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Prognostic and Health Management System for Fly-by-wire Electro-Hydraulic Servo Actuators for detection and tracking of actuator faults

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Abstract

Maintenance of flight control actuation systems is currently performed on a scheduled basis, however air fleet operators and component manufacturers are willing to move from scheduled maintenance to Condition Based Maintenance (CBM) in order to reduce maintenance costs and improve aircraft dispatchability. Prognostics and Health Management (PHM) systems are a critical part of CBM and are perceived as a breakthrough technology to effectively respond to an urgent and critical need to improve the readiness, availability, reliability, safety and maintainability of aerospace vehicles. This paper presents the results of an ongoing research activity focused on the development of a PHM system for fly-by-wire Electro-Hydraulic Servo Actuators (EHSA) without adding new sensors. The PHM system is being developed with the objective of detecting the most common faults, according to a failure mode effects and criticality analysis (FMECA). The paper describes in particular the tools used for detection and tracking of internal leakage faults of the hydraulic actuator, which is one of the most common faults of hydraulic servo-actuators in service, and for predicting its remaining useful life (RUL). The research work has been supported by the development of a nonlinear model for a reference EHSA, that has been implemented using physical equations and system parameters, taking into account environmental condition and disturbances. The model was validated through tests runs on a flight control actuator of a civil aircraft. Simulations are performed in nominal conditions and with progressive injection of degradation to verify the PHM algorithm. The performances of the PHM algorithms are evaluated by means of proper metrics.

Keywords: Fly-by-wire; Electro-Hydraulic Servo Actuators;Prognositcs and Health Management ; Data-Driven ;

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1. Introduction

The development and implementation of PHM solutions in the aircraft industry has been primarily focused on structures and power drives. On the actuation side many research work has been reported on PHM systems for Electro-Mechanical Actuators (EMAs), however only little address EHSAs. However, EHSAs represents the state of the arts for primary flight control systems and most commercial airliners in service still rely on hydraulic actuators and they will likely operate for the following decades. Therefore airliners and component manufacturer are strongly interested on PHM systems for EHSA.

Accordingly to FMECA studies a critical fault of EHSA is internal leakage of the hydraulic actuator. It consists in the presence of an uncontrolled flow of hydraulic fluid between the two chamber of the hydraulic actuator, mainly caused by the degradation of the seals. This fault is subtle to detect because the closed loop control can compensate it by increasing the flow to the actuator chambers. However the fault may develop into a critical failure that will cause a critical degradation of the system performance. The PHM system herein presented is able to detect the fault before a failure appears and is able to forecast the fault evolution and the remaining useful life (RUL). The PHM system developed for this scope and presented in this paper uses only sensors available on the legacy EHSA, it operates injecting a properly designed stimuli in pre/post-flight and extracting a set of relevant Features. The fault detection technique herein presented is based on data-driven

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techniques, able to learn adaptively without requiring any previous knowledge of the fault-to-failure model, exploiting probabilistic techniques to detect the fault. The RUL forecast is performed with the aid of particle filter, where the only previous knowledge consists in the failure threshold, i.e the ultimate value at which prediction is stopped and the End of Life (EOL) is assessed.

2. EHSA configuration

The EHSA, used in this research is a typical electrohydraulic actuator for primary flight control surfaces (Fig. 1). The actuation system is described in [1], some details are herein presented for the sake of comprehension. The EHSA consists of a two stages flapper-nozzle Electrohydraulic Servo-Valves (EHSV) and a linear hydraulic actuator equipped with a Linear Variable Differential Transducer (LVDT). The torque motor of the EHSV is controlled by the control unit that uses the reference signal issued by the flight control computer and the actuator position signal as a feedback to close the loop. The end-rod of the actuator is connected to the flight control surface by the mean of a spherical joint whereas another spherical joint connects the actuator case to its fixed mounting frame.

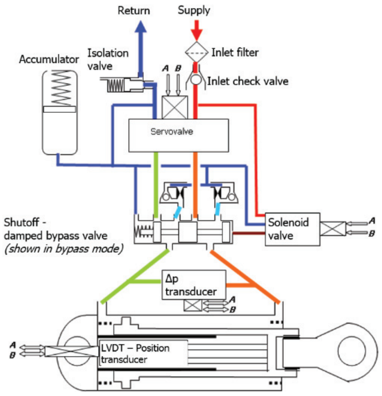

Fig. 1. EHSA reference system [1]

2.1. EHSA signals

The legacy EHSA allows for the acquisition of :

- Position command: issued by the flight control computer.
- Feedback position: acquired by the actuator LVDT and used for loop closure.
- EHSV current: generated by the controller to supply the coils of the torque motor.
- Differential pressure transducer: used for monitoring and to perform pressure equalization control logic to compensate the effect of different servo valves offsets when the system operates in active/active mode.
- Spool position: an additional LVDT is connected to the EHSV spool to detect small amplitude and high frequency oscillations of the spool, caused, by instance, by a seizure of the feedback spring.

Moreover the oil temperature and supply pressure are available at system level in the hydraulic circuit of the aircraft.

3. Mathematical Model

The system behavior in nominal and degraded conditions is analyzed with the aid of a high-fidelity validated mathematical model implemented in Matlab-Simulink, presented in [1]. The non-linear physical relations involve physical parameters of each component, degradations are then simulated by modifying those parameters.

The servo-valve torque motor is modelled using equations presented in [2], where the torque is expressed as a function of the armature position, misalignment and unequal air-gap thickness. The electromagnetic torque is combined with the dynamic equation of the flapper, connected to the spool by means of the feedback wire. The position of the flapper results in a variation of the differential pressure between the two nozzles, that drives the valve spool. The effect of flow forces and friction acting on the spool of the valve is considered. The control flow is function of the spool position, radial clearance, Reynold number and pressure, taking into account the presence of laminar and turbulent flow. Each parameter of the equations, such as feedback wire stiffness, Coulomb and viscous friction, flow gains and pressure gains can be modified to induce degradation. Oil properties, such as density, viscosity and Bulk modulus, are computed using a set of equations, functions of oil temperature.

Continuity equations describe flows and pressures inside the chambers of the actuator, taking into account the presence of undissolved air in the calculation of the oil Bulk modulus. The actuator Coulomb friction is a function of the dynamic condition of the rod and of the geometrical and physical data of the seal as well as of the pressures in the actuator chambers [3].

A 3-DOF model, where compliance of the linkages on the mounting side and on the rod-end side of the actuator are considered, describes the dynamic motion of the hydraulic linear actuator.

LVDTs are modelled including low-pass demodulation filters and analog-to-digital converters, taking into account electrical noise. The mathematical model allows simulating the aerodynamic load acting on the rotor, comprised of the sum of four components: aircraft velocity, atmospheric wind, wind gust and turbulence, implemented using the Dryden model.

Internal leakage is modeled as a function of the differential pressure between the actuator chambers, taking into account a term proportional to the differential pressure [4], and a turbulent orifice flow, proportional to the square of the differential pressure:

$$Qli = k_{li,1} \cdot \Delta p + k_{li,2} \cdot \sqrt{|\Delta p|} \cdot sign(\Delta p) \qquad (1)$$