A Prognostic Model for Electrohydraulic Servovalves

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ABSTRACT

Servovalves are critical components of the hydraulic servos and their correct operation is mandatory to ensure the proper functioning of the controlled servosystem. A continuous monitor is typically performed that can detect a servovalve loss of operation, but falls short of recognizing other malfunctionings. A research was performed aimed at developing a prognostic algorithm able to identity the precursors of a servovalve failure and its degradation pattern. A model based technique was used that fuses several information obtained by comparing actual with expected response of the servovalve to recognize a degradation. The research was focused to flight control systems, but it can be used in other application areas. To assess the robustness of the algorithm a simulation test environment was developed. Simulations were run in which a servovalve controlled actuator was subjected to sequences of commands and loads representative of those encountered during actual operation, and variations of the servovalve characteristics within their normal range were applied. At the same time, degradations of the servovalve were superimposed and the merit of the prognostics algorithm was verified. The results showed an adequate robustness and confidence was gained in the ability to detect servovalve degradations with low risk of false alarms or missed failures.*

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1 FLOW CONTROL VALVES FOR FLIGHT CONTROL SYSTEMS

Flight control systems of many civil and military aircrafts use hydraulic power to drive the aerodynamic control surfaces of the aircraft according to the commands provided by the pilot or the autopilot through the flight control computer. This is performed by modulating the flow of the hydraulic fluid to an actuator converting hydraulic into mechanical power (Fig. 1).

The modulating device is a hydraulic power control valve providing an output flow which is a function of the input signal. Most of today's flight control systems make use of electrical signals to measure the actuator position and to command the flow control valve and are known as fly-by-wire systems.

The valves accepting an electrical input signal to control the output flow are of two different types: direct drive valves (DDVs) and electrohydraulic servovalves (EHSVs). DDVs have a purported greater robustness and reliability, but require larger electrical currents for their operation, while EHSVs have a two-stage arrangement with an internal hydraulic amplification which allows large flows to be controlled by very small electrical currents, but have internal parts more sensitive to wear and contamination.

Both DDVs and EHSVs are presently used in hydraulic servoactuators of fly-by-wire flight control systems and the preference for either of the two valve types depends on the entire flight control system architecture and design philosophy.

It is a known fact that the sensitivity of electrohydraulic servovalves to contamination and wear is regarded as one of their main negative factors when compared with the direct drive valves, a research initiative was therefore undertaken to

develop a prognostics model able to recognize a progressive deterioration of the servovalve characteristics, thereby alerting of a trend toward an unacceptable servovalve behaviour or a failure. A valid and reliable prognostics model for the EHSVs could partly offset the weak points of these components, which on the other hand offer the merits of lower weight, much lower electrical power consumption, greater chip shear capability and lower cost when compared with DDVs.
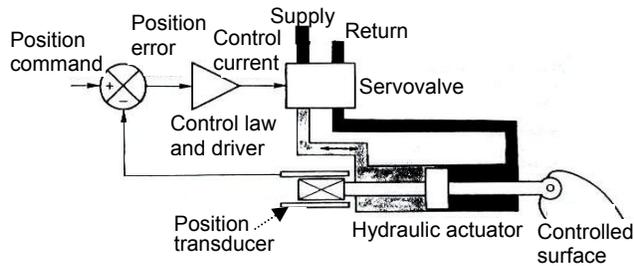

Figure 1: Concept schematic of an electrohydraulic servoactuator

2 SERVOVALVE CONFIGURATIONS

Electrohydraulic servovalves are two-stage devices in which the first stage accepts the electrical input current and converts this input into a pressure signal driving a second stage spool which meters the flow to the hydraulic actuator. EHSVs have two possible configurations depending on their first stage configuration, as it is shown in Fig. 2.
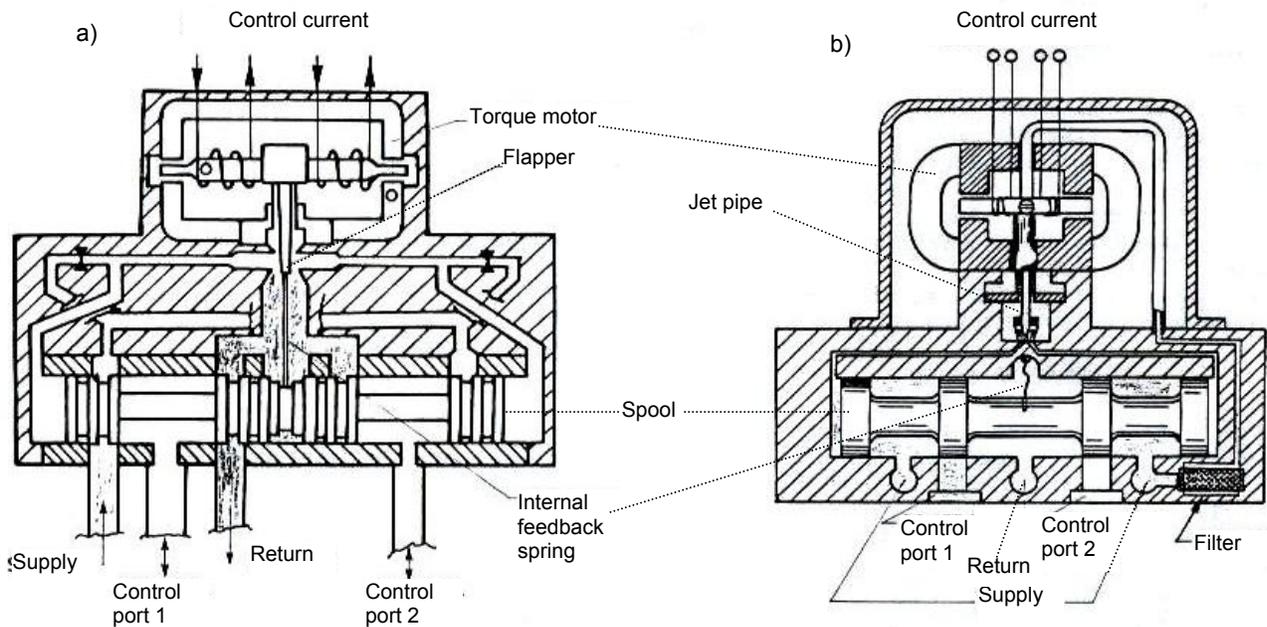
For both configurations the second stage consists of a sliding spool, while the first stage can be either a flapper-nozzle (Fig. 2a) or a jet pipe (Fig. 2b) driven by a torque motor.

In the flapper-nozzle arrangement the input current provided to the torque motor coils creates a torque acting upon the flapper which is consequently displaced and unbalances the pressures at the two sides of the second stage spool forcing it to move and displace the end of a spring connected to the flapper. A torque is therefore created on the flapper in the opposite direction and the spool moves up to a position in which the spring torque balances the motor torque and the flapper is again centered with a resulting zero pressure differential between the two sides of the spool.

The operation of a jet pipe servovalve is quite similar: a torque proportional to the input current acts on the jet pipe, which rotates and gives rise to a differential pressure in the two receiving ducts of the spool.

3 EHSV FAILURES AND DEGRADATIONS

Servovalves are complex devices and there are several ways in which they can fail, or show defects and performance degradations. 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 fracture of the internal feedback spring, the clogging of a nozzle or of the jet-pipe, or a large metallic chip stuck in the radial clearance between spool and sleeve preventing the spool movement.

Figure 2: Electrohydraulic servovalves configurations: flapper-nozzle (a) and jet pipe (b)

All these failures are normally sudden unpredictable events leading to a servovalve lack of operation, or uncommanded movement that are recognized by a dedicated monitoring logic which eventually issues an appropriate command to a shutoff valve upstream of the servovalve, thereby removing the hydraulic power supply from the servovalve and inhibiting any further operation.

In general, the servovalves are provided with an LVDT type position transducer that senses the spool position; by comparing the servovalve current with the spool position a lack of response or an uncommanded movement can be detected. There are however several other scenarios in which a progressive degradation of a servovalve occurs, which does not initially create an unacceptable behaviour, but, if undetected, may lead to a condition in which the servovalve, and hence the whole servoactuator operation is impaired.

Some along the possible progressive degradations of a servovalve are the following:

1. Increased contamination of the first stage filter (shown only in Fig. 2b, but always present also in the flapper-nozzle servovalves). As dirt and debris accumulate in the 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 results in a slower response of the servovalve, with increased phase lag and reduction of the servoactuator stability margin.

2. Reduction of the torque sensitivity of the first stage torque motor. This can be the result of a shorting of some adjacent coils of the torque motor due to the presence of metallic debris, or to a degradation of the magnetic properties of the materials. As for the above case, a progressively slower response of the servovalve is obtained.

3. Increase in the backlash at the mechanical interface between the internal feedback spring and the second stage spool. This is the result of a 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 servoloop.

4. Increase in 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.

5. Increase in 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.

The objective of the prognostic model is to put together different pieces of information to recognize that a servovalve degradation is under way and predict the remaining useful life before its behaviour becomes unacceptable and such to lead to an undesirable shutdown while in flight. It must be emphasized that the main purpose of the prognostics model is to detect a progressive degradation and estimate the remaining time to failure, while it does not specifically indicate which is the cause of the degradation, which can be positively assessed only after disassembling the servovalve.

4   PHYSICAL MODEL OF AN EHSV

The authors have developed mathematical models of hydraulic servosystems in which EHSVs or DDVs were controlling the flow delivered to either a linear hydraulic actuator or to a hydraulic motor. Models of different complexity and accuracy were built, depending on the required accuracy level. Examples of mathematical models developed by the authors for hydraulic servosystems are those for the AMX stabilizer actuation system (two torque summed hydraulic motors, EHSV controlled), the C27J elevator and rudder servoactuators (hydro-mechanical servoloops), the Eurofighter leading edge flap actuation system (two torque summed hydraulic motors, DDV controlled), the M346 leading edge flap actuation system (two torque summed hydraulic motors, EHSV controlled), the force control systems of the M346 iron bird (linear hydraulic actuators with EHSV control).

All these models were "physical-based" models in which all the system components were modelled with equations representative of their physical characteristics. The comparison between the simulations and the test results allowed to progressively tune the mathematical model which eventually reached a good fidelity in representing the actual system behaviour.

The proven fidelity of the mathematical models of hydraulic servos that were developed for the analysis of the above mentioned systems provided us the necessary confidence to use a similar mathematical model for predicting the behaviour of a hydraulic servo over the whole range of normal and degraded conditions without performing expensive and time consuming tests. The model is very detailed and describes the physical behaviour of each part of the servovalve.

A concept block diagram of the servovalve model is shown in Fig. 3. This block diagram specifically refers to a flapper-nozzle servovalve, but it can as well be applied to a jet pipe servovalve.

The servovalve mathematical model accepts the input current and works out the torque developed by the torque motor according to the equations describing in details its electromagnetics. The model computes the fluxes through the air gaps and how they are modified by the electrical current through the coils, and eventually determines the

value of the torque acting on the servovalve first stage. The accuracy of this part of the servovalve model was verified by comparing its outputs with the experimental results obtained by Urata [1] who actually measured the flux densities in the air gaps and the flapper displacement as a function of the current.

The 1st stage dynamics is described by a modified second order transfer function that includes modelling of the 1st stage end-of-travel and of the backlash at the mechanical interface between the spool and the flapper spring end. A backlash increase due to the wear of these parts reduces the servoactuator stability margin and had to be duly taken into account. The pressure-flow characteristics of the 1st stage are described by the equations relating pressure and flow through the 1st stage internal passageways. The pressure differential acting on the two end sides of the 2nd stage spool is eventually determined and the resulting force is fed to a model representative of the 2nd stage spool dynamics inclusive of spool end-of-travel. This model takes into account the friction and the flow forces acting on the spool whose velocity and position are hence computed.

Once the spool position is known, the pressure/flow characteristics of the servovalve can be determined. The servovalve model accurately describes the flow through each of four servovalve internal flow passageways: from supply to control port 1, from control port 1 to return, from supply to control port 2 and from control port 2 to return.

Starting from the pressures at the supply, return and control ports, the flow rates through each of the four passageways are determined taking into account the actual passage area, which depends on spool displacement, valve laps and radial clearance between spool and sleeve. Also, the variation of the flow discharge coefficient with the Reynolds number, with the corner radius and with the aspect ratio of the control port is taken into account. Moreover, when the relative position between spool and sleeve is such that a servovalve internal passageway actually consists of a small annular passage between spool and sleeve, the appropriate flow equations are written.

This EHSV model was successfully used in past activities as a part of mathematical models of several servoactuators for flight control systems. An example of the accuracy of the servovalve model is shown in Fig. 4, relevant to the servovalve of a servoactuator of the M346 advanced trainer. In the diagrams of this figure, the servovalve spool position is plotted as a percentage of its maximum travel.

The main diagram of Fig. 4 shows the actual and computed time histories of the spool position starting from the same time history of the input current. The actual spool position is that measured by an LVDT type position transducer placed on the spool. The differences between measured and computed spool positions are minimal. To further show the accuracy of the servovalve simulation model, Fig. 4 includes an inset referring to a small portion of the time history in which sudden variations of the servovalve current were given.

The favourable comparison of the servovalve simulation model with the test data provided the necessary confidence for using this model to test the prognostics algorithm which was then developed and which is described in the following of this paper.

The merit of the servovalve model is to be built on a physical representation in which the values of all construction parameters are introduced, which enables to change their values and evaluate the corresponding changes of servovalve performance, as it will be presented in the following sections.

As it will be outlined in section 8, the servovalve parameters that are more likely to change during the servovalve operation were varied with time simulating a growing fault and the servovalve performance was hence determined.
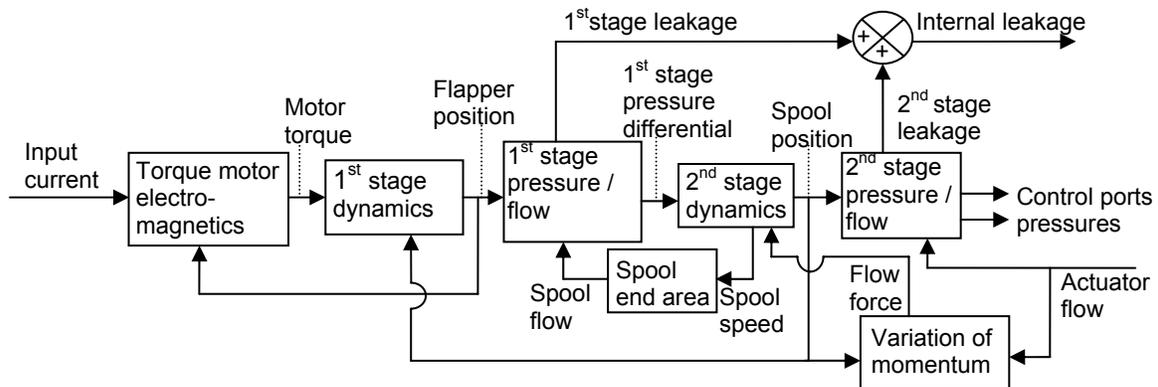

Figure 3: Concept block diagram of the mathematical model for an electrohydraulic servovalve
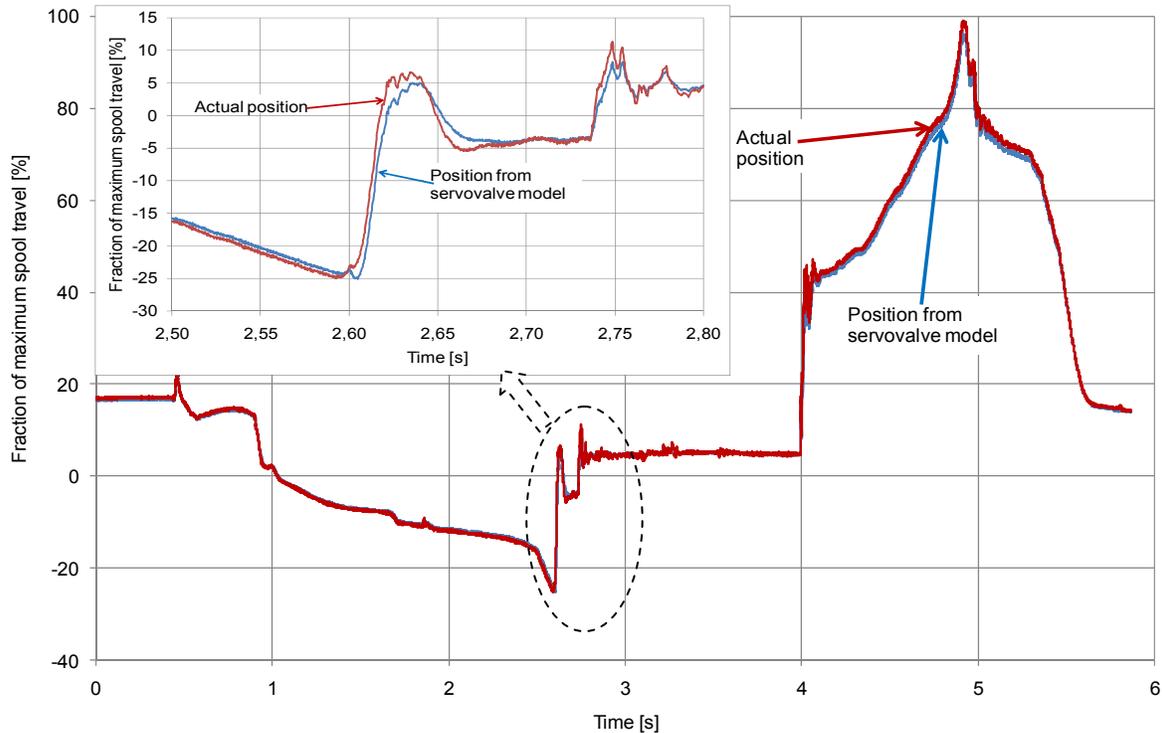
Figure 4: Example of time history of a servovalve spool position: comparison between measured and computed positions in response to identical time history of the input current

5 SERVOACTUATOR MATHEMATICAL MODEL OF THE PROGNOSTIC ALGORITHM

The purpose of the prognostics algorithm is to establish correlations among different measured system parameters to identify if an EHSV degradation is under way and to determine its remaining useful life. To achieve this target, a mathematical model needs to be developed for servovalve and actuator able to detect degradations, but at the same time simple enough to avoid an excessive computational burden and allow real time simulation.

A linear model of an EHSV controlled servoactuator with saturation limits on the EHSV 1st and 2nd stage displacements and on the maximum pressure differential turned out to provide the best balance between the above two conflicting needs. This model is shown in the block diagram of Fig. 5. The symbols definition is the following:

Variables:

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

Parameters:

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AJ	= Actuator area
ASV	= Spool end area
CJ	= Actuator viscous resistance coefficient
GP	= Servovalve pressure gain
GQ	= Servovalve flow gain
GQFm	= 1st stage flow gain
GAP	= Control law proportional gain
GM	= Torque motor gain
KFt	= 1st stage mechanical gain (spring stiffness)
KSFm	= Servovalve feedback spring stiffness
PSR	= Maximum pressure differential
MJ	= Actuator mass
XFM	= Flapper maximum displacement (half stroke)
XSM	= Spool maximum displacement (half stroke)
XJM	= Actuator maximum displacement (half stroke)
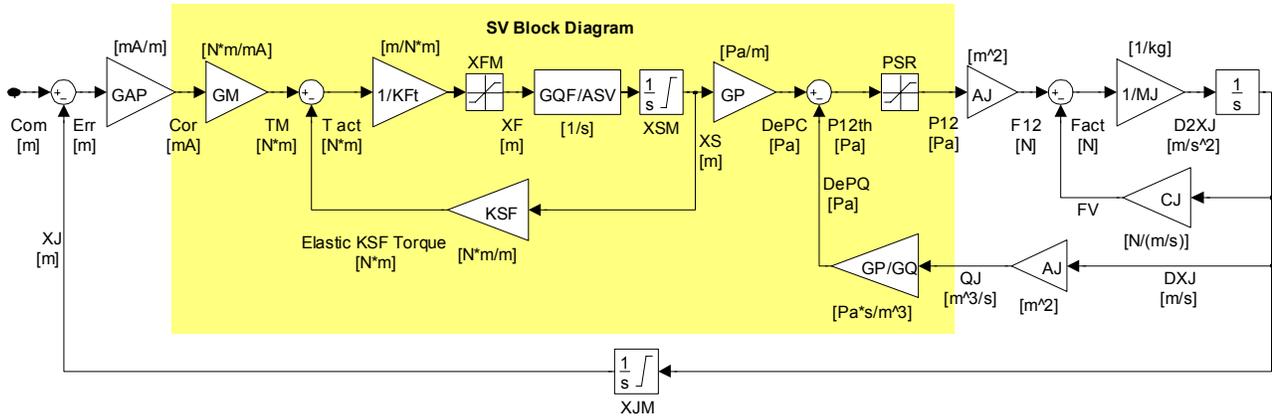
Figure 5: Block diagram of the servoactuator mathematical model used for the prognostic algorithm

6   IDENTIFICATION OF SERVOVALVE DEGRADATIONS

As it is known, sudden failures of a servovalve, such as a hardover or a fracture are normally detected by a continuous monitor that compares the current command with the actual one (current wrap-around monitor) and compares the current with the servovalve spool position. The spool position is typically measured by an LVDT type position transducer and it must be proportional to the input current under steady-state, or quasi steady-state conditions. The purpose of the prognostics model is to use the available information, without using additional sensors, to identify servovalve degradations leading to a performance outside the acceptable range and eventually to abnormal operating conditions. The prognostics algorithm consists of performing three different checks, with each check defining a characteristic parameter. One check is performed continuously during flight while the other two performed as preflight checks when the servoactuator is unloaded. These checks are described hereunder.

Mean error. This check is performed continuously while the system is operating and computes the average of the absolute value of the difference between the true value x_T of the servovalve spool position, which is measured by its LVDT, and the value x_M calculated by the model in real time as a function of the measured input current:

$$|e| = \frac{1}{T}\int_0^T |x_T - x_M|\, \mathrm{d}t \qquad (1)$$

Under normal operating conditions the absolute value of $|e|$ varies, but remains within a limited range, while anomalous conditions can yield a progressive increase of $|e|$, thereby signalling a servovalve degradation.

Examples of conditions leading to an increase of $|e|$ are: increase of the servovalve offset, increase of the friction force between spool and sleeve, wear of the mechanical connection between internal feedback spring and spool, and a servovalve instability. If any of the above conditions prevails, it is reflected into an increase of $|e|$.

For instance, a temporary variation of the servovalve offset, as it can occur in a servovalve under normal conditions, determines an increase of $|e|$ which decreases again as the condition ceases that determined the variation of the servovalve offset. However, if the offset increase is the result of a degradation or wear of a servovalve internal part, and this process progresses with time, then a well definite trend can be derived from the time history of $|e|$ and an alert signal can be generated.

Fidelity coefficient. This check is performed in preflight when the actuator is unloaded or subjected to little load. The purpose of this check is to evaluate the servovalve dynamic response and to signal reductions in responding to the changes of the input current.

While the actuator is in its middle position the entire servoloop is operated in an open-loop mode for a short time, such to limit the actuator travel and prevent it from hitting its hard stops. While in this open-loop mode, an input current is issued to the servovalve as a small positive step, then the current is brought back to zero with a second step (Fig. 6).
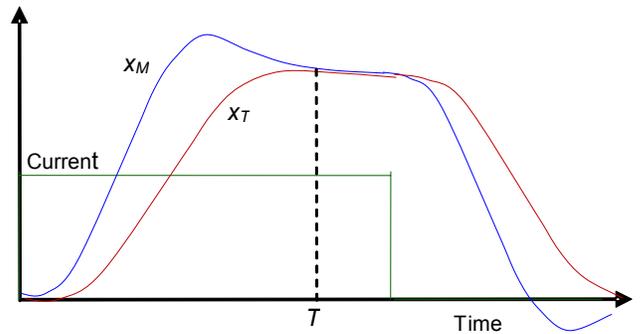

Figure 6: Servovalve spool response to a step input current

As for the mean error, the fidelity coefficient is determined using the true value x_T of the servovalve spool position measured by its LVDT, and the value x_M resulting from real time calculation as a function of the measured input current. The correlation coefficient is defined as:

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

The integration is performed for a time T equal to the expected time response of the servovalve to a step input of amplitude equal to the one which is given. If the actual spool position x_T is at any time equal to the one x_M computed by the mode, then the fidelity coefficient is equal to 1. The larger the difference between x_T and x_M, the more r differs from 1, being either greater or lower depending on how the actual servovalve step response differs from the ideal one.

If a progressive increase or decrease of r is detected, and a definite trend is positively recognized, an alert that the servovalve response is degrading is issued. Possible causes of an increase or decrease of r are: progressive clogging of the first stage filter, deterioration of the torque motor with a lower torque developed for the same input current, increase of the friction between spool and sleeve. This check can be easily performed during a preflight routine while it would be difficult to get significant data for a fidelity coefficient looking at the time histories of x_T and x_M during the aircraft flight mission. However, by storing in a memory the values of r obtained at each preflight check a degradation trend can be positively recognized.

Correlation function. The two checks defined above can detect most of 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 behaviour 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 about proportional; this is

not entirely true around the hydraulic null, but a displacement of the spool from the hydraulic null will anyhow port some flow to the actuator. 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 servoactuator. The actuator speed is not known, but the measurement of the actuator position is available, which is lagging of 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 servoactuator 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 is defined as:

$$E(\tau) = \frac{1}{T} \int_0^T x_T(t + \tau) y(t) \, dt \qquad (3)$$

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, hence obtaining a stepwise function of $E(\tau)$. 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 servovalve degradation is generated.

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.

7 SIMULATION TEST ENVIRONMENT

In order to assess the merit of the prognostics algorithm, an appropriate simulation test

environment was defined. Simulations were run in which an EHSV controlled hydraulic servoactuator was subjected to time histories of commands and loads representative of those that could be encountered during flight, and variations of the servovalve offset within its normal range were simultaneously applied. At the same time, progressive degradations of the servovalve were superimposed and the ability of the prognostics algorithm to identify them was verified. The simulation campaign was performed with reference to a balanced area servoactuator with the following characteristics:

- Stall load: 16000 N at a pressure of 20.7 MPa
- Total travel: 400 mm
- No-load speed: 300 mm/s
- Inertia reflected to actuator linear output: 10 kg
- Stiffness of the attachment point (surface): 8×10^7 N/m
- Stiffness of the attachment point (earth): 5×10^7 N/m
- Rated servovalve current: 20 mA

In order to cover the maximum possible variety of operating conditions, time histories of servoactuator commands were generated consisting of a sequence of steps of different amplitudes x_C and lengths δt_C, and issued with different time intervals δt_A (Fig. 7). Each of these three quantities was made randomly variable in order not to reproduce a fixed pattern of commands. In particular, it was defined:

$x_C = \alpha \, x_{CMAX}$ with x_{CMAX} = 200 mm and α is a random variable in the range from -1 to +1

$\delta t_C = \beta \, \delta t_{C \, MAX}$ with $\delta t_{C \, MAX}$ = 2 s and β is a random variable in the range from -1 to +1

$\delta t_A = \gamma \, \delta t_{A \, MAX}$ with $\delta t_{A \, MAX}$ = 20 s and γ is a random variable in the range from -1 to +1
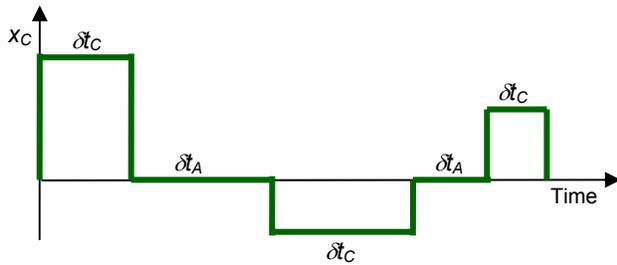

Figure 7: Definition of time history of commands

In parallel to the servoactuator commands a time serie of the actuator loads was generated. The aerodynamic loads acting on a flight control actuator were considered to be the sum of two terms as indicated in Eq. (4). The first term (kx_C) is proportional to the servoactuator command and hence to the flight control surface deflection; the second term (F_{TURB}) depends on turbulence and gusts and

was assumed to be randomly variable throughout the simulations in a range from a minimum to a maximum:

$$F = kx_C + F_{TURB} \qquad (4)$$

The maximum absolute value of F_{TURB} was taken equal to 20% of the maximum actuator load. In addition to the time histories of servoactuator commands and loads, the simulations also took into account the variations of the servovalve offset that occurs under normal operating conditions due to the variations of the parameters such as return pressure and temperature of the hydraulic fluid. The servovalve offset was accounted for by adding a disturbance current i_o defined as the sum of three terms:

$$i_o = i_{o1} + \; i_{o2} + i_{o3} \qquad (5)$$

In this equation i_{o1} is a constant offset equal to 2% of the rated current. The second term i_{o2} is a short term variation of the servovalve offset and was assumed to occur as a step, reach a maximum of $\pm 3\%$ of the rated current, last up to 2 s and be repeated with a time interval up to 10 s according to a random pattern. The third term is a long term variation of the offset, which is mainly related to fluid temperature changes. It was assumed to take place as a ramp variation, have a maximum of $\pm 5\%$ of the rated current, last up to a minute and occur in a random way.

The combination of time histories of servoactuator commands, loads and EHSV offsets outlined above provides a continuously variable simulation test environment which can be considered well representative of the conditions encountered by a flight control servoactuator in real flight. This flight simulation test environment was therefore used to compute the mean error $|e|$ of the prognostics algorithm for normal and progressive degrading conditions of the servovalve and verify the ability to positively recognize the degradations.

In order to limit the simulation time, the parameters were assumed to vary from nominal to maximum assumed degraded values in 2000 s. The degradation process will very likely occur in a longer time, but the merit of the prognostic algorithm can be positively evaluated from the accelerated simulations.

The fidelity coefficient r and the correlation function $E(\tau)$ of the prognostic algorithm are evaluated in preflight in response to deterministic commands while the actuator is unloaded. However, the preflight checks could occur for different return pressure and temperature of the hydraulic fluid for which different servovalve offsets could prevail.

The characteristic parameters r and $E(\tau)$ address servovalve degradations other than abnormal

variations of its offset, and the effects of such degradations could be partially hidden by the normal offset variations during the dedicated preflight checks. Therefore, an initial reading of the spool position and the relevant current must be performed while the actuator is stationary and unloaded before running the preflight checks. By relating spool position and current in these conditions the servovalve offset can be easily derived and a compensating current can be added to the input current during the preflight checks thereby ensuring that the initial spool position is the hydraulic null.

However, though the effect of different servovalve offsets while running the preflight checks can be cancelled out as described above, still the preflight checks performed on a perfectly operational servoactuator can lead to some different values of r and $E(\tau)$ due to variations of the fluid properties within their normal range as a result of different temperatures and amount of free air entrained by the hydraulic fluid. The simulations of the preflight checks were thus performed assuming that each preflight check was carried out at a different temperature according to a random distribution of temperature from -30 °C to +70 °C and the fluid properties at each temperature were considered. Also, a variable content of free air was assumed.

8 EFFECTIVENESS OF THE PROGNOSTIC ALGORITHM

Five different servovalve degradations were considered, that were outlined in paragraph 3, and the ability of the prognostics algorithm to positively identify them was assessed. Each degradation was progressively increased in a linear way while continuous variations of the operating environment were simulated as outlined in section 7. The linear degradation increase does not represent a limitation for the evaluation of the effectiveness of the prognostics algorithm. In fact, the key point is how well a variation of a servovalve parameter can be recognized by the mathematical model while the other operational parameters are varying within their normal operating range. This can be assessed whichever degradation growth pattern is used. The effects of servovalve degradations on the three characteristic parameters of the prognostics algorithm are discussed hereunder.

Increased contamination of the first stage filter

This degradation is most effectively detected by the fidelity coefficient r (Fig. 8). In the diagram of Fig. 8 a contamination of the 1st stage filter up to 75% was simulated.

Reduction of the torque sensitivity of the first stage torque motor

This degradation is most effectively detected by the fidelity coefficient r (Fig. 9). The diagram of Fig. 9 refers to a decrease of the torque motor sensitivity down to 20% of nominal.
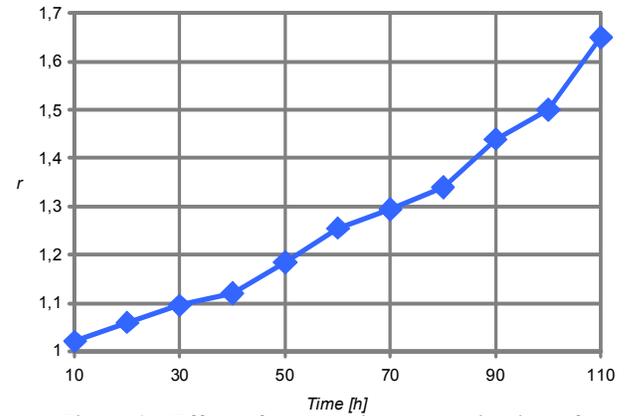

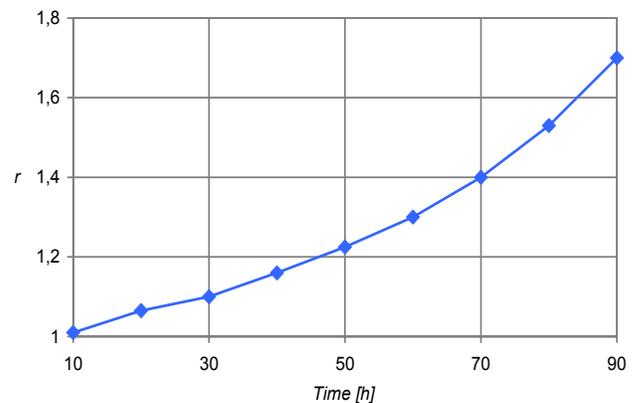Figure 8: Effect of progressive contamination of the 1st stage filter

Figure 9: Effect of progressive decrease of the torque motor gain

Internal backlash increase

This degradation is most effectively detected by the absolute value of the mean error $|e|$. Figure 10 shows how the absolute value of the mean error increases as the backlash between feedback spring and spool increases from 1 to 20 μm. A backlash increase is the result of the wear at the spool / feedback spring interface and brings about a reduction of the stability margin of the servoactuator. As it can be seen from this diagram, an initial settling time is necessary before the position errors associated to the normal servoloop operation are averaged and the actual mean error prevails. The prognostic algorithm must thus ignore the initial outputs

Increase of the friction force between spool and sleeve

This degradation is most effectively detected by the absolute value of the mean error $|e|$ (Fig. 11). This diagram refers to an increase of the spool friction up to 20 times its nominal value.
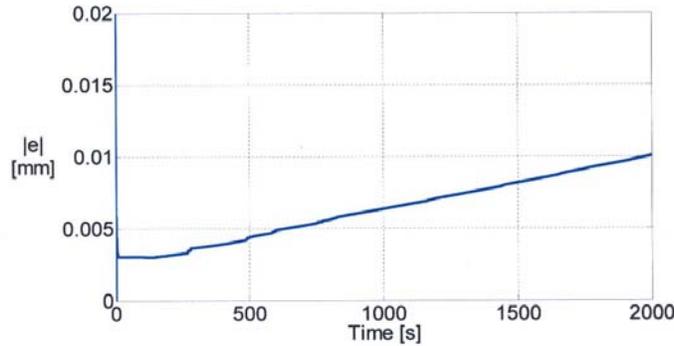
Figure 10: Effect of progressive increase of the backlash between spool and feedback spring
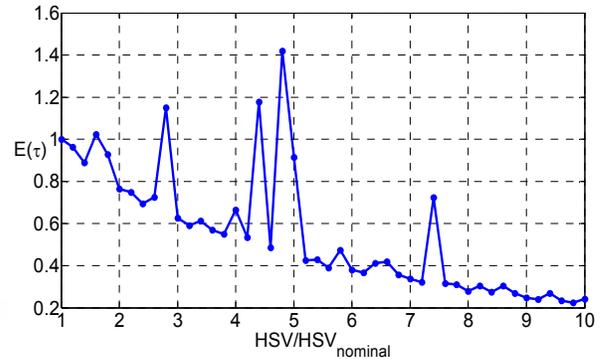

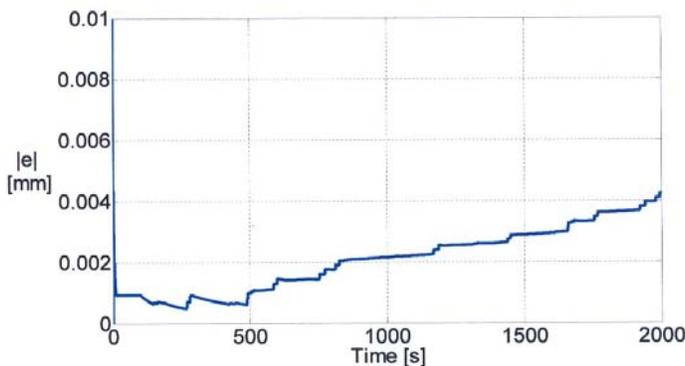Figure 11: Effect of an increase of the friction force between spool and sleeve

Figure 12: Effect of an increase of the radial clearance between spool and sleeve

Increase of the radial clearance between spool and sleeve

This degradation is most effectively detected by the correlation function $E(\tau)$, (Fig. 12). The diagram of this figure presents the plot of the correlation function $E(\tau)$ versus the ratio between the actual radial clearance (*HSV*) and the one for a new valve (*HSV*)$_{nominal}$. The values of $E(\tau)$ were obtained for a sinusoidal command of the servovalve current of 0.5 mA at 5 Hz.

The diagram of the correlation function $E(\tau)$ show a few peaks which correspond to a test performed at a very low temperature. Nonetheless, a clear trend for $E(\tau)$ can be identified.

9 DETERMINING THE REMAINING USEFUL LIFE

The simulation tests results outlined in the previous paragraph provide a strong confidence in the ability of the prognostics algorithm to identify progressive servovalve degradations without generating nuisance warnings. The following step is to predict the remaining useful life before the servovalve degradation reaches a point to create a critical malfunctioning of the servoactuator.

The main challenge in the prediction of the remaining useful life for a servovalve is the uncertainity of the degradation pattern. The experience gained from servovalve manufacturers is that degradations related to parts wear progress at a roughly approximately constant rate, but others such as the contamination of the first stage filter or the reduction of the torque motor sensitivity may progress with an unpredictable pattern. It is then hard to establish a comprehensive clear and highly reliable fault-to-failure propagation model for a servovalve as it is done in other engineering applications. A procedure was then defined to estimate the time-to-failure based on recognizing the degradation pattern during an observation period of time and assuming that the same pattern would continue in the follow up operation. The following description refers to the remaining life estimate determined by variations of the absolute value of the mean error, but similar procedures can be followed for the other two characteristic parameters of the prognostics algorithm.

Three different levels are established, which are defined as threshold, warning and failure. The threshold level corresponds to the range of values of |e| expected in normal operating conditions. When |e| is below the threshold level, no action is taken since the servoactuator behaviour is normal. If |e| goes beyond the threshold level, the prognostics algorithm uses a least square interpolating function to evaluate the trend of |e| beyond the threshold level, but no alert is issued since a positive confirmation of a degradation can be given only after enough data are collected and a degradation trend is positively recognized.

If the degradation actually proceeds and a warning level is overcome, then an alert of servovalve degradation is generated and the remaining time-to-failure is computed by taking the ratio between the difference between failure and warning level and the slope of the tangent to the

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curve of the interpolating function at the time in which the warning level is passed (Fig. 13).
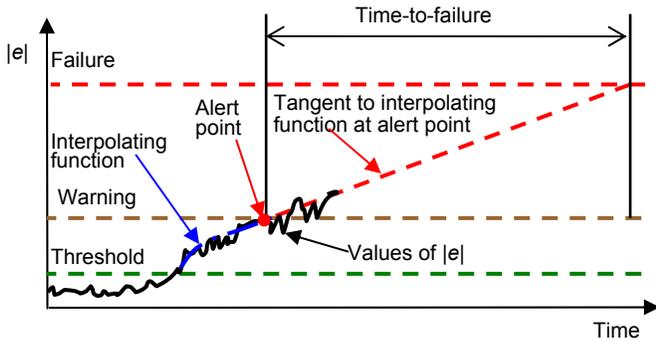

Figure 13: Time-to-failure prediction

As it was stated before, a similar procedure can be applied to the other two characteristic parameters r and $E(\tau)$ of the prognostics algorithm. The only difference is that while $|e|$ increases as a result of a servovalve degradation, r and $E(\tau)$ can either increase or decrease from their values for a healthy servovalve. Therefore, warning and failure levels are to be set for both higher and lower than normal values of the characteristic parameters.

A fundamental question is how reliable this procedure is in evaluating the remaining useful life of a servovalve. As it was stated before, if the duty cycle of a servovalve is constant, the wear developing in the servovalve parts is known by experience to keep increasing at a constant rate. This is definitely the case of servovalves used in flight control applications in which the duty cycle averaged over a few flight cycles is approximately constant. Hence, the above defined procedure for determining the remaining useful life should be fairly accurate when the servovalve degradation is caused by the wear between spool and feedback spring or between spool and sleeve.

The other servovalve faults may progress according to a much more random pattern also because external sources such as fluid contamination level can be a contributing factor.   A lack of a definite fault growth model makes the prediction of the remaining useful life uncertain for these other cases. Notwithstanding that, a linear extrapolation of the degradation trend determined during the time interval in which the fault progresses from threshold to warning can provide a clear indication that a fault mechanism is at work and a first rough indication of the time frame in which the servovalve performance would become unacceptable.

The prognostic model presented in this paper is a self-contained model since it is based only on data relevant to the servovalve. A further development that could improve the reliability of the remaining useful life prediction for the servovalve would be the development of life prediction model based on data of parameters other than those of the servovalve itself. If data such as fluid cleanliness and viscosity could be made available, a fusion of internal and external data could be made such to create a more effective life prediction model with decision making capabilities.

10   CONCLUSIONS

The work herein presented was carried out in order to define a way of recognizing the most common degradations that can occur in an electrohydraulic servovalve and evaluate the remaining useful life after the degradation has been positively confirmed. Extensive simulations were performed in which the prognostics algorithm was evaluated in a simulation test environment in which time histories of commands, loads and environmental changes covering the typical range of operating conditions were appropriately mixed up. The results of the simulation campaign proved the robustness of the prognostics algorithm and a confidence was hence gained in its ability of detecting servovalve degradations with minimum risk of false alarms or missed failures. Starting from the results obtained from this research activity, further work is planned aimed at testing servovalves in which damages will be created on purpose and the merits of the prognostics algorithm be further assessed.

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