ICAS-98-5,5,2

MECHANICAL FAILURES OF FLAP CONTROL SYSTEMS AND RELATED MONITORING TECHNIQUES

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Abstract

This work analyses some monitoring techniques related to different troubles affecting flap control systems in order to compare the dynamic behaviour of a typical irreversible actuator architecture sytem and a typical reversible actuator (with wingtip brakes) architecture system under the main mechanical and supply pressure failures.
The monitoring mathematical models and the related simulation computer program of a typical control system under the above mentioned failures have been prepared. This computer simulation program furtherly analyses the flight control dynamic behaviour and the airplane lateral-directional behaviour under the action of the primary and secondary flight controls and of the autopilot.
The purpose of this paper is to evaluate the effects of different monitoring strategies in failure conditions.
Some simulations of the control system and airplane behaviour with the above mentioned failures have been performed.
The results of the present work show the high sensitivity of the aircraft controllability to the monitoring technique used to detect flaps asymmetries and the prevention of major troubles related to the wingtip brakes failure, to the irreversibility failure following structural vibrations and to the supply pressure drop.

Introduction

The flap actuation systems of most commercial and military aircraft consist of a centrally located Power Drive Unit (PDU), a shaft system and a certain number of actuators (normally two for each flap surface). Depending on the performance requirements and on the specified interface with the other aircraft systems and structure, several different configurations have been used in the design of such actuation systems. PDU's can be either hydromechanical or electromechanical and be either of a single or dual motor type. In the last case the outputs of the two motors can be either torque summed or speed summed. The shaft system generally consists of torque tubes connecting the PDU output with the right and the left wing actuators; however, the flap actuation systems of small commercial aircrafts often use flexible drive shafts rotating at high speed in place of the low speed rigid shafts. The actuators are normally linear and are based on ballscrews, though some flap actuators use an ACME screw; some flap actuators are of a rotary type.
Whichever the actual configuration of the flap actuation system is, the limitation of the asymmetry between the left and the right wing flaps is one of the major requirements for the design of the actuation and control system. Under normal operating conditions the actual asymmetry between the right and the left flaps (or slats) is generally very small because the backlash and the deflection of the mechanical transmission (actuators and shaft system) under non symmetrical loads are generally a small fraction (much less than 1% total) of the full travel. However, if a fracture occurs in the mechanical transmission, an increasing asymmetry builds up between the flaps surfaces, which may became excessive and turn to be flight safety critical if appropriate corrective actions are not taken.
It must be noted that a mechanical failure can occur in any component of the actuation system (shafts, PDU, actuators). The failure of the PDU or of an actuator results in the inability to operate the affected flap system. Such a failure condition, though been regarded as a major type of failure, is not critical for the flight safety, as it is the case of large asymmetries between left and right surfaces resulting from uncontrolled shaft failures.
If a shaft failure occurs the following events take place. The part of the actuation system upstream of the fracture point keeps rotating with the PDU in the commanded direction until a shutoff command is not given to the PDU. The portion of the shaft system downstream of the fracture point exhibits a behaviour that depends on its design characteristics. If the actuators are non reversible (Fig. 1), this part of the system decelerates rapidly to a stop because the aerodynamic loads cannot backdrive the actuators and the small kinetic energy of the shaft system is soon dissipated by the tare losses of the rotating shafts. If the actuators are reversible, the aerodinamyc loads are capable of backdriving the failed part of the actuation system, which can accelerate fast when subjected to large loads because of its low inertia. In this case, in order to stop the uncontrolled surfaces, the actuation system must be equipped either with wingtip brakes (Fig. 2) or irreversibility brakes (Fig. 3). These two alternate configurations are based on:
- controlled wingtip brakes (one for each wing) located at the end of the transmission line, close to the position transducers (Fig. 2), that become engaged and brake the system after a failure has been positively recognized;
- self-acting irreversibility brakes within each actuator, which self engage when the actuator output overruns the input shaft (Fig. 3).

The relative merits of the three solutions (non reversible actuators, reversible actuators with wingtip brakes, reversible actuators with irreversibility brakes) and which of the three is better is a long debated matter: the maximum asymmetry in failure conditions is greater with the wingtip brake solution, the solution with non reversible actuators requires higher hydraulic power owing to its lower efficiency and the irreversibility brake solution, that overcomes the shortcomings of the two previous solutions, is more expensive. Therefore, the

21st ICAS Congress
13-18 September 1998
Melbourne. Australia

most commonly used architecture for high-medium performance aircrafts employes the reversible actuators with wingtip brakes and centrally located PDU (of a dual motor type for operational reliability) because it is cheaper and more efficient, neverthless the associated high asymmetries in case of failure; whereas for low-medium performance aircrafts the most commonly used architecture employes the irreversible actuators, neverthless the associated lower efficiencies.

Whichever design solution is taken, an asymmetry between the surfaces upstream and downstream of the failure develops as long as the PDU is running and the wingtip brakes, if present, are not engaged. This developing asymmetry must be detected and a corrective action taken in order to keep its maximum value within a safe limit by means of appropriate monitoring devices equipped with suitable software whose selection is dealt in [13].

Furtherly, when a failure occurs in the wingtip brakes (reversible actuators architecture), consisting of the inability to apply the proper brake torque to the transmission, a flight safety critical condition can arise, particularly following a previous shaft failure; a similar condition can occur when the irreversible actuators turn to be reversible because of structural vibrations and/or temperature troubles.

Another possible trouble can occur when the supply pressure of the hydraulic system drops under a defined value, not allowing position servomechanism proper operations.

The monitoring system must be able to detect and properly correct the above mentioned failures.

Aims of the work

Aim of the work is the comparison between the dynamic behaviour of a typical irreversible actuator architecture sytem and a typical reversible actuator (with wingtip brakes) architecture system under all the above discussed failure conditions with eventually different monitoring devices and related software types.

Monitoring techniques

According to the different failure modes above mentioned, different monitoring techniques are considered.

In case of asymmetry, three monitoring techniques, characterised by increasing complexity and perfomances, are employed in this work: differential position control, differential position and speed control, active differential position and speed control.

In the event of the inability of the wingtip brakes (reversible actuators architecture) to apply brake torques or in the event of an irreversible actuator turning to be reversible (irreversible actuators architecture) the following monitoring technique is employed: if a position error greater than a defined value is produced by a surface position variation without any command variation, then wingtip brake or irreversibility failure is recognized and the hydraulic system is permanently repressurized.

In case of a supply pressure drop in the hydraulic system the monitoring device is able to shutoff the control system until the correct pressure is restored.

Differential position control

The asymmetry detection is normally obtained by comparing the electrical signals of position transducers which are placed at the ends of the right and left shaft systems. If a difference greater than an established limit is measured, and it persists for more than a given time, an asymmetry is recognized and shutoff commands are provided to the PDU and to the wingtip brakes. The affected flap or slat system is thus brought to a standstill with a limited asymmetry and it remains inoperative in that condition for the remainder of the flight. This asymmetry control technique is used in the large majority of flap and slat actuation systems and will herein referred to as asymmetry control technique 1.

The maximum resulting asymmetry in a failure condition is a value that depends on several factors and in some cases may become large unless appropriate asymmetry control techniques are taken. The maximum asymmetry after a shaft failure mainly depends on the following factors:

- value of the established threshold beyond which the position difference between left and right position sensors signals is considered an asymmetry;

this threshold in turn depends on the position sensors accuracy, backlash and stiffness of the shaft system, accuracy errors of the associated electronics;

- asymmetry confirmation time; if an asymmetry is signalled, it must persist for a certain amount of time to be positively confirmed to avoid nuisance system shutdown;
- delay travel of the system over the period of time between asymmetry confirmation and beginning of system deceleration as a result of brakes engagement and power removal;
- shutdown travel from power removal to a standstill.

In order to limit the maximum asymmetry following a shaft failure each of the above factors should be minimized. However, not much can be done on the delay and shutdown travels since they depend on physical factors such as system components inertia and time response of the electrical and hydraulic components, which are generally at the minimum attainable with today technology. Moreover, the delay and shutdown travels make up a low portion of the total asymmetry.

The asymmetry threshold is a parameter that provides a large contribution to the final asymmetry. It is generally in the range of 2 to 3% of the full travel to avoid nuisance disconnection of the actuation system resulting from an adverse combination of all the components errors in normal operating conditions. However, since the developing asymmetry, in case of a shaft failure, can be in a direction opposite to that of the components errors, the actual asymmetry between right and left surfaces before an asymmetry is detected is equal, in the worst case, to the sum of the threshold plus all the components errors and could end up in being 4 to 5% of full travel without counting yet the other above mentioned effects. In order to reduce this contribution to the final asymmetry, position sensors and associated electronics with lower errors should be used. Accuracy improvements are possible, but they are practical only up to a given limit, beyond which the cost effectiveness of the improvement is negative.

If the final asymmetry in a flap system after a failure must be maintained within tight limits, one of these two other asymmetry control techniques should be used, which are briefly outlined.

Differential position and speed control

This asymmetry control technique is based on detecting the differences of both position and speed of the two ends of the transmission shafts.

If either the position or the speed differential exceeds an established threshold for more than a given amount of time, than an asymmetry is recognized and a system shutdown is performed in the same way as for the differential position control technique described in the former paragraph.

This control technique is faster in detecting rapid developing asymmetries since it recognizes an asymmetry as soon as large speed differences originate between the right and the left ends of the transmission shafts. Thus, the system shutdown procedure can be initiated well before the differential position threshold is reached, with a resulting lower final asymmetry.

The measurement of the speed at the end of the transmission shaft can be obtained either from dedicated speed sensors or as a result of an algorithm that computes the speed as the time derivative of the position measured by the position sensor. It must in fact be noted that the positions of the two ends of the transmission shafts must always be measured and compared with each other to detect asymmetries which could develope at a slow rate and thus not be picked up by the differential speed control.

Each of the two solutions (additional speed sensors or time derivation of the position measurements) has its own advantages and drawbacks. Speed sensors present the advantage of providing a clean analogue signal proportional to the speed; this signal is continuously available and can be used by either an analogue or a digital control to detect asymmetries. The time derivation of the position measurements presents the advantage of not requiring additional components and the associated wiring along the aircraft wing.

However, the time derivation is a process which is much more sensitive to all sort of signal disturbances, therefore the calculated speed is less precise and is provided with some delay to filter out the noise by means of some filtering technique. This partly reduces the rapidity of this control technique in detecting fast developing asymmetries and increases the workload of the computer.

Active differential position and speed control

The active differential position and speed control is a technique which has the purpose of minimizing the final asymmetry between right and left flap surfaces following a failure by driving the part of the actuation system which is still connected to the power drive unit to a standstill in a controlled position.

The active differential position and speed control is based on the concept that if the actuation system control is performed by a digital controller, and an asymmetry occurs, the controller has all the information available to understand which of the two position sensors (left or right) is connected to the failed part of the transmission shaft.

Therefore, the computer can command the wingtip brake of the failed part of the transmission shaft to engage so to arrest it; at the same time the computer can command the healthy portion of the system to move to the same position reached by the failed part and stay there for the remainder of the flight. By doing so, a minimum final asymmetry is obtained.

This control technique provides the advantage of yielding a minimum final asymmetry. It can be pursued, however, only if the asymmetry control is performed by means of a digital controller; moreover it creates an additional burden to the computer.

Wingtip brakes or irreversibility failures

Wingtip brakes failure.

This type of failure, which is referred to the architecture shown in Fig. 2, is a possible consequence of wear, high operating temperatures, environmental injuries or structural vibrations. This failure can be dormant or evident. In the first case the failure event occurs when the hydraulic system is pressurized and the brakes disengaged, so the trouble cannot arise until the system is depressurized and the brakes engaged. In the last case the failure event occurs when the system is depressurized and the brakes engaged, so the trouble is quickly evident in form of inadvertent surface movements under the aerodynamic loads.

Irreversibility failure

For this type of failure, referred to the architecture shown in Fig. 3, the same above reported considerations are still applicable.

Supply pressure drop in the hydraulic power system

The supply pressure given by the hydraulic power system is a function of the flow rate requested by the various connected subsystems; if an high flow request occurs, the supply pressure can drop below a defined value which is critical for the correct operation of the flap system. Therefore, by means of a supply pressure transducer, the growth of a counter is commanded when the pressure is lower than its critical value. If this condition persists for more than a given amount of time, the counter reaches a threshold value and a system shutdown is performed. If the actuators are non reversible, the aerodynamic surfaces decelerate rapidly to a stop because the aerodynamic loads cannot backdrive the actuators; if the actuators are reversible, the aerodinamyc loads are capable of backdriving the system, till to the engage of the wingtip brakes produced by the drop of the supply pressure below the critical value. As this type of trouble may persist for a limited time, eventually followed by a supply pressure growth, the monitoring system is programmed to attempt periodical restarts of the system; if the trouble persists, a further shutdown is given, otherwise the flap system is again fully operational.

Actuation system modelling

In order to compare the relative merits of the different asymmetry monitoring techniques, an actuation system was considered, typical of those currently used for flaps actuation (Fig. 1). The schematic of such actuation system is shown in Fig. 4. The system consists of a Power Control and Drive Unit (PDU), a shaft system and ballscrew actuators (BS) driving the flaps (or slats). Each ballscrew actuator is an assembly containing a gear reducer (ZS) and a ballscrew. The two torsion bars (CTB) between the PDU and the inboard actuators are considered to be the weak link in the power drive system. At the two outer ends of the shaft system are located the wingtip brakes (WTB), the position transducers (PT) and the speed sensors, if present.

The system control is performed by an Electronic Control Unit (ECU), not shown in Fig. 1, 2 and 3, which closes the position control loop.

The position information provided by the transducers is also used by appropriate monitoring routines to detect possible asymmetries between right and left flap (or slat) surfaces.

The PDU contains the hydraulic motors, the gear reducer (ZM), the solenoid, shutoff and control valves. The hydromechanical system considered for this work was assumed to also contain tachometers for a continuous actuation speed control.

Fig. 4 shows the mechanical model of the actuation system. The model takes into account the hydraulic and mechanical characteristics of all system components, including their friction, stiffnes and backlash. In particular, the model takes into account the following:

- Coulomb friction in the PDU (FFM), in the actuators (FFS) and in the position transducers (FFPT),
- stiffness (K1G) and backlash of the torsion bar of the right and left shaft systems,
- errors and temperature effects in the position transducers and backlash (BLPT) within the position transducers drive,
- errors in the position transducers electronics and in the A/D conversion,
- stiffness (K2G), backlash (BLG) and lead errors of the ballscrew actuators,
- second order electromechanical dynamic model of the servovalve with position and speed limitations and complete fluid-dynamic model [6],
- dynamic and fluid-dynamic hydraulic motor and high speed gear reducer model taking into account, beside the above mentioned Coulomb friction, viscous friction and internal leakage.

It must be pointed out that the stiffness K1G and the backlash BLPT are within the system servoloop; the stiffness K2G and the backlash BLG are parameters of a system branch off the servoloop.

The mathematical model takes also into account a activation/deactivation logic of the flaps hydraulic actuation system. According to this logic, when the system is depressurized and an actuation command is given, exceeding a defined value and persisting for more than a defined time, first of all a pressurization command is performed by means of a solenoid valve - shutoff valve assembly, then, following the monitoring of the correct supply pressure level, the true actuation command is given by means of the control valve to the hydraulic motor.

When the commanded position is reached with an error lower than a defined value for more than a defined time a shutoff command is given in order to depressurize the hydraulic system, so avoiding the continuous oil leakage from the supply to the return pressure which affects the pressurized system.

Aircraft and autopilot modelling

In order to assess the amount of perturbations induced on the aircraft attitude by the failures of the flap actuation system, the lateral-directional dynamics of the aircraft and of its autopilot have been simulated. The autopilot control laws have been assumed to be of a PID type, which is adequate to approximate the actual autopilot control for the objective of the present work. By measuring the aircraft angle of roll the autopilot PID controller generates the commands to the ailerons and to the rudder. These flight controls have in turn been simulated as second order systems with a saturation on their maximum speed and position. The aircraft data taken for the simulations were typical of a business jet of the Gulfstream IV class.

System mathematical modelling and simulation results

The above described models of the actuation system, of the aircraft and of the autopilot have-been used to build a mathematical model of the whole system and a dedicated computer code written in Fortran 77 has been prepared. The computer code contains the models of:

- the three different asymmetry monitoring techniques,
- the wingtip brakes or irreversibility failures monitoring technique,
- the supply pressure drop monitoring technique.

Several simulations have been run for the case of a mechanical failure of the transmission shaft with a resulting asymmetry between right and left surfaces.

In the following figures DThM is the motor speed, ThSL and ThSR are the left and right flaps positions, ThA is the deflection angle of the ailerons and RoA is the aircraft roll angle.

Figures 5, 6 and 7 show the simulations results for the cases of deploying flaps with reversible actuators in the final part of their stroke to the landing position under the maximum loads, that act as opposing to the flap deployment. The simulation results shown in these figures refer respectively to the cases of monitoring techniques 1, 2 and 3.

For all the simulations the transmission shaft failure occurs at time = 0.4 s, while the actuation system is running at the rated speed, following the tempo di attivazione del sistema . In this case of large opposing loads the part of flap system downstream of the failure decelerates very fast under the action of the load and then accelerates backward until the asymmetry is recognized and the wingtip brake engages providing its braking torque to arrest the system. Meanwhile, the other part of the system is driven by the PDU until the asymmetry monitor provides the shutdown command.

As it can be expected, the asymmetry monitoring routine 2 (Fig. 6) allows a faster detection of the developing asymmetry and thus leads to a lower final asymmetry then monitoring routine 1 (Fig. 5). It must be noted that in all these figures the asymmetry is given by the differences between the two state variables ThSR and ThSL.

Figure 7 shows the system behaviour for the same loading condition and for the case of monitoring technique 3. Such a technique performs an active asymmetry control and is thus better than the other two.

The effects of the asymmetry monitoring techniques on the aircraft attitude are shown by the curves ThA and RoA. It can be seen that the roll angle RoA increases as the asymmetry develops; at the same time the autopilot generates a command to the ailerons to realign the aircraft; this take place through a dynamic response which includes a dutch roll component. The maximum roll perturbation with the resulting aileron commands decreases moving from monitoring technique 1, through the technique 2, to technique 3.

Moreover, if irreversibility brakes are used in place of the wingtip ones, the transient response following a failure is faster and the aircraft disturbance is smaller. Although the asymmetry monitoring technique 1 is generally used and considered sufficient to maintain the aircraft control after a failure, the results of this study clearly indicate that a careful analysis should be conducted to verify whether the margins of safety are not becoming too small under a combination of adverse conditions. In such a case one of the other two monitoring techniques should strongly be considered for improving the aircraft handling after a flap transmission shaft failure.

Figures 8, 9 and 10 show the simulations performed for the case of retracting flaps with large aiding loads and with the monitoring techniques 1, 2 and 3. In these simulations too the failure of the transmission shaft occurs at time = 0.4 s, while the actuation system is running in a steady condition, following the tempo di attivazione del sistema.

Since these simulations have been run for large aiding loads cases, the portion of the shaft system downstream of the failure accelerates rapidly under the action of the loads with a resulting asymmetry until the system shutdown occurs. As for the case of large opposing loads of Figures 5, 6 and 7, the monitoring techniques 2 and 3 provide a faster response and a final lower asymmetry with a resulting lower rolling perturbation of the aircraft.

With the values of the aircraft parameters taken for this simulation, if an asymmetry occurs under maximum aiding loads and monitoring technique 1 is used, the rolling moment created by the asymmetric flaps is slightly lower than the maximum rolling moment obtainable by the ailerons and the aircraft control is partially compromised.

As a matter of fact the maximum rolling rate that can still be obtained after a flap asymmetry, and in the direction opposite to that of the asymmetry, is reduced to 20% of rated if monitoring technique 1 is used, to 50% for the technique 2 and only to 95% for the technique 3.

Figures 11, 12, 13, 14, 15 and 16 refer to the flaps with irreversible actuators and show the simulations results for the cases of deploying (11, 12, 13) and retracting (14, 15, 16) surfaces in the final part of their stroke to the landing position under the maximum loads.

Each simulation is performed in the same way as for the corresponding one related to the reversible actuators.

As it could be expected, the maximum asymmetry between left and right surfaces with the irreversible actuators, and the resulting disturbances on the aircraft are much lower than for the reversible ones. The reason of this behaviour lies in the values assumed by the drag torques and efficiency losses in the actuator and shaft system, able to decelerate rapidly to a stop, without any backward acceleration, the flap surfaces downstream of the failure point (left surfaces).

The above mentioned considerations are particularly true for the monitoring techniques 1 and 2, while for the technique 3 further considerations are necessary. Such a technique performs an active asymmetry control and should thus be better than the other two. However for such a type of actuator it leads to a final asymmetry greater than that of the technique 2. The reason of that lies in the fact that an error of the opposite sign was assumed for the two position transducers in all the simulations. Therefore, the flap system control commands the healthy portion of the flap system to a position slightly different from that of the failed part because of the transducers errors, which are responsible of the same final asymmetry both in the case of the irreversible actuators and of the reversible ones. It must be noted that in the failure transients the asymmetry temporarily performed by the irreversible actuators system is lower than this given by the reversible one.

The following figures refer to different types of malfunctioning caused by the wingtip brakes failure (Figg. 17 and 18), irreversibility failure caused by structural vibrations (Figg. 19 e 20) and supply pressure drop (Figg. 21 and 22) without any asymmetry coming from a torsion tube failure.

Figures 17 and 18 show the simulation performed for the case of deploying flaps with reversible actuators in the final part of their stroke to the landing position under the maximum opposing loads.

In the simulation of Fig. 17 the wingtip brakes failure occurs at time = 0.7 s while the actuation system is running in a steady condition towards the commanded position; the failure event occurs when the hydraulic system is pressurized and the brakes disengaged, so the trouble cannot arise until the system is depressurized and the brakes engaged (time = 1.3 s approx.) as a consequence of the inability to keep the surfaces in a stop condition under the aerodynamic loads. When the surfaces start moving inadvertantly from the commanded position, the specific monitoring technique provides a pressurization command (at time = 1.4 s approx.), preventing any subsequent hydraulic system depressurization. So the control actuation system is able to drive again and maintain the surfaces to the commanded position.

In the simulation of Fig. 18 the wingtip brakes failure occurs at time = 2.0 s while the actuation system is in a stop condition, the hydraulic control system depressurized and the brakes engaged: the trouble is quickly evident in form of inadvertent surface movements under the aerodynamic loads. The same monitoring technique as before provides a pressurization command (at time = 2.15 s approx.), preventing any subsequent hydraulic system depressurization and the control system actuation drives again and maintains the surfaces to the commanded position.

Figures 19 and 20 show the simulation performed for the case of deploying flaps with irreversible actuators in the final part of their stroke to the landing position under the maximum opposing loads.

In the simulation of Fig. 19 the irreversibility failure occurs at time = 1.0 s while the actuation system is running in a steady condition towards the commanded position; the failure event occurs when the hydraulic system is pressurized, so the trouble cannot arise until the system is depressurized (time = 1.2 s approx.) as a consequence of the inability to keep the surfaces in a stop condition under the aerodynamic loads. When the surfaces start moving inadvertantly from the commanded position, the specific monitoring technique provides a pressurization command (at time = 1.37 s approx.), preventing any subsequent hydraulic system depressurization. So the control actuation system is able to drive again and maintain the surfaces to the commanded position.

In the simulation of Fig. 20 the irreversibility failure occurs at time = 2.0 s while the actuation system is in a stop condition, the hydraulic control system depressurized: the trouble is quickly evident in form of inadvertent surface movements under the aerodynamic loads. The same monitoring technique as before provides a pressurization command (at time = 2.20 s approx.), preventing any subsequent hydraulic system depressurization and the control system actuation drives again and maintains the surfaces to the commanded position.

Figure 21 refers to a malfunctioning caused by pressure drops in the hydraulic system without any asymmetry coming from a torsion tube failure and any brake failure; the simulation is performed for the case of deploying flaps with reversible actuators in the final part of their stroke to the landing position under the maximum opposing loads.

In this simulation the pressure drop (10 Mpa) below the value critical (14 Mpa) for the correct operation of the flap system occurs at time = 1.0 s while the actuation system is running in a steady condition towards the commanded position. By means of a specific monitoring technique the growth of a counter is commanded; because this condition persists for more than a given amount of time, the counter reaches a threshold value and a system shutdown is performed. The aerodinamyc loads backdrive the system, till to the engage of the wingtip brakes produced by the drop of the supply pressure below the critical value. The trouble persists till to time = 2.5 s, followed by a supply pressure growth to the correct value (26 Mpa). The monitoring system, programmed to attempt periodical re-engages of the system (each 1 s), performs two restart attempts: the former (at time = 2.0 s) fails, whereas the latter, following the pressure growth, re-engages the system reaching the commanded position.

Figure 22 refers to the same malfunctioning reported in Fig. 21in the case of irreversible actuators.

The simulation history is quite similar to figure 21, except for the effects of the aerodynamic loads, which are no longer able to backdrive the system, rapidly decelerating to a stop.

Conclusions

The results of the present work show the high sensitivity of the aircraft controllability to the monitoring technique used to detect flaps asymmetries.

The simulations reported in figures 5 to 16 refer to the case of asymmetries of the flaps because they are more critical than the asymmetries of the slats; however similar, thought less critical, results can be obtained if a mechanical failure of the slat transmission shaft system is considered.

It has been shown that the aircraft control during the transient of the developing flaps asymmetry and in the following asymmetric flaps condition can be greatly improved by using non conventional monitoring techniques. These more sophisticated monitoring techniques do not necessarily require additional sensors, but can generally be implemented by making an appropriate use of the existing information.

The malfunctioning caused by the wingtip brakes failure (figures 17 and 18), by the irreversibility failure following structural vibrations (figures 19 and 20) and by the supply pressure drop (figures 21 and 22) without asymmetries are all maintained within acceptable values by the specific monitoring technique.

List of symbols

BLG Ballscrew actuator backlash
BLPT Position transducer backlash
BS Ballscrew actuator
BSN Ballscrew actuator with built-in irreversibility brake
CTT Critical torsion tube
DThSL Left flap angular rate
DThM Motor angular rate
FFM Motor Coulomb friction torque
FFPT Position transducer Coulomb friction torque
FFS Surface and actuator Coulomb friction torque

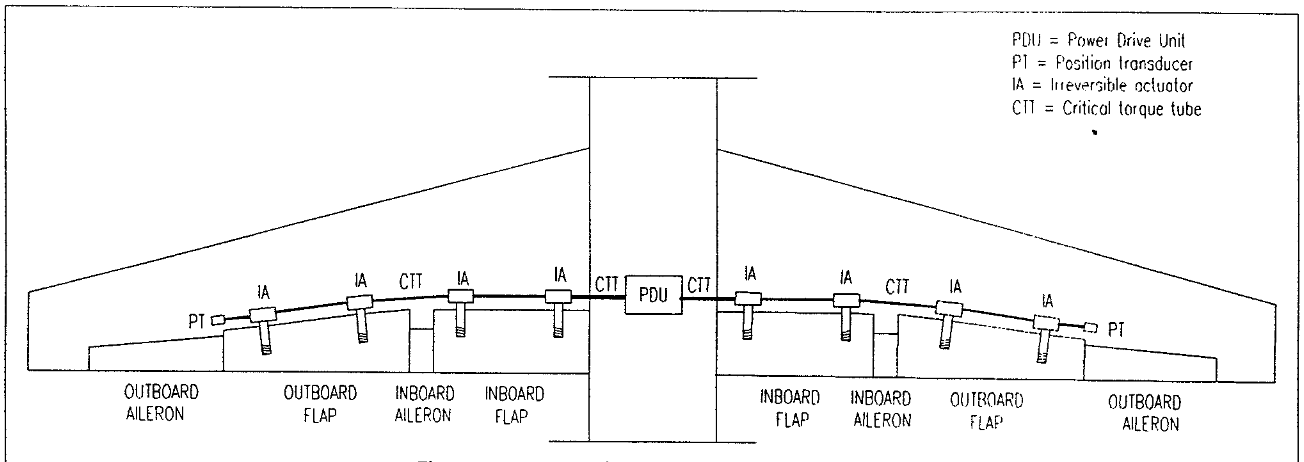

Fig. 1 – Irreversible actuator architecture

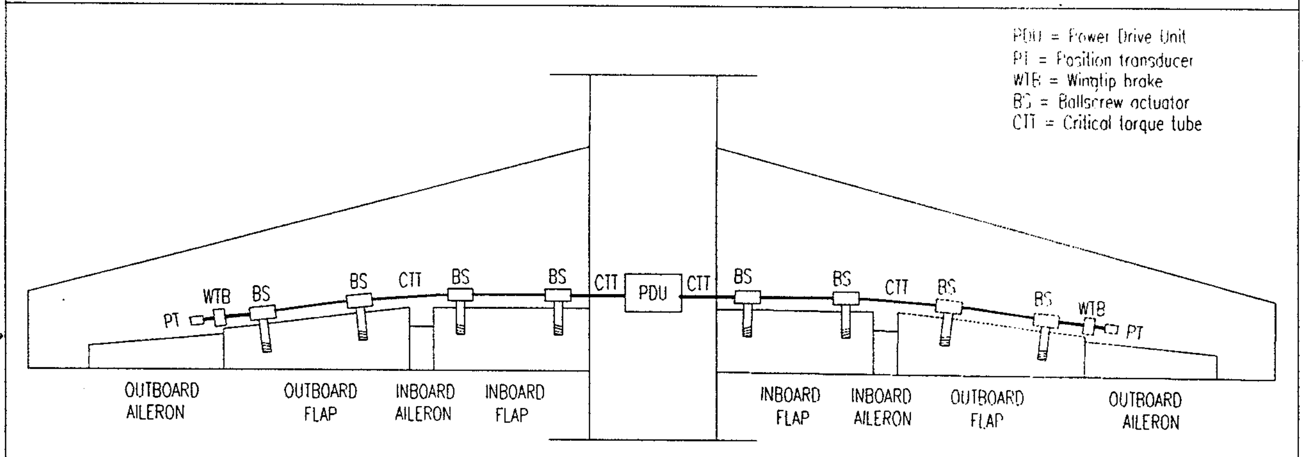

Fig. 2 – Wingtip brakes architecture

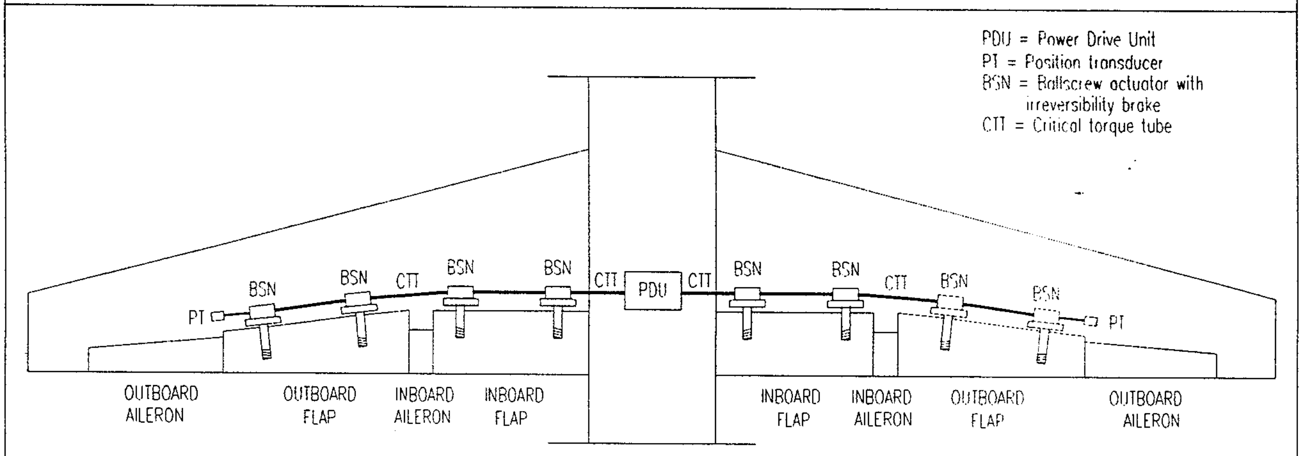

Fig. 3 – Irreversibility brakes architecture

K1G Torsion bar stiffness
K2G Ballscrew actuator stiffness
PDU Power Drive Unit
PSV Servovalve supply pressure
PT Position transducer
RoA Aircraft roll angle
ThA Angle of command for the ailerons
ThSL Left flap position
ThSR Right flap position
WTB Wingtip brake
ZM Motor gear reducer
ZS Actuator gear reducer

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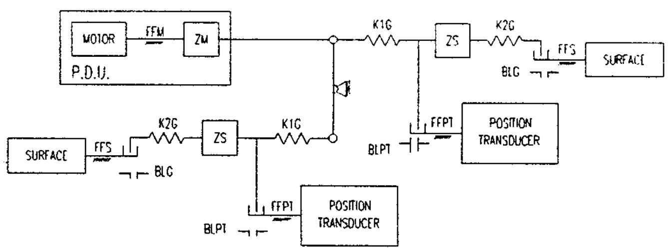

Figure 4 - Actuation system mechanical model

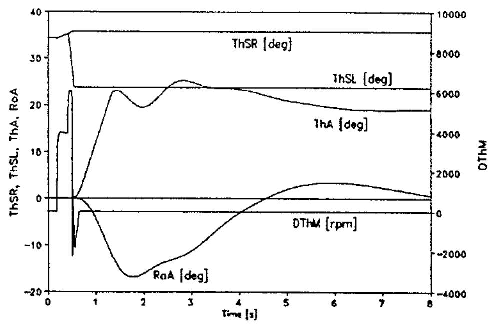

Figure 5 - Flaps deployment under high loads - Reversible actuators - Asymmetry monitoring technique 1

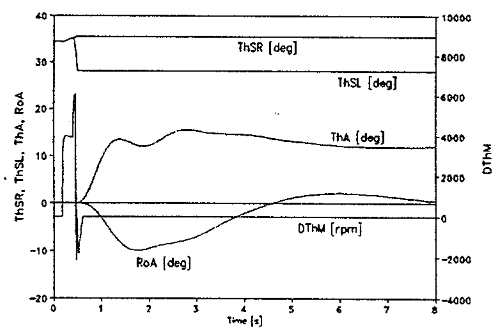

Figure 6 - Flaps deployment under high loads - Reversible actuators - Asymmetry monitoring technique 2

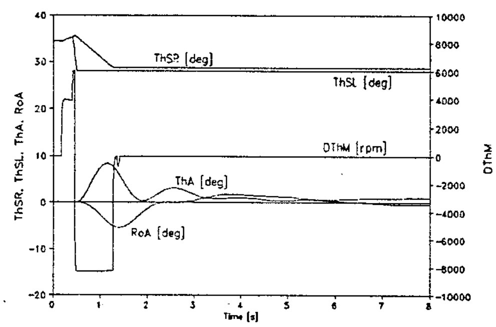

Figure 7 - Flaps deployment under high loads - Reversible actuators - Asymmetry monitoring technique 3

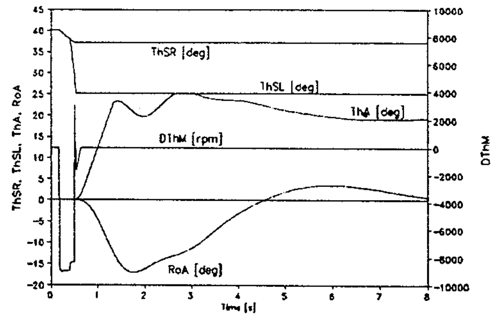

Figure 8 - Flaps retraction under high loads - Reversible actuators - Asymmetry monitoring technique 1

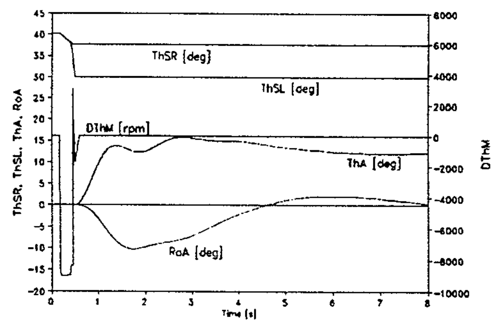

Figure 9 - Flaps retraction under high loads - Reversible actuators - Asymmetry monitoring technique 2

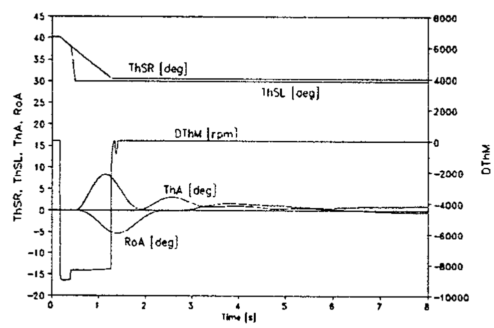

Figure 10 - Flaps retraction under high loads - Reversible actuators - Asymmetry monitoring technique 3

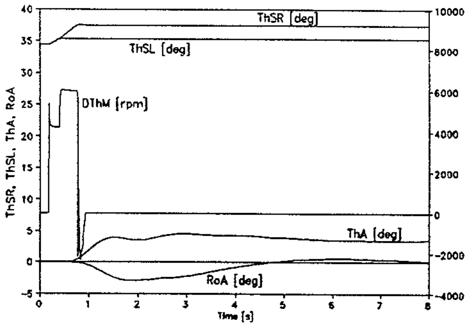

Figure 11 - Flaps deployment under high loads - Irreversible actuators - Asymmetry monitoring technique 1

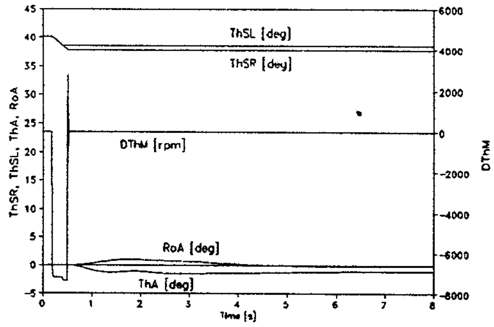

Figure 14 - Flaps retraction under high loads - Irreversible actuators - Asymmetry monitoring technique 1

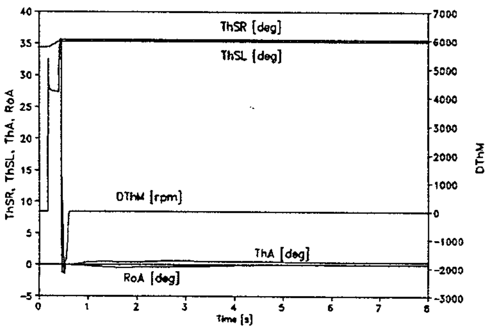

Figure 12 - Flaps deployment under high loads - Irreversible actuators - Asymmetry monitoring technique 2

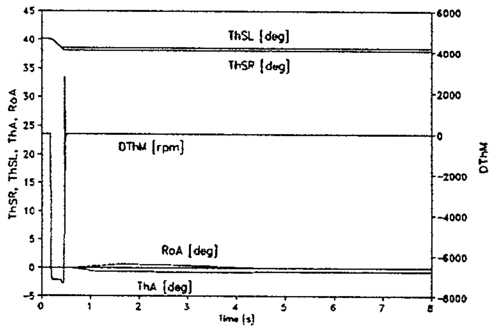

Figure 15 - Flaps retraction under high loads - Irreversible actuators - Asymmetry monitoring technique 2

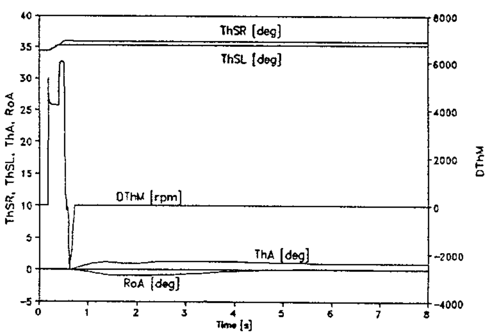

Figure 13 - Flaps deployment under high loads - Irreversible actuators - Asymmetry monitoring technique 3

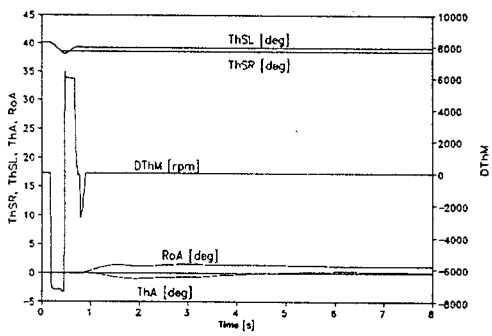

Figure 16 - Flaps retraction under high loads - Irreversible actuators - Asymmetry monitoring technique 3

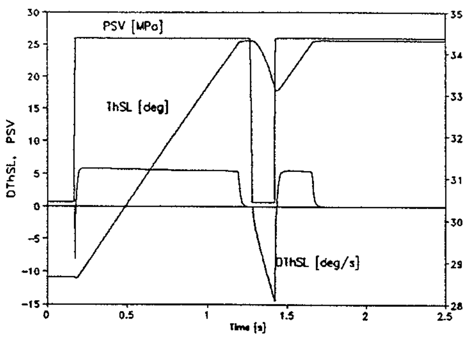

Figure 17 - Flaps deployment under low loads - Reversible actuators - Wingtip brakes failure during the actuation

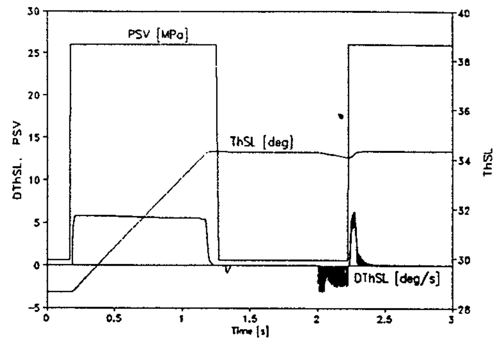

Figure 20 - Flaps deployment under low loads - Irreversible actuators - Loss of irreversibility at the end of the actuation

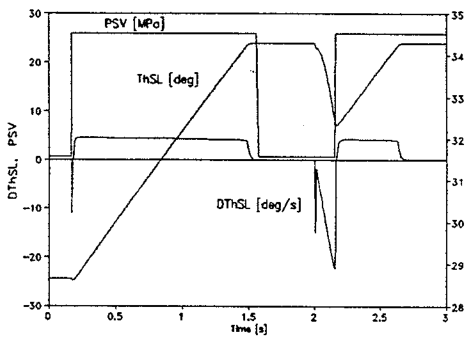

Figure 18 - Flaps deployment under high loads - Reversible actuators - Wingtip brakes failure at the end of the actuation

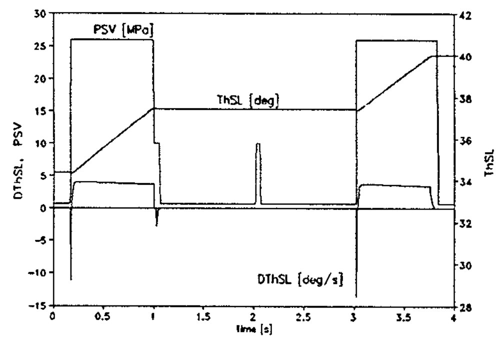

Figure 21 - Flaps deployment under high loads - Reversible actuators - Supply pressure drop

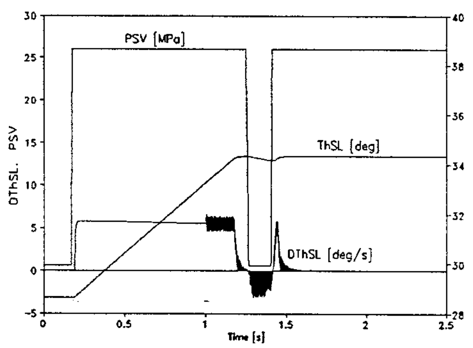

Figure 19 - Flaps deployment under low loads - Irreversible actuators - Loss of irreversibility during the actuation

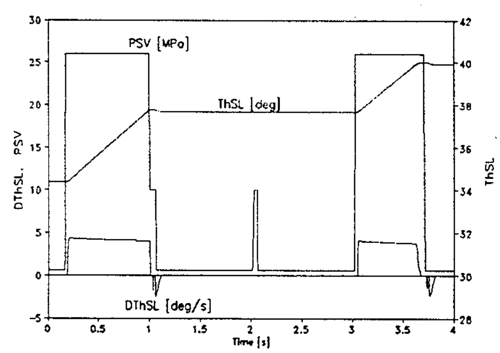

Figure 22 - Flaps deployment under high loads - Irreversible actuators - Supply pressure drop