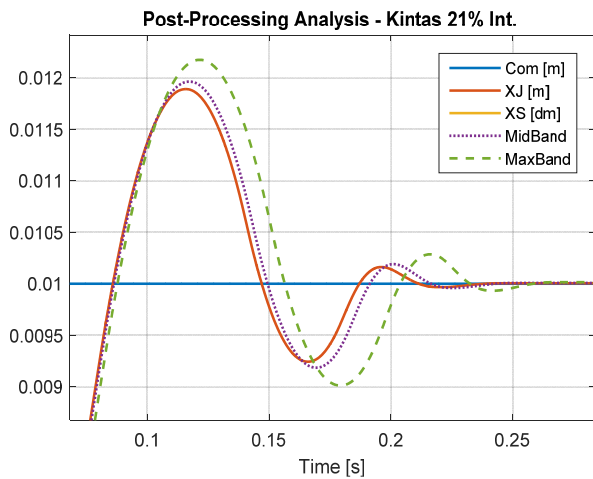
Fig. 9: Particular of EHA response vs. command input: initial step section and related post-processing bands
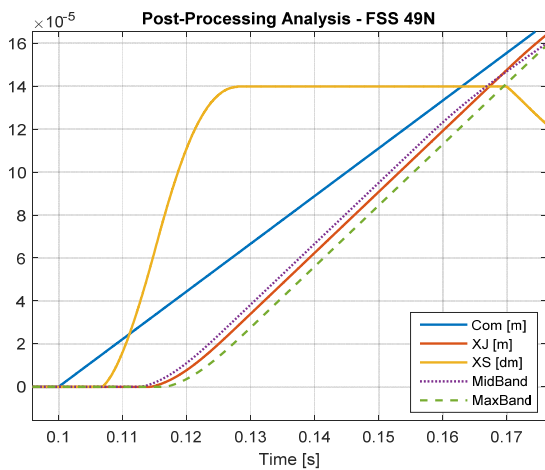

Fig. 10: Particular of EHA response vs. command input: small slope section and related post-processing bands
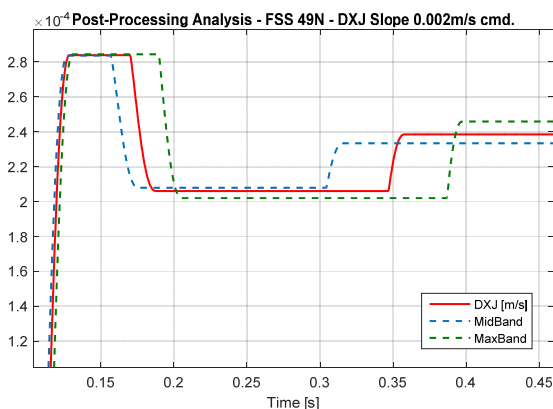

Fig. 11: Particular of EHA actuation speed calculate for small slope section and related post-processing bands

To ensure the identification of the prevailing failure, the algorithm compares the actual response of the EHA with respect to a couple of degraded bands (Fig. 9-10); therefore, the algorithm is able to discern three failure levels:

- Acceptable level (possible failures are barely distinguishable from measurement uncertainties and EM noise)
- Maintenance required (Midband)
- Non-nominal performance (MaxBand)

Finally, comparing the two classification levels assigned, the algorithm indicates which is the ruling (and, then, most probable) faults combination.

In case of events of over bands, the algorithm is also able to evaluate these two main factors:

- Number of events outside the band, in order to avoid false positive detections.
- Time of entry and exit point of over band, in order to evaluate the health of the whole EHA.

To obtain good performance in classification of the failure level is important well define the bands. To assessment the best performance, the authors have performed some statistical evaluations. It has been found that below the values reported as "mid band" in the Table 1, the performance of the EHA are still acceptable, so the identification is much harder and not always accurate; differently, within the two bands it is possible to operate a prognostic analysis in order to avoid a further increasing of the failure. In particular, the "max band" represent a limit value beyond which the performances of the actuation system are not enough good.

Table 1: Definition of the bands failure level

Kintas [#]		FSS [N]	
MidBand	0.25	MidBand	35
MaxBand	0.35	MaxBand	70

It must be noted that, despite its simplicity, the proposed bands method performs properly the identification of a single failure and, in our tests, it has been always possible recognize a possible degradation; furthermore, a first coarse estimation of the failure presence could be directly performed by comparing the actual response with the band failure level. Anyways the algorithm is not able to estimate the actual degradation level, in facts, it operates a discrete identification and classification, this type of approach is quite common in prognostic algorithm even with more advanced ones (e.g. FDI algorithms based upon neural networks [11] or pattern recognition methods implemented by means of multinomial logistic regressions [12]).

In case of multiple faults, an improvement of prognosis is required; to this purpose the authors propose to use the monitoring model as a tracker of the response of the system.

In this way, minimizing the RMS error (1) calculated between the responses provided by EHA and monitoring model, it is possible estimate the value of the parameters considered.

$$RMS_{MONITOR} - RMS_{EHA} \qquad (1)$$

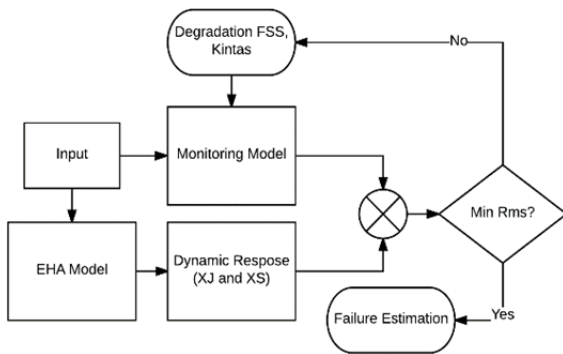The logic of proposed multi-failure FDI algorithm is depicted by the flowchart of Fig. 12.

Fig. 12: Schematic of the proposed

The dynamic response calculated by the monitoring for the different combinations of faults is compared with that of the real system, so as to identify the possible couples of failure which minimize the RMS error. In order to avoid missing identification and allow a lighter computation cost, the possible combinations of faults are discretized obtaining the failure grid shown in Fig. 13.
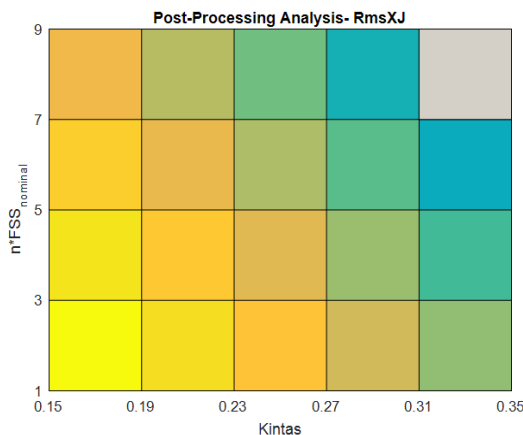

Fig. 13: Schematic of the DFI failure grid

By means of (1) it is possible to evaluate every sector of this failure grid in order to identify the possible combination of damages that minimize the RMS error; once identified this minimum area, it is then possible to implement a more accurate analysis using more refined methods (but more expensive in terms of time and power) such as deterministic optimization algorithms, Simulated Annealing or Genetic Algorithms.

8 Fault Detection and Identification

This work analyses the effects of two progressive failures on the dynamic behavior of EHA in order to identify system-representative parameters which are suitable for prognostic activities and to propose a new model-based fault detection and identification (FDI) method. The study has been performed on a numeric test bench (simulating the real EHA) that implements several kinds of failure; by means of proper simplifications, the aforesaid numerical model was then reduced obtaining the monitoring model. Overall the proposed algorithm demonstrates good statistical confidence in identification of the failure; furthermore, it could be used without any other additional sensors required and all the post-processing proposed could be execute to a common PC on ground. In authors' opinion, these aspects are more important, especially in order to improve the predictive maintenance of the analyzed component (i.e. prognostic analysis performed daily during the usual on-field operations).

References:
[1] G. Vachtsevanos, F. Lewis, M. Roemer, A. Hess, B. Wu, *Intelligent Fault Diagnosis and Prognosis for Engineering Systems*, Wiley, 2006, ISBN: 978-0-471-72999-0.
[2] C. S. Byington, W. Watson, D. Edwards, P. Stoelting, A Model-Based Approach to Prognostics and Health Management for Flight Control Actuators, *IEEE Aerospace Conference Proceedings*, 2014, USA.
[3] L. Borello, M. D. L. Dalla Vedova, G. Jacazio, M. Sorli, A Prognostic Model for Electro hydraulic Servovalves, *Proceedings of the Annual Conference of the Prognostics and Health Management Society*, 2009, San Diego.
[4] P. Maggiore, M. D. L. Dalla Vedova, L. Pace, A Desando, Proposal of fault analysis parametric method applied to an electro mechanical servomechanisms affected by failures, *International Journal of Prognostics and Health Management*, Vol.6, No.1, 2015, ISSN: 2153-2648.
[5] T. J. Viersma, *Analysis Synthesis and Design of Hydraulic Servo systems and Pipelines*, Elsevier, Delft, 1980.
[6] P. Dransfield, *Hydraulic Control Systems. Design and Analysis of their Dynamics*, Springer Verlag, Berlin, 1981.
[7] G. Jacazio, L. Borello, A non-linear model of an electrohydraulic servo system with axial piston hydraulic motor, *7th International Fluid Power Symposium*, 1986, Bath, England.

[8] G. Jacazio, L. Borello, Mathematical models of electrohydraulic servovalves for fly-by-wire flight control systems, *6th Int. Congress on Mathematical Modelling*, 1987, St. Louis.

[9] P. Maggiore, M. D. L. Dalla Vedova, L. Pace, Proposal of prognostic parametric method applied to an electrohydraulic servomechanism affected by multiple failures, *WSEAS Trans. on Environment and Development*, Vol.10, 2014, pp. 478-490, ISSN: 1790-5079.

[10] D. Karnopp, Computer simulation of stick-slip friction in mechanical dynamic systems, Journal of Dynamic Systems, *Measurement, and Control*, Vol.107, 1985, pp. 100-103.

[11] M. D. L. Dalla Vedova, P. Maggiore, L. Pace, S. Romeo, Proposal of a model based fault identification neural technique for more-electric aircraft flight control EM actuators, *WSEAS Transactions On Systems*, Vol.15, Art.3, 2016, pp. 19-27, ISSN: 1109-2777.

[12] M. D. L. Dalla Vedova, D. De Fano, P. Maggiore, Neural Network Design for Incipient Failure Detection on Aircraft EM Actuator, *International Journal of Mechanics and Control (JoMaC)*, Vol.17, No.1, 2016, pp. 77-83, ISSN: 1590-8844.