A DUAL-DUPLEX ELECTROHYDRAULIC SYSTEM FOR THE FLY-BY-WIRE CONTROL OF A HELICOPTER MAIN ROTOR

G. Jacazio, P. Serena Guinzio, M. Sorli
Politecnico di Torino, Department of Mechanics
Keywords*: Fly-by-Wire, Electrohydraulic control systems, Helicopters*

Abstract

This paper presents a study relevant to a fly-by-wire flight control system for the main rotor of a helicopter, aimed at ensuring the maximum level of system safety while keeping the wiring complexity as little as possible. The system is quadruplex electrical, dual hydraulic, arranged as a dual-duplex configuration. The paper addresses all main issues relevant to the fly-by-wire control: system architecture, performance, monitoring functions, failure behaviour, reliability. The merits of this system and its behaviour for a reference helicopter under normal and degraded conditions, as well as during the transients following a failure, its detection and the consequent reconfiguration of the system control are all addressed in the paper.

1 Helicopter Fly-By-Wire systems: a technology under evolution

Fly-by-wire control systems are nowadays widely used in primary and secondary flight controls of fixed wing aircrafts, while most of the rotary wing aircrafts still make use of conventional hydraulic servos for the pitch control of the main and tail rotors. The resilience to move from mechanical to electrical signalling for the main and tail rotors control systems is mainly due to safety issues. A failure of a primary flight control system of a fixed wing aircraft leads to a critical condition, but an appropriate reconfiguration of the entire flight control system after the failure has been recognized still allows the aircraft to be flown and to land safely. The loss of a rotor pitch control in a rotary wing aircraft is a flight safety critical condition, and the awareness of its vital function made engineers cautious in using fly-by-wire systems for the controls of helicopter rotors. However, the advantages associated with fly-by-wire systems exerted a growing pressure on the engineering community to develop fly-by-wire system architectures for helicopters such to obtain an extremely low safety critical failure rate.

A limited use of electrical signalling in rotor pitch control was implemented in some helicopters as stability control and augmentation systems (SCAS) providing some aid to the pilot. A SCAS system accepts the electrical input signals from the autopilot to generate mechanical commands that act on the same linkage transmitting the pilot input. These systems, however, have a limited authority and the pilot can override them in case of failure or of conflicting commands.

The path towards a full fbw system was first taken by Eurocopter, that eventually developed a fbw control system for their NH90 multi-role naval and tactical transport helicopter. This fbw system is a dual hydraulic system using quad-electrical redundant torque motors driving a single shaft that activates two sections of a rotary valve controlling the flows to a tandem hydraulic actuator. Meanwhile, Sikorsky developed a demonstrator of a fbw system, known as the H92, to explore the merits of these systems, and a fbw version of the Blackhawk is under development.

A research activity has been performed by the Mechatronics and Servosystem Group of the Department of Mechanics of the Politecnico of Turin (Italy) to explore different possible architectures of fbw systems controlling the variable pitch mechanism of the main rotor of a helicopter. All the solutions examined in the trade-off study assumed hydraulic actuation technology, the presence of two independent hydraulic power supplies and that flow control was performed by two physically separated flow control valves. Hydraulic actuation was considered because of the extremely low probability of a hydraulic actuator seizure, which is in the order of $1x10^{-10}$ per flight hour, compared to a value somewhere between $1x10^{-7}$ and $1x10^{-8}$ for an electromechanical actuator. The presence of two independent hydraulic systems was assumed since this is a standard for the vast majority of helicopters. Two physically separated flow control valves have been considered because this feature greatly enhances the system safety. Though the probability of seizure of a control valve spool is considered to be very low, and a special valve construction, such as a dual-concentric valve spool, can limit the effect of a seizure, still the control of the actuators flows by means of two separate valves reduces to zero the possibility of uncontrolled actuator movement due to a flow control valve failure.

The outcome of the trade-off study was the selection of a system architecture based on a dual-duplex servosystem as the best compromise among different characteristics: performance, failure behaviour, safety, complexity, mass, cost. The following paragraphs present a description of the main characteristics of this system.

2 Architecture of a dual-duplex fly-by-wire system

The dual-duplex architecture is based on two hydraulic systems and four electrical lanes, with two lanes associated to one hydraulic system. The concept block diagram of the system is shown in figure 1.

Two parallel mounted hydraulic linear actuators are mechanically synchronized and provide the force required to drive the variable pitch mechanism; the flow to each actuator is controlled by a 4-way electrohydraulic servovalve (EHSV) with two independent coils accepting the control currents from two different flight control computers (FCCs). In the diagram of figure 1, EHSV 1 is controlled by FCCs A and C, while EHSV 2 is controlled by FCCs B and D.

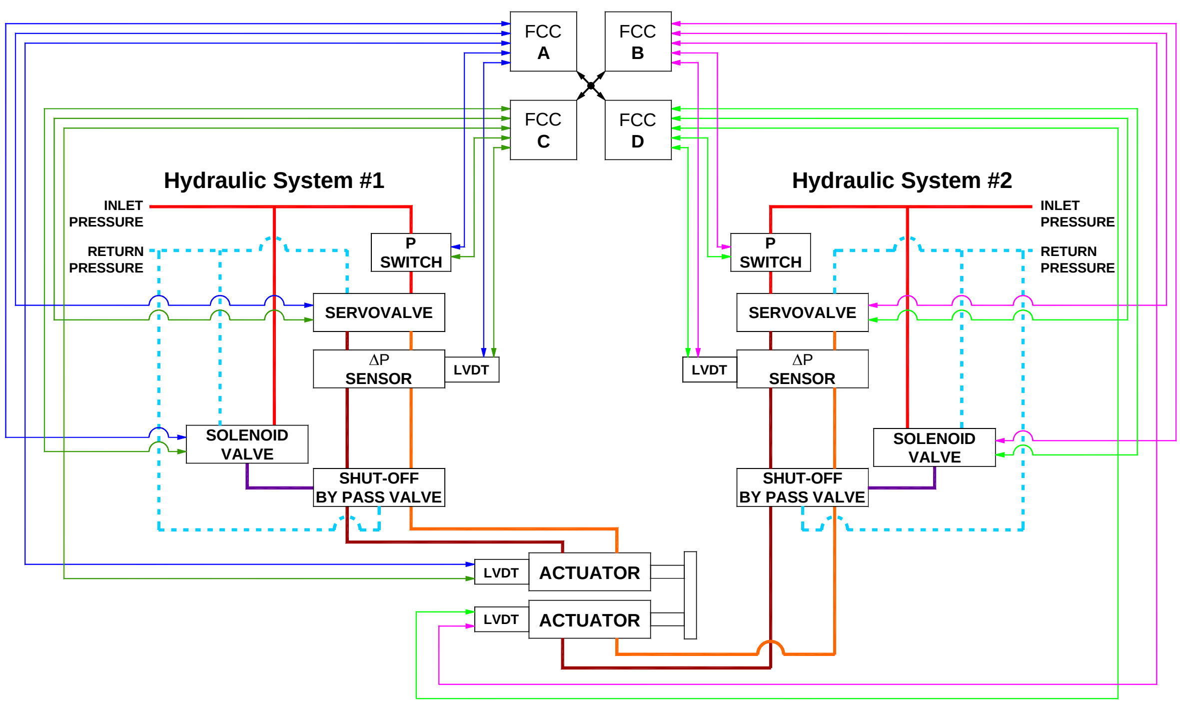

Fig. 1

A solenoid operated shutoff/bypass valve is placed between the servovalve and the actuator; the purpose of this valve is to enable the actuator operation under normal conditions and to interconnect the two actuator chambers while closing the hydraulic connections with the servovalve control ports in case of loss of the hydraulic power supply or of a failure preventing the correct actuator operation. The shutoff/bypass valve is switched to the "enable" position when a pilot pressure signal is provided by the solenoid valve, which occurs if the relevant hydraulic system is active and if any of the two independent coils of the solenoid valve is energized. As for the servovalves, the two coils of solenoid valve 1 are connected to FCCs A and C, and the coils of solenoid valve 2 to the FCCs B and D. In the "disable" position the shutoff/bypass valve allows a recirculation of fluid flow between the two actuator chambers and connects them to the return line to establish a low reference pressure. A differential pressure sensor is placed between the EHSV and the shutoff/bypass valve to sense the difference between the pressures of the two servovalve control lines. As for the other electrical components, this sensor is dual electrical and it interfaces with the FCCs in a way identical to that of the other electrical components. The signals generated by the two Δp-sensors are instrumental in implementing an equalization between the forces of the two hydraulic actuators and in allowing a monitor of the servovalve status. The output position of the actuators is measured by two dual electrical LVDT type position transducers, so that a total of four electrical signals is available. Each of the four FCCs provides the excitation voltage to one LVDT coil and demodulates the relevant output voltage; the excitation frequency of one LVDT differs of about 10% from the excitation frequencies of any of the other LVDTs to prevent undesired cross-coupling among them.

Two dual electrical pressure switches are located on the hydraulic supply lines upstream of the servovalves to provide indication that the relevant hydraulic system is pressurized.

The four FCCs controlling the system are supplied by four independent electrical systems and exchange data via optoisolated links, so that each FCC has available the complete information of the system status and can thus generate the control signals based on the knowledge of all the system state variables.

2.1 System control law

Each of the four FCCs performs a closed loop control of the actuators position by comparing the input command established by the aircraft flight control system with the actuator position resulting from the consolidation of the four feedback signals provided by the two LVDT lanes of each of the two actuators. The consolidation process follows a different logic, depending on whether all four LVDT signals are available, or some of them are no longer available because of failures. The error of the position control loop is processed by an appropriate control law and a control current is generated by each FCC for the relevant servovalve coil, thereby causing a displacement of the servovalve spool and thus porting the pressurized fluid flow to the actuator in the required amount and direction.

It is however well known that EHSVs are subjected to unpredictable variations of their offsets (difference between electrical null and hydraulic null), and that such variations can lead to a force-fight condition and to a dead band in the current/force diagram, as it is schematically shown in figure 2. A dead band in the current/force diagram yields a loss of the servoloop stiffness that is totally unacceptable. To get rid of that, differential pressure transducers have been placed at the EHSV outlets to sense the actual pressure differential created by the two servovalves, and the signals generated by these transducers are compared to each other to obtain the difference of the pressure differentials. This difference is on its turn processed by an adaptive control law generating a compensation signal that is added to or subtracted from the control signal provided by the control law of the position servoloop. The technique of creating a pressure differential equalization has found limited use in the past due to difficulties related to the stability of the differential pressure equalization loop, to the proper authority to be granted to the equalization and to the amount of the transient uncommanded movement subsequent to different types of failures. All these problems have been duly addressed and an equalization control law was developed that proved effective under normal operating and failure conditions.

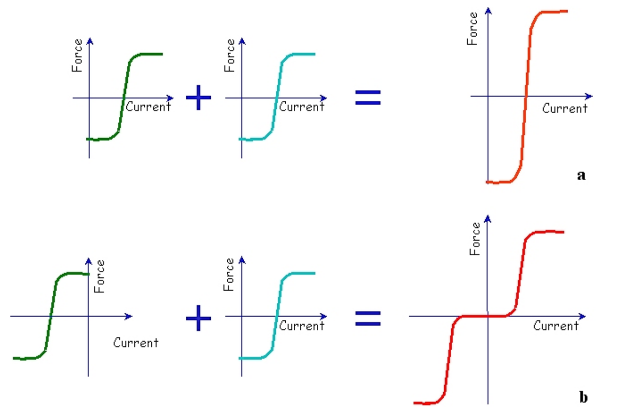

Fig. 2 Total load drive force provided by two servoactuators connected to the same flight control surface for the cases of servoactuators controlled by servovalves with identical offsets (a), and of servoactuators controlled by servovalves with opposite offsets (b)

The block diagram of the system control law is shown in figure 3. The control law of the differential pressure equalization loop accepts the difference $\delta p_{1\text{-}2} = \delta p_1 - \delta p_2$ between the two pressure differential signals and routes it through an activation block that is commanded by the enable/disable control logic. In order for the equalization function to be activated, both hydraulic actuators must operate correctly and be pressurized, which condition is signalled by the pressure switches of the two hydraulic systems. If both pressure switches signals are "on", an enable signal is sent to the activation block that transfers the $\delta p_{1\text{-}2}$ signal to the following control function $G_{eq}(s)$; on the contrary, the output of the activation block is equal to zero.

The $\delta p_{1\text{-}2}$ signal is processed by a modified PI controller in which the gain K_{IC} of the integral part of the controller is varied with time when the equalization logic is activated, starting from an initial large value at switch-on to a smaller one after the initial equalization transient has settled. The integrator output signal is saturated to maximum / minimum values; the saturation limits are enabled if both pressure switches signals are "on"; on the contrary they are set to zero. The output signals of the integral and proportional control functions are summed up and the resulting equalization signal is injected with the appropriate sign into the summing points of the forward paths of the control loops.

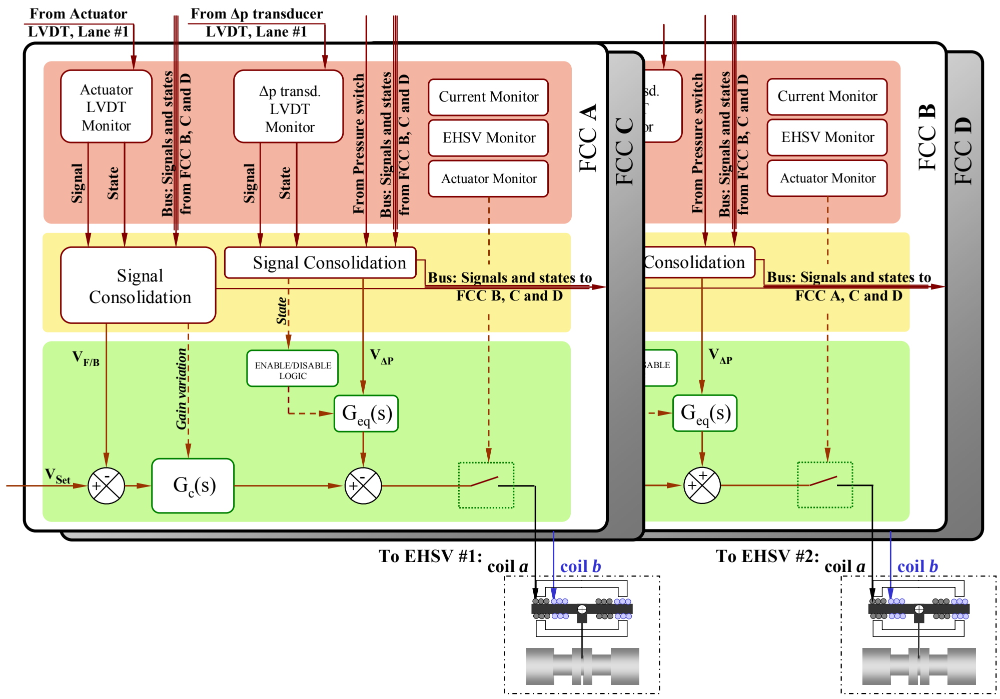

Fig. 3

Besides enabling the equalization of the forces developed by the two hydraulic actuators, the signals generated by the differential pressure transducers can be used for closing an internal pressure feedback loop with the purpose of improving the system dynamic response.

2.2 Case study

As a case study for the fbw dual-duplex architecture, the control system for the main rotor of a helicopter was addressed. The values of all parameters assumed for the system analysis do not refer to a specific helicopter model, but are representative of those that could be found on a medium-size helicopter using of state-of-art components. With both hydraulic actuators operating, the system provides a force of 20000 N at a speed of 280 mm/s and the total actuator stroke is equal to 80 mm. The two hydraulic systems have a supply pressure of 20.7 MPa and a return pressure of 0.35 MPa; hydraulic fluid is conforming to MIL-PRF-83282. The overall system inertia is equivalent to a mass of 10 kg translating with the actuators output. The stiffness of each actuator attachment point is equal to $2x10^7$ N/m.

Each servovalve has two independent coils with a rated current of 20 mA, with each coil accepting the controlled current from a different FCC. Under normal operating conditions each servovalve driver provides a maximum current of 10 mA, so that the sum of the currents through the two servovalve coils brings about the full servovalve displacement. If one of the two currents is brought to zero as a result of a failure, the FCC driving the remaining healthy electrical lane of the servovalve doubles the electrical gain of the control loop and sets the maximum current to 20 mA, thereby ensuring an unabated servovalve performance.

The solenoid valve is an on/off device accepting a discrete input voltage signal: a pull-in voltage of 16 V_{dc} switches the valve into the open position bringing the pilot pressure signal to the supply pressure level; the time delay from input voltage application to pilot pressure reaching the supply pressure is 30 ms. This same time delay occurs for the depressurization of the pilot pressure signal when the input voltage drops below 3 V_{dc}. The shutoff/bypass valve is a spring preloaded spool valve; when the pilot pressure is provided by the solenoid valve is below 7 MPa, the passages between servovalve control lines and actuator lines are closed and the two actuators lines become mutually interconnected and connected to return. When the pilot pressure goes above 7 MPa, the pressure force generated onto the spool end opposite to the spring overcomes the spring force and causes the spool to move into a position in which the actuator lines are connected to the servovalve lines and the interconnecting passage is closed.

Each of the two actuators is equipped with a dual electrical LVDT type position transducer; the transducer is of a 5-wire type providing the output voltages of the two secondary coils, which allows the implementation of continuous monitor of the LVDT. The LVDT output signals are demodulated by 2^{nd} order type of filters.

The differential pressure transducer consists of a spring centered piston whose position is also sensed by a dual electrical LVDT. When a pressure difference prevails between the two servovalve control lines, a force is originated on the piston that pushes it in one direction and is eventually balanced by the variation of the spring force. The piston position is measured by the LVDT and the resulting signal provides a measurement of the pressure differential. The LVDT type and demodulation are the same of those of the actuators LVDTs.

The position and differential pressure feedback loops are closed within the FCCs that operate with a recursion rate of 640 Hz for the pressure equalization loop and with a rate of 320 Hz for the external position loop; the computation time is 1 ms for both loops.

The study was performed assuming a hydraulic fluid temperature of 70 °C, which is an average value during a typical mission flight. Although the operation at different temperatures would lead to some differences in the system performance, no anomalous system behaviour is expected that could impair the merits of the proposed architecture.

3 System performance under normal conditions

The system performance under normal operating conditions was first evaluated and the values of the parameters of the control law were defined to get the optimum performance. The system has a phase margin of 79° and a gain margin of 19 dB, which ensure an adequate stability. In order to prove the ability of the proposed architecture to prevent actuators force fighting and to ensure a large stiffness also in presence of different servovalves offsets, the performance analysis was conducted for the case of the two servovalves having opposite offsets equal to 10% of the rated current, which can be considered as a limit case for normal operating conditions.

The system frequency response for an input command equal to 5% of maximum input amplitude (figure 4) has 3 dB attenuation at 12 Hz and 90° phase lag at 14 Hz, which well meets the typical requirements for a main rotor control system. A slight amplification of 0.5 dB exists at a frequency of 1 Hz, which also is within the acceptable amplitude envelope for the frequency response. Figure 5 shows the corresponding step response to a large command. It can be noticed from this diagram that although maximum opposite servovalve offsets were assumed, only a limited difference between the pressure differentials acting on the two hydraulic actuators is generated during the transient, and that such difference vanishes after about 0.2 s. Figure 6 shows the dynamic stiffness, which is expressed in Nm. The first exciting frequency associated to the rotor speed and number of blades could be in the 30 to 50 Hz range. The minimum dynamic stiffness in that range is 141.5 dB, corresponding to 1.19×10^7 N/m; a load fluctuation equal to ±20% of maximum load would cause an actuator output oscillation of ±0.34 mm, equal to about ±0.4% of full actuator stroke, which is certainly acceptable for a main rotor control system. All these diagrams thus clearly indicate an excellent dynamic response, which could not have been obtained in presence of servovalve offsets without the pressure differential equalization logic.

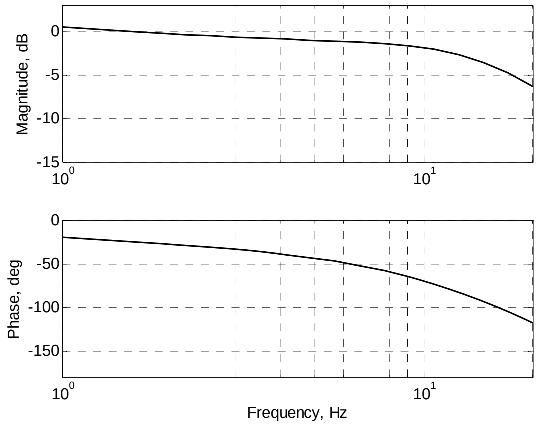

Fig. 4

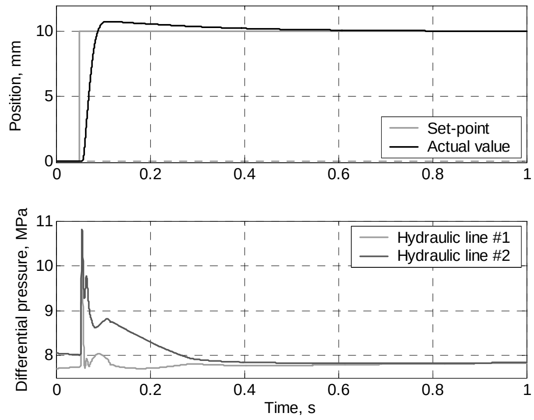

Fig. 5

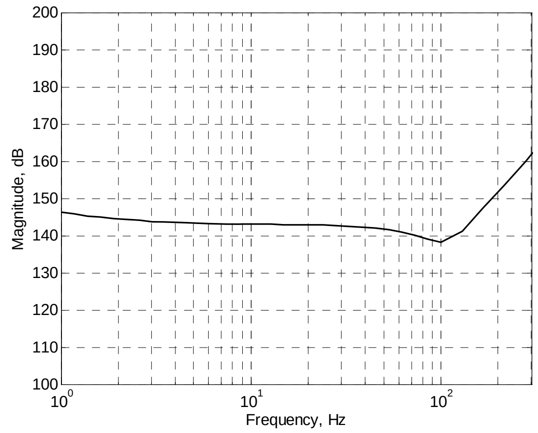

Fig. 6

4 System monitor

The critical system components are continuously monitored to detect possible failures, isolate the failed equipment and reconfigure the system control to enable the system to continue its operation in the most effective way for the remainder of flight. A continuous monitor is performed for the following components:

- ***LVDT monitor***: it is performed by checking that the summed output voltage $V_A + V_B$ of the two secondary coils is within a specified band. This monitor may not pick up minor failures leading to some deviations of the transducer characteristics, but it definitely recognizes critical failures. Minor LVDT deviations can be detected by comparing the signal outputs of the two electrical sections of an LVDT: if the signals differ of more than a specified limit, a warning signal is generated.
- ***Differential pressure transducers monitor***: since these transducers are based on LVDTs, the same monitoring technique described above can be used.
- ***Servovalve current monitor***: a current wrap-around is performed in which the current command generated by the FCC will be compared with the actual current through the relevant servovalve coil; a difference larger than a limit will be recognized as a failure.
- ***Servovalve performance monitor***: a monitor of the servovalve to detect a possible seizure of the servovalve spool, or a hardover condition resulting from the failure of the servovalve first stage is normally performed by measuring the spool position with an LVDT and comparing spool position with input current. Since the system herein described has transducers measuring the pressure differential across the servovalve control ports and transducers measuring the actuators position, all the pieces of information are available to perform a servovalve monitor without the additional burden of LVDTs on the servovalves spools. By performing the time derivative of the actuators LVDTs, the actuators speed, and thus the servovalves flows are calculated; the calculated flow can be fed to a servovalve model together with the measured pressure differential and servovalve current to check the correct servovalve operation.
- ***Uncommanded movement monitor***: although an uncommanded movement would be the result of an uncontrolled behaviour of the servovalve, which is detected by the above described monitor, an additional monitor to detect uncommanded movements can be performed due to the criticality of this failure. The uncommanded movement monitor is performed by comparing the input command with the actuators movement and by checking the coherence of these signals.

In addition to these continuous monitors, a preflight check can be conducted to verify the correct operation of the solenoid and shutoff/bypass valves to make sure that no dormant failure be present. With the solenoid valve deenergized an actuator command is given by the FCC; if an actuator movement is detected, a failure is recognized. After this first check, the solenoid valve is energized and an actuator command is again given by the FCC: an actuator movement equal to the command must now be measured by the LVDT, otherwise a failure is recognized. This operation is performed in sequence for each electrical lane to make sure the two solenoid and shutoff/bypass valves and their respective electrical sections are properly functioning.

5 Failure analysis

The system architecture with the associated monitoring functions ensures the following general failure behaviour of the system:

- System is fully operational after all single electrical failures
- System is fully operational after most combinations of two electrical failures
- Some combinations of two electrical failures, such as two Δp transducers of same hydraulic system lead to some performance degradation
- Loss of two electrical lanes controlling the same servovalve or solenoid/shutoff valve lead to a loss of one hydraulic system
- Loss of one hydraulic system halves the total actuators stall force

- System is inoperative after loss of two hydraulic systems or four electrical lanes, or two electrical lanes controlling one hydraulic system + loss of other hydraulic system

This last condition is practically no worse than what can be found on helicopters with conventional controls, since the probability of loss of two electrical systems is definitely much lower than the probability of loss of a single hydraulic system.

An extensive analysis was conducted on the system transients after the failure occurrence until the FCCs have recognized the failure, isolated the failed components, reconfigured the system control and the transient has eventually settled. A few significant cases are reported hereunder to emphasize the robustness of the system architecture:

- The system receives a large step command, such to require full servovalves opening. One of the two servovalves fails and remains fully open (figure 7). There is a 2.7 mm overshoot corresponding to about 3.4% of total actuator stroke and a settling time of 0.3 s.
- Starting from a stationary system, a step command is given, but one of the two servovalves is jammed in the closed position (figure 8). Force fighting between the actuators causes a high error position till the failure is recognized and isolated. The remaining healthy lane is able to provide an effective position control with a settling time of 0.7 s.
- Starting from a stationary system, a step command is given; at some point the mechanical connection of the dual LVDT measuring the position of one actuator breaks and a sudden loss of the output voltages of both LVDTs of that actuator occurs (figure 9). A transient disturbance of 8 mm, corresponding to 10% of maximum actuator travel is originated, which settles in about 0.08 s. This transient disturbance is relatively large, but the settling time is very low and it must also be considered that the probability of this failure is extremely low since a negligible force is transmitted between the actuator rod and its LVDTs.

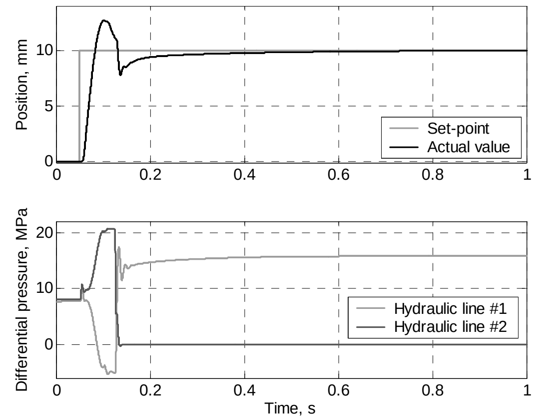

Fig. 7

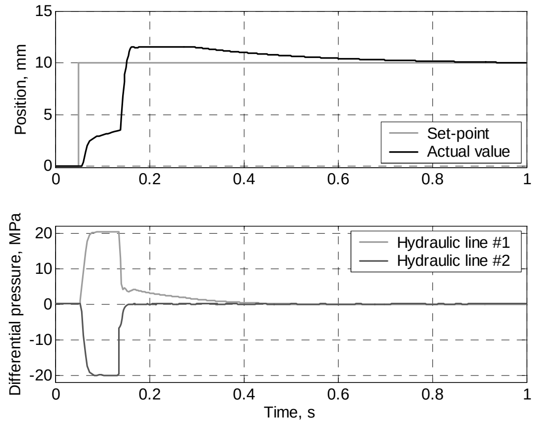

Fig. 8

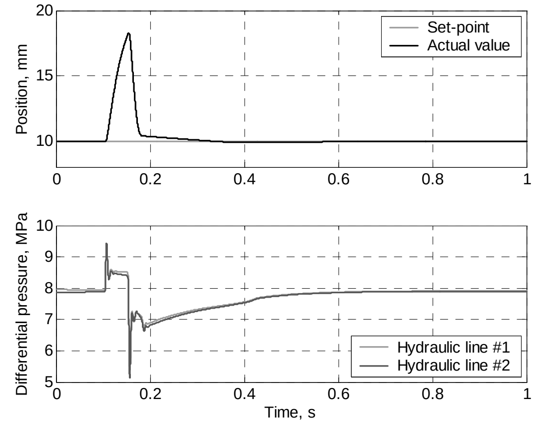

Fig. 9

- While the system is stationary in one position and subjected to a large external load, one of the two electrical lanes of a pressure differential transducer fails providing zero output voltage (figure 10). A minor transient disturbance of 0.2 mm corresponding to 0.25% of full actuator stroke is generated.

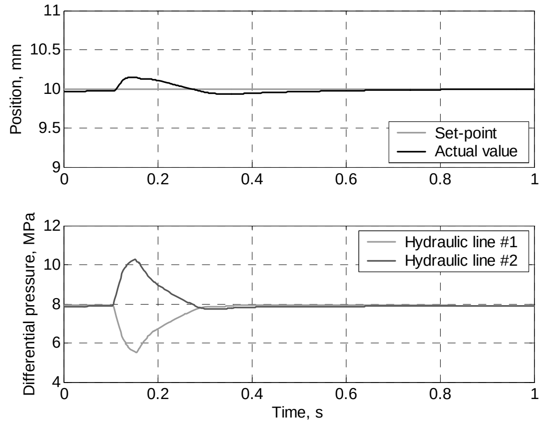

Fig. 10

5.1 Reliability assessment

An assessment was made of the system reliability. Since the purpose of the research work was to evaluate the merits of a fly-by-wire dual-duplex architecture, the reliability figures that are reported hereunder do not include the failure rate of the hydraulic systems, since two hydraulic systems are also present in the conventional mechanical flight controls. On the basis of recognized figures for the failure rates of aircraft quality components, the following results were obtained.

- All types of failures: 1.64×10^{-4} per flight hour (corresponding to an MTBF of 6097 hours)
- Major failures (leading to a reduction of system performance): 1.67×10^{-5} per flight hour
- Flight safety critical failures (total loss of system operation): 7.05×10^{-10} per flight hour

All these values are consistent with the typical requirements of helicopter flight control systems.

Conclusions

The main results of a research activity aimed at defining an innovative concept for the fly-by-wire control of the main rotor of a helicopter have been outlined. The system described in the paper uses two independent electrohydraulic servovalves to control two force-summed hydraulic linear actuators, while pressure differential transducers enable the implementation of an effective equalization of the actuators forces, thereby preventing a force-fighting and ensuring the required system stiffness.

The four FCCs controlling the system make appropriate use of the signals generated by the system sensors and of the control signals to implement a continuous monitor able to ensure system robustness and multiple failures survival, while still keeping a simple architecture which is beneficial to the system reliability.

References

[1] Vernon, R.S.; Morris, J.W.; Jenney, G.D. Fly-by-Wire *SAE, 1998*

[2] Jacazio, G. and Balossini, G. A high performance force control system for dynamic loading of fast moving actuators. *Proceedings of the Power Transmission and Motion Control, 2005*, pp. 3- 15

[3] Bassett, J.; Boczar, B.; Brinkmeier, N. H-92 Fly-By-Wire System Integration Laboratory (FBW SIL). *Proceedings of the American Helicopter Society 62nd Annual Forum,2006*, Virginia Beach, Virginia, pp. 467-478.

[4] Vidal, P.A. NH 90 Helicopter Fly-By-Wire Flight Control System. *Proceedings of the American Helicopter Society 53rd Annual Forum,1997*, Phoenix, pp. 915-923.

Acknowledgment

The research activity presented in this paper has been supported by a grant provided by the Regione Piemonte of Italy.

Copyright Statement