SECONDARY FLIGHT CONTROLS: MECHANICAL FAILURES OF TRANSMISSION LINES AND RELATED ASYMMETRY PROBLEMS

G. JACAZIO, Department of Mechanics - Politecnico di Torino, Italy
L. BORELLO, G. VILLERO, Department of Aerospace Engineering - Politecnico di Torino, Italy

Abstract

This work analyses three typical asymmetry monitoring softwares for flap (and slat) control systems and compares their performances. The monitoring mathematical models and the related simulation computer program of a typical control system under a transmission failure 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 control strategies on the maximum asymmetry in failure conditions.
Some simulations of the control system and airplane behaviour with and without the mentioned failures have been performed.
The conclusions remark the high sensitivity of the failure behaviour of the secondary flight control systems (either in transient or in steady condition) and of the airplane to the employed monitoring model.

Introduction

The flap and slat 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 or slat 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 to the right and left wing actuators (Fig. 1 and 2); 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 and several slat actuators are of a rotary type.
Whichever the actual configuration of the flap (or slat) actuation system is, the limitation of the asymmetry between the left and right wing flaps (or slats) 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 (or slats) surfaces, which may become 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). If the PDU fails, the mechanical power cannot be transmitted any longer to the shaft system, that eventually stops. A failure of one actuator leads to a jam of the surfaces and thus to a system standstill. Therefore, in both these cases a mechanical failure results in the inability to operate the affected flap or slat 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 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, 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 aerodynamic 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 the actuation system can be equipped either with wingtip brakes (Fig. 1) or irreversibility brakes (Fig. 2) that become engaged and brake the system after a failure has been positively recognized.
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 tran-

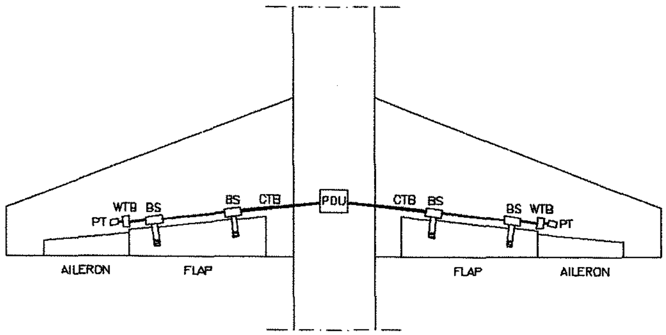

Fig. 1 Wingtip brakes actuation system architecture

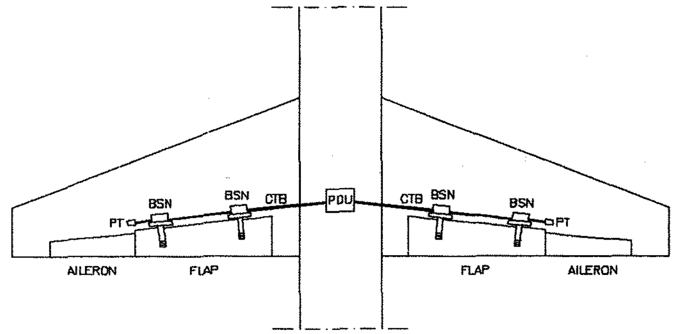

Fig. 2 Irreversibility brakes actuation system architecture

sducers (Fig. 1);
- irreversibility brakes within each actuator, wich self engage when the actuator output overruns the input shaft (Fig. 2).

Aims of the work

The relative merits of the two solutions (non-reversible actuators or reversible actuators with wingtip brakes) and which of the two is better is a long debated matter. Since the purpose of this paper is to evaluate the effects of different control strategies on the maximum asymmetry in failure conditions and the wingtip brake solution is giving rise to a greater asymmetry, this solution will be considered in the following of this paper.
Whichever design solution is taken (non-reversible actuators or wingtip brakes), an asymmetry between the surfaces upstream and downstream of the failure develops as long as the PDU is running and wingtip brakes, if present, are not engaged. This developing asymmetry must be detected and a corrective action taken in order to limit its maximum value to a safe limit.

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 asym-

metry, 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 or slat 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 techinque 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 anologue 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 (or slat) 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.

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 ans slats actuation (Fig. 1). The schematic of such actuation system is

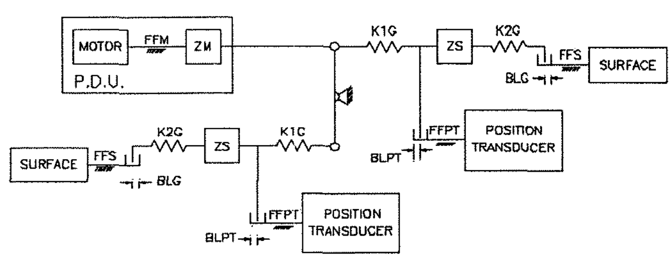

Fig. 3 Actuation system mechanical model

shown in Fig. 3. 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. 3 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 [8],
- 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.

Aircraft and autopilot modelling

In order to assess the amount of perturbations induced on the aircraft attitude by the failures of the flap (or slat) 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 has options for the three different asymmetry monitoring techniques described in this paper, so to evaluate their effectiveness in limiting the aircraft disturbances after an asymmetry has occurred.

In order to validate the computer code, a few simulations have first been run under maximum asymmetric loading of the flap surfaces but without any failure, and considering the three different asymmetry monitoring techniques. None of the asymmetry monitoring techniques leds to a nuisance system disconnection and the simulation results for all the three cases were thus equal, which are reported in Fig. 4. In this figure XS is the spool position, DThM is the motor speed, ThSL and ThSR are the left and right flaps positions. In the simulation of Fig. 4 the antisymmetric loading is applied as a step at time equal to 0.1 s. As such a load is applied a small variation of the speed occurs as a result of the non unity efficiency of the actuation system.

After having verified the system behaviour under extreme, albeit correct, operating conditions, several simulations ha-

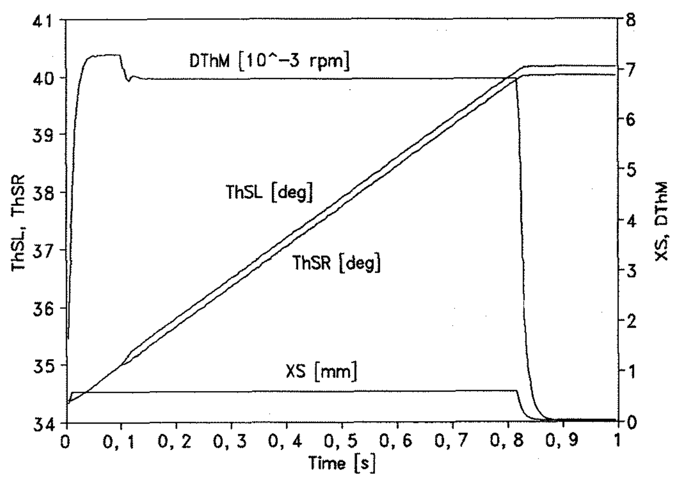

Fig 4 - Flaps deployment under maximum asymmetric loading without failure

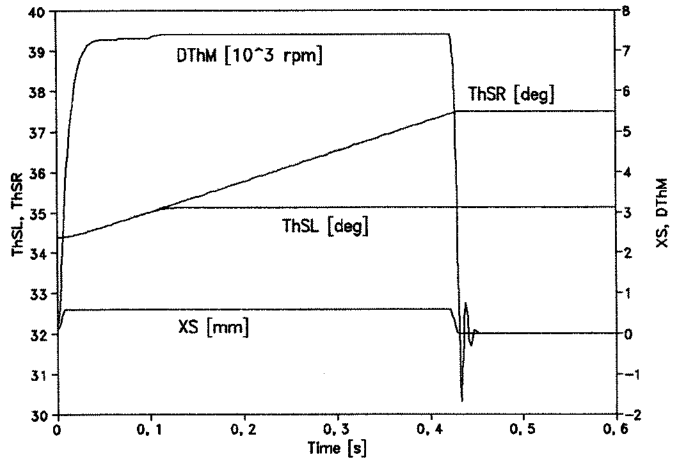

Fig. 5a - Flaps deployment with failure under low loads
Monitoring technique 1 - System behaviour

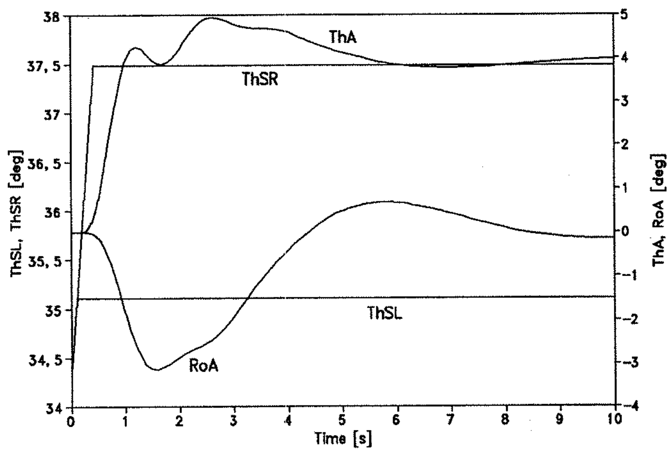

Fig. 5b - Flaps deployment with failure under low loads
Monitoring technique 1 - Aircraft behaviour

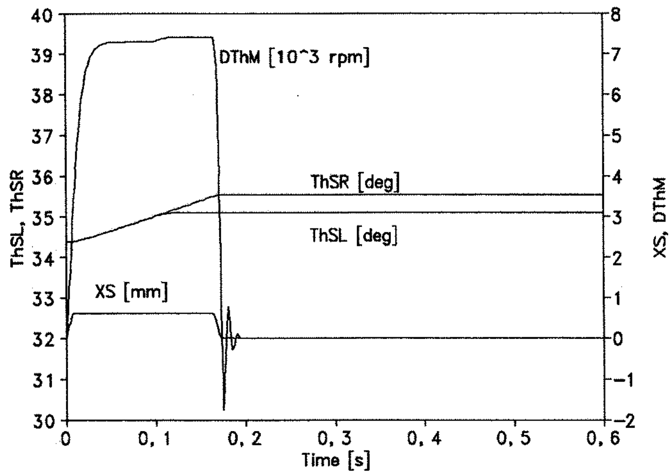

Fig. 6a - Flaps deployment with failure under low loads
Monitoring technique 2 - System behaviour

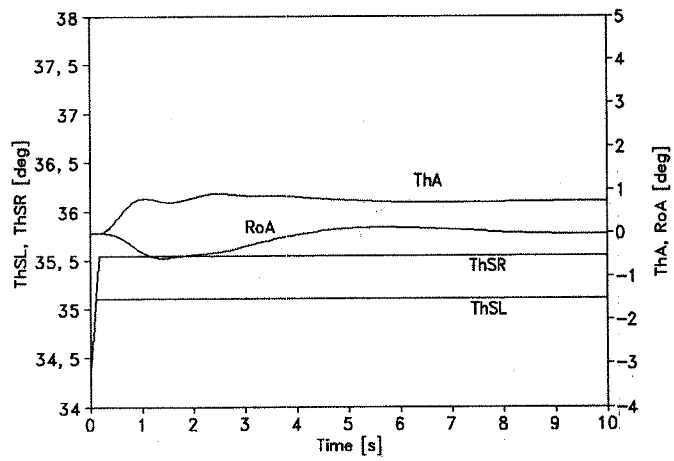

Fig. 6b - Flaps deployment with failure under low loads
Monitoring techinque 2 - Aircraft behaviour

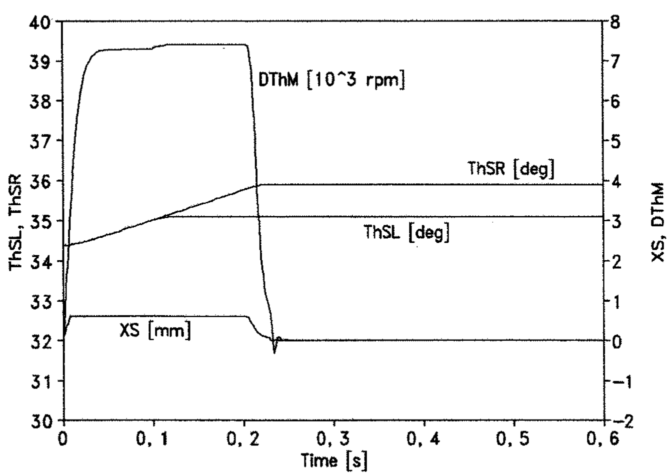

Fig. 7a - Flaps deployment with failure under low loads
Monitoring technique 3 - System behaviour

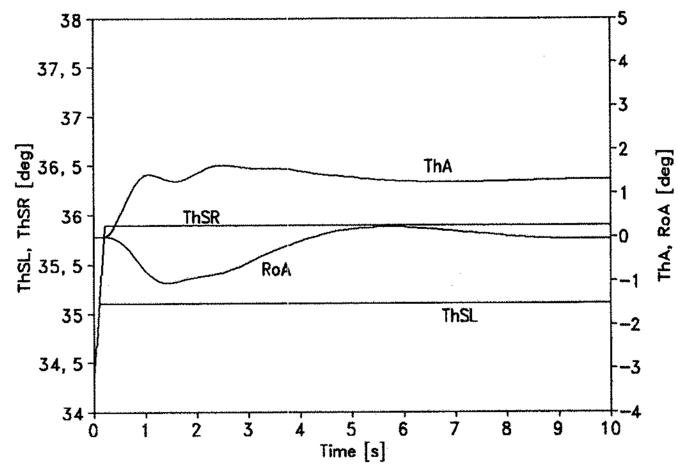

Fig. 7b - Flaps deployment with failure under low loads
Monitoring technique 3 - Aircraft behaviour

ve been run for the case of a mechanical failure of the transmission shaft with a resulting asymmetry between right and left surfaces. Figures 5a, 6a, 7a show the simulation results for the cases of deploying flaps in the final part of their stroke and for a low loading condition, considering the monitoring techniques 1, 2 and 3. For all the simulations the transmission shaft failure occurs at time = 0.1 s, while the actuation system is running at the rated speed. For this case of failure in low loading conditions the drag torques and efficiency losses in the actuator and shaft system are such that the flap surfaces downstream of the failure point (left surfaces) decelerate to a stop before the wingtip brake is engaged. As it can be expected, the asymmetry monitoring routine 2 (Fig. 6a) allows a faster detection of the developing asymmetry and thus leads to a lower final asymmetry then monitoring routine 1 (Fig. 5a). 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 7a 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 should thus be better than the other two. However for such a low loading case it leads to a final asymmetry greater than that of the first two cases. 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.

The effects of the asymmetry monitoring techniques on the aircraft attitude are shown in Figures 5b, 6b and 7b. In these figures ThA is the deflection angle of the ailerons, while RoA is the aircraft roll angle. It can be seen from the same figures 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 to monitoring technique 2, while it slightly increases for monitoring technique 3 for the reasons outlined before.

Figures 8a, 9a and 10a show the deployment of the flaps 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.

Also in these simulations the transmission shaft failure was assumed to take place at time = 0.1 s, while the flap actuation system runs at its rated speed. 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 could be expected, the maximum asymmetry between left and right surfaces, and the resulting disturbances on the aircraft (Figures 8b, 9b and 10b) are much greater than for the previous case of low aerodynamic loads. In this case of large loads and resulting asymmetries following a failure the benefits of monitoring technique 3 over 2 and 1 are clearly evident. In particular, it can be seen from Fig. 8b that if a shaft failure occurs in these conditions and the monitoring technique 1 is used, the flap asymmetry is such to create a rolling moment on the aircraft that cannot be any longer balanced by the ailerons and the aircraft control is then lost. Should this actually occur, a catastrophic condition is originated. It must however be pointed out that since the purpose of this paper was the evaluation of the relative merits of different asymmetry monitoring techniques, the values of all aircraft and system parameters used for the simulation, though corresponding to possible actual values, were taken such to maximize the aircraft disturbances following a flap asymmetry. The actual aircraft behaviour may not be that bad; it is in fact known that existing aircraft using an asymmetry monitoring technique 1 maintain a sufficient lateral-directional control after an asymmetry develops following a transmission shaft failure. Moreover, if noback devices are used in place of the wingtip brakes, 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 11a, 11b, 12a, 12b, 13a and 13b 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 = 0.1 s, while the actuation system is running in a steady condition. 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 8a, 8b, 9a, 9b, 10a and 10b, the monitoring techniques 2 and 3 provide a faster response and a final lower asymmetry with a resulting lower rolling perturbation of the aircraft.

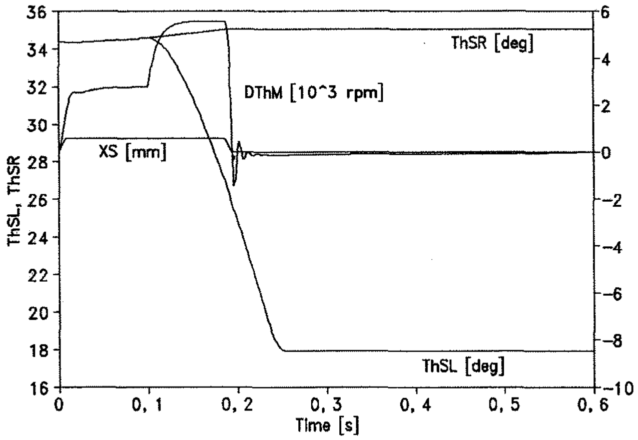

Fig. 8a - Flaps deployment with failure under maximum loads
Monitoring technique 1 - System behaviour

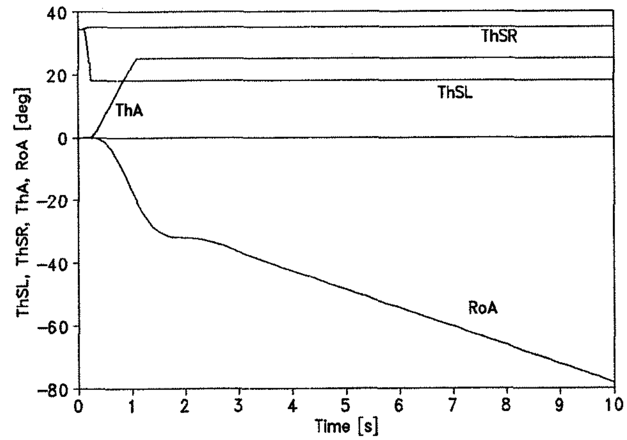

Fig. 8b - Flaps deployment with failure under maximum loads
Monitoring technique 1 - Aircraft behaviour

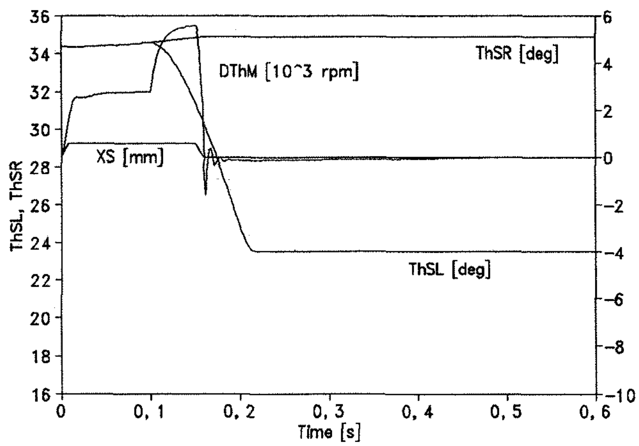

Fig. 9a - Flaps deployment with failure under maximum loads
Monitoring technique 2 - System behaviour

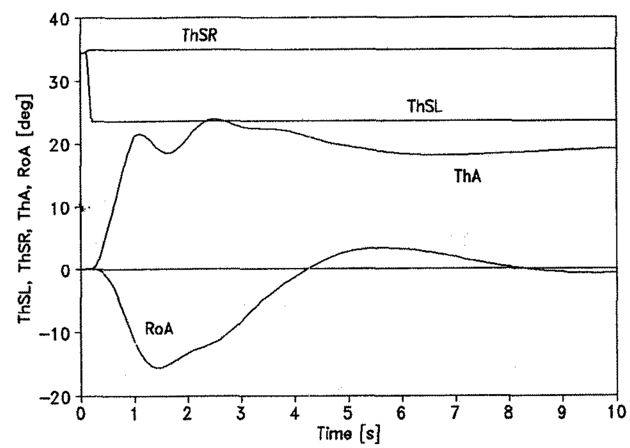

Fig. 9b - Flaps deployment with failure under maximum loads
Monitoring technique 2 - Aircraft behaviour

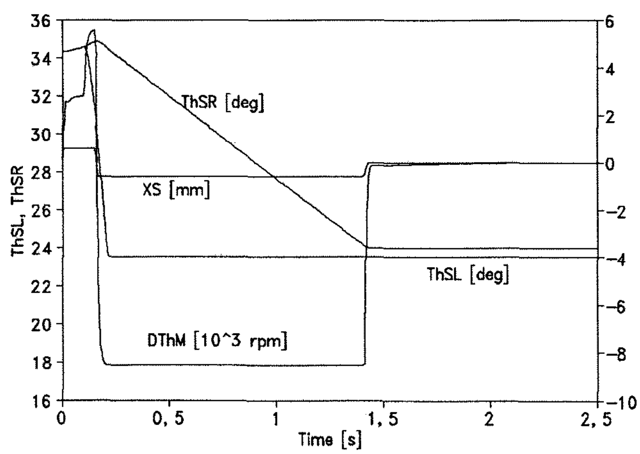

Fig. 10a - Flaps deployment with failure under maximum loads
Monitoring technique 3 - System behaviour

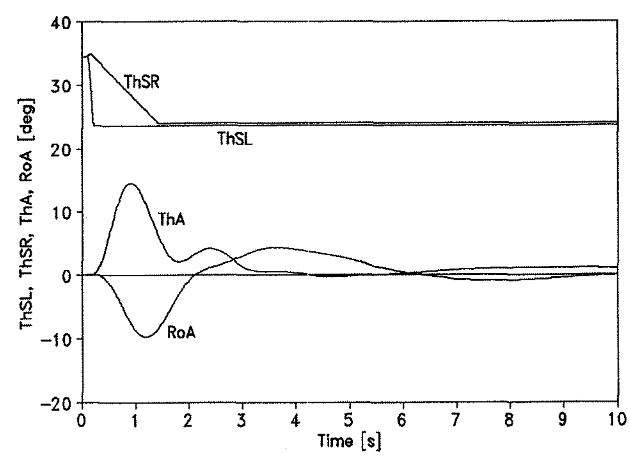

Fig. 10b - Flaps deployment with failure under maximum loads
Monitoring technique 3 - Aircraft behaviour

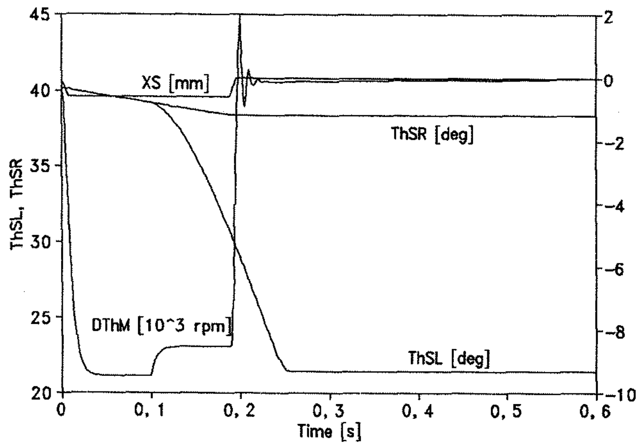

Fig. 11a - Flaps retraction with failure under maximum loads
Monitoring technique 1 - System behaviour

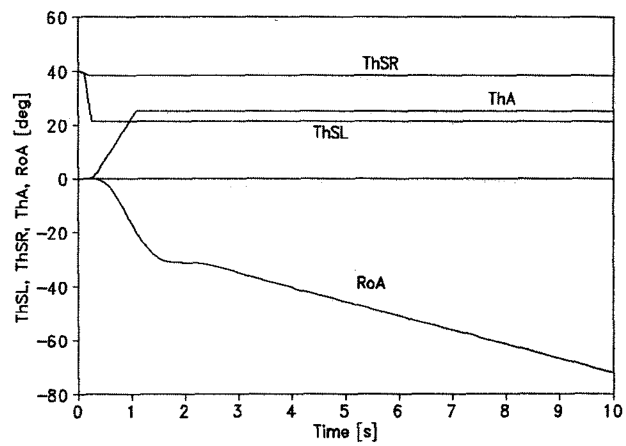

Fig. 11b - Flaps retraction with failure under maximum loads
Monitoring technique 1 - Aircraft behaviour

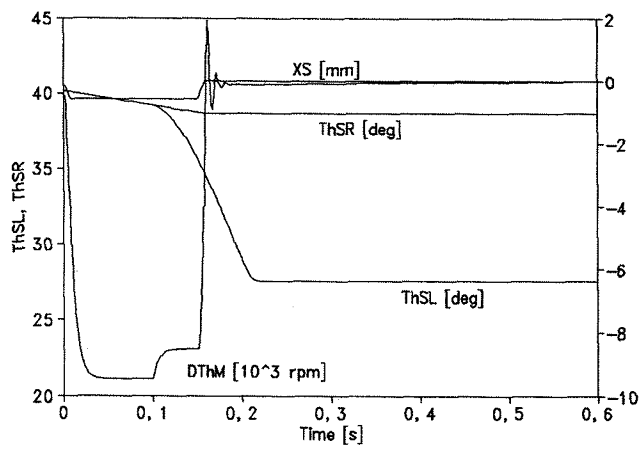

Fig. 12a - Flaps retraction with failure under maximum loads
Monitoring technique 2 - System behaviour

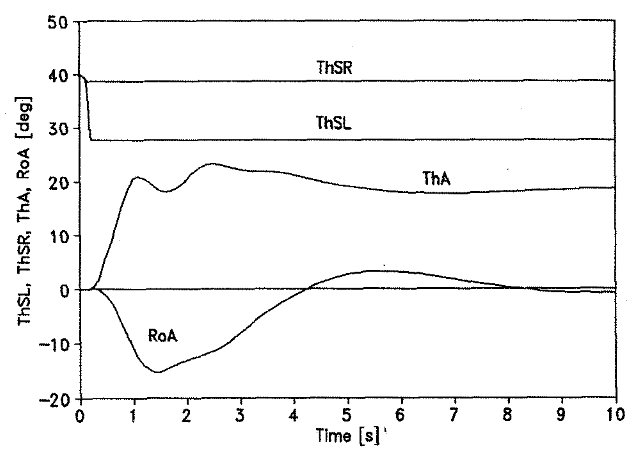

Fig. 12b - Flaps retraction with failure under maximum loads
Monitoring technique 2 - Aircraft behaviour

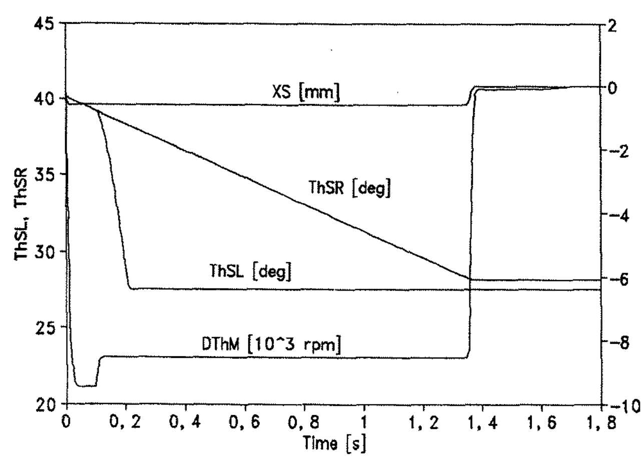

Fig. 13a - Flaps retraction with failure under maximum loads
Monitoring technique 3 - System behaviour

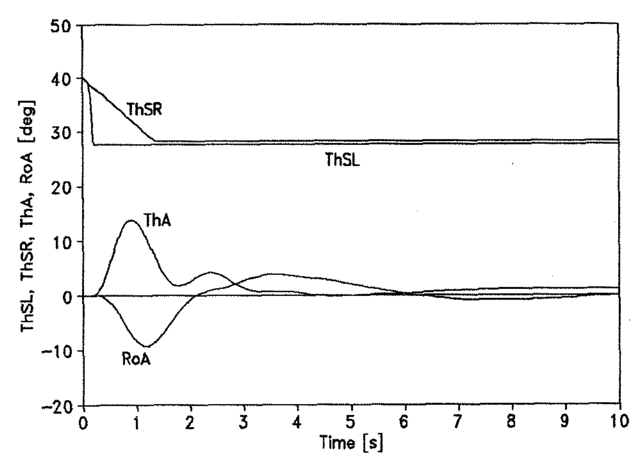

Fig. 13b - Flaps retraction with failure under maximum loads
Monitoring technique 3 - Aircraft behaviour

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 overcomes the maximum rolling moment obtainable by the ailerons and the aircraft control is lost. If monitoring technique 2 is used 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 17% of rated if monitoring technique 2 is used but only to 94% of rated if monitoring technique 3 is used.

Conclusions

The results of the present work show the high sensitivity of the aircraft controllability to the monitoring technique used to detect flaps (or slats) asymmetries. The simulations reported in this work all 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.

List of symbols

BLG Ballscrew actuator backlash
BLPT Position transducer backlash
BS Ballscrew actuator
BSN Ballscrew actuator with built-in irreversibility brake
CTB Critical torsion bar
DThM Motor speed
FFM Motor Coulomb friction torque
FFPT Position transducer Coulomb friction torque
FFS Surface and actuator Coulomb friction torque
K1G Torsion bar stiffness
K2G Ballscrew actuator stiffness
PDU Power Drive Unit
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
XS Servovalve spool position
ZM Motor gear reducer
ZS Actuator gear reducer

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