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Flap failure and aircraft controllability: Developments in asymmetry monitoring techniques †

Lorenzo Borello, Giuseppe Villero and Matteo D. L. Dalla Vedova*

Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

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Abstract

The asymmetry limitation between left and right wing flap surfaces is one of the most severe requirements for the design of the actuation and control system. When the position asymmetry exceeds a defined value, it must be detected and limited by appropriate monitoring devices equipped with a suitable software. In the design of a new flap control system the development of the asymmetry monitoring subsystem plays a very important role and, together with the flap system layout selection, it was and still is a debated matter in the industry. The currently used monitoring technique is based on differential position detection between left and right surfaces. Their use generally slightly reduces the asymmetry, but in some cases it may have an unreliable behavior. To overcome the shortcomings of the previous models, we propose new and different monitoring strategies and assess their positive effects on the maximum asymmetry following a torque tube failure; in particular, the asymmetry reduction coming from the employment of the proposed techniques in the considered operative conditions (typical deployment / retraction flap actuations), with respect to a previous type of technique, can be evaluated in the order of 30%.

Keywords: Aircraft controllability; Asymmetry monitoring techniques; Flap actuation system

1. Introduction

The flap actuation systems of today's high technology aircraft generally consist of a centrally located Power Drive Unit (PDU) controlled by a Power Control Unit (PCU), a shaft system and a certain number of actuators (normally two for each flap surface). Several different configurations have been used in the design of these actuation systems (as shown in Figs. 1-3), as a consequence of the performance and reliability requirements and of the specified interface with the other aircraft systems and structure (PDU either hydromechanical or electromechanical, each characterized by single or dual motor; in the latter case the outputs of the two motors can be torque summed or speed summed). The shaft system generally consists of torque tubes connecting the PDU output with right and left wing actuators; however, the flap actuation systems of small commercial aircraft often use flexible drive shafts rotating at high speed instead of the medium speed rigid shafts. Normally, the actuators are linear and based on ballscrews, though some flap actuators use an ACME screw and others are of a rotary type. The asymmetry limitation between left and right wing flaps is one of the most severe requirements for the design of the actuation and control system, regardless of the actual configuration of the flap actuation system.

In normal operating conditions the actual asymmetry between right and 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 (backlash lower than 0.05%, deflection lower than 0.5%) of the full travel. However, if a fracture occurs in the mechanical transmission, an increasing asymmetry builds up between left and right flaps surfaces, which may become excessive and flight safety critical without an appropriate corrective action. A mechanical failure may occur in any component of the actuation system (shafts, PDU, actuators), but only the shaft failure must be considered potentially safety critical because it involves large asymmetries between left and right surfaces, resulting in an eventually uncontrolled roll-rate and sideslip of the aircraft; the other types of failure only result in the inability to operate the affected flap system without any effect on the system symmetry. If a shaft failure occurs, the part of the actuation system upstream the fracture point keeps rotating with the PDU in the commanded direction until a shutoff command is not given to the PDU, while the portion of the shaft system downstream the fracture point exhibits different behaviors, under the action of the aerodynamic load aiming to drive it in the retraction mode:

*Corresponding author. Tel.: +39 0110906850, Fax.: +39 0110906899
E-mail address: matteo.dallavedova@polito.it; matteodv@yahoo.it
† Recommended by Associate Editor Kyeongsik Woo

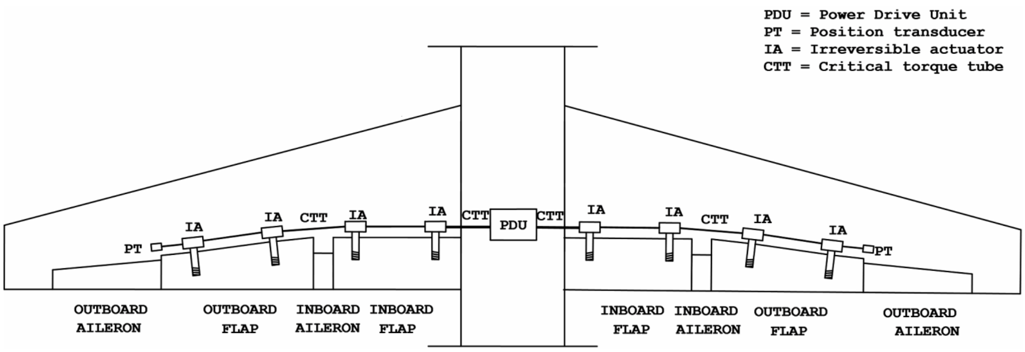

Fig. 1. Irreversible actuator architecture.

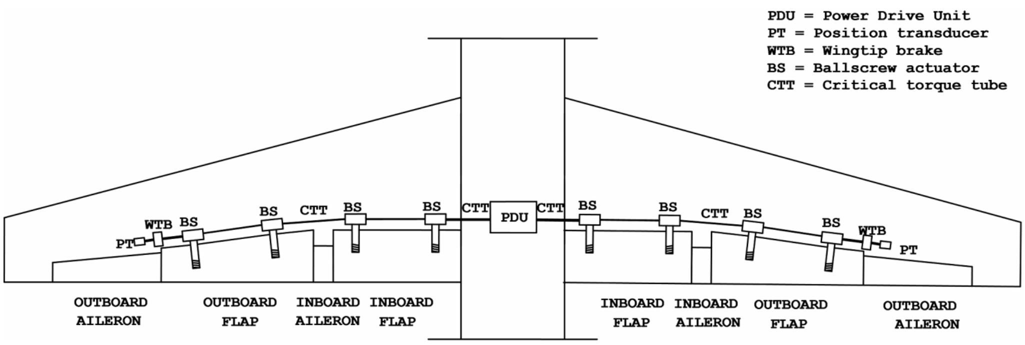

Fig. 2. Wingtip brake architecture.

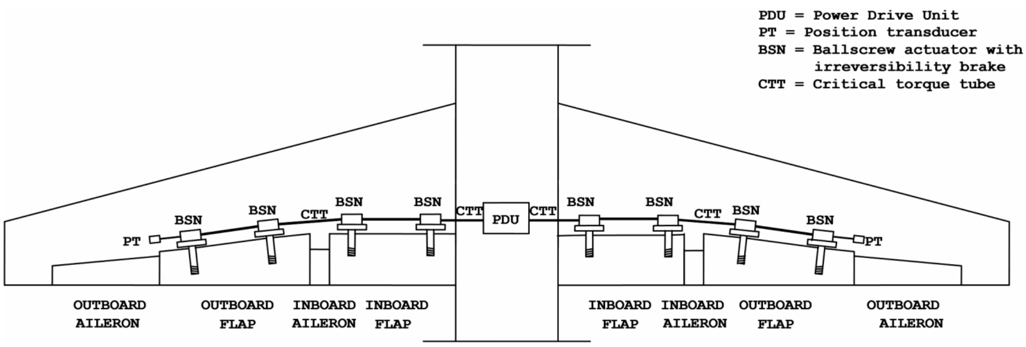

Fig. 3. Irreversibility brake architecture.

- If the actuators are non-reversible (Fig. 1), this part of the system performs high deceleration followed by a standstill, because the aerodynamic load cannot back-drive 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 load can develop high acceleration in retracting the failed part of the actuation system. In this case the stop of the uncontrolled surfaces can only be obtained by means of 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, that become engaged by an appropriate corrective action 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.

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 more suitable are long controversial topics: the wingtip brake solution exhibits a greater maximum asymmetry in failure conditions, the solution with non-reversible actuators requires higher hydraulic power because of its lower efficiency and the irreversibility brakes solution, which overcomes the shortcomings of the two previous solutions, is more expensive. Note that the wing tip brakes are expensive units and whether they offer a cost advantage or not depends on several factors and cannot be taken for granted. Furthermore, the wing tip brakes solution easily performs the pre-flight checks to verify their correct operation, which is very complex if non-reversible actuators or irreversibility brakes are employed.

Therefore, reversible actuators with wingtip brakes and centrally located PDU (of a dual motor type for operational reliability) represent the most commonly used architecture for high-medium performance aircraft as a consequence of its cost-effectiveness and, mainly, simplicity in performing pre-flight checks (nevertheless the associated high asymmetries in failure conditions), whereas irreversible actuators (nevertheless the associated lower efficiencies) are the most commonly used architecture for low-medium performance aircraft and irreversibility brakes are generally used in combat aircrafts to prevent the otherwise extremely high accelerations involving the failed part of the mechanical subsystem. Whichever design solution is taken, an asymmetry between the surfaces upstream and downstream 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 to keep its maximum value within a safe limit by means of appropriate monitoring devices equipped with suitable software.

Furthermore, a wingtip brake failure (Reversible actuators architecture), consisting of the inability to apply the proper brake torque to the transmission, particularly after a previous shaft failure, may lead to a flight safety critical condition.

It may occur when the irreversible actuators become 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 equipped with suitable software must be able to detect and properly correct the above-mentioned failures, or, at least, prevent undesired movements. Regarding the shaft failure (producing surface asymmetry) the usually employed monitoring technique is based on the differential position control between left and right surfaces, eventually implemented by lead-lag filter operating on differential position signal. The purpose of this filter is to produce a phase lead, acting in some way as future differential position sensor. Nevertheless, in the event of particularly severe conditions of high aerodynamic loads acting on the flaps (or slats), the above-mentioned technique may be unable to prevent potentially critical asymmetries; to limit these shortcomings we proposed and developed some innovative monitoring techniques in previous papers [1-4]. In comparison with the differential position control technique (asymmetry monitoring technique 1 shown in Ref. [4]), in similar initial conditions their use generally slightly reduces the asymmetry, but in some cases (particularly asymmetry monitoring technique 2 reported in Ref. [4]) may perform an unreliable behavior, producing a nuisance system shutdown or may require very complex monitoring logic to detect correctly the failed transmission portion (left or right) and consequently avoid wrong actions on the system.

2. Aims of work

To overcome the eventual shortcomings of the previous models, we developed and proposed new different monitoring strategies to limit flap (and slats) position asymmetries and assess their effects on the maximum asymmetry following a shaft failure. As the worst cases in terms of asymmetry criticality concern the behavior of the architecture based on reversible actuators and wingtip brakes, all the following considerations about the monitoring techniques are applied to this type of architecture.

3. Previously considered monitoring techniques

As reported in Refs. [1-4], six asymmetry monitoring techniques, characterized by increasing complexity and performances, were previously considered:

- Differential position control (asymmetry monitoring technique 1).
- Differential position and speed control (asymmetry monitoring technique 2).
- Differential position and speed conditioned control (asymmetry monitoring technique 2a).
- Differential dynamic position control (asymmetry monitoring technique 2b).
- Differential position and speed proportional conditioned control (asymmetry monitoring technique 2c).
- Differential position and speed variable conditioned control (asymmetry monitoring technique 2d).

The **differential position control technique** (hereafter referred as asymmetry monitoring technique **1**) performs the flap asymmetry detection by comparing the electrical signals of position transducers placed at the ends of left and right shaft subsystems (θ_{EL} and $\theta_{ER,}$ respectively). If a difference greater than a defined limit $\Delta\theta_E$ 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 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. Practically, it is based on a counter IWrn which increases or decreases with a defined time rate when the differential position $|\theta_{EL} - \theta_{ER}|$ exceeds or not a defined limit $\Delta\theta_E$ (threshold); the asymmetry is confirmed when the counter exceeds the given value, having so the required confirmation time. The selection of the proper values of asymmetry threshold and confirmation time affects the final value of the flap position asymmetry, as fully explained in Ref. [1].

The asymmetry monitoring technique 1 in the event of particularly severe conditions of high aerodynamic loads acting on the flaps (or slats) may be unable to detect with sufficient quickness the increasing asymmetry so giving rise to potentially critical flight conditions: indeed, the differential position threshold beyond which the asymmetry is recognized as well as the confirmation time cannot be selected too small in order to avoid nuisance system shutdown. If the final asymmetry in a flap system after a failure must be maintained within tight limits, more advanced monitoring techniques should be used.

The **differential position and speed control technique** (hereafter referred to as monitoring technique **2**) is based on detecting both position and speed differences of the two ends of the transmission. If either the position or the speed differential exceeds its established threshold for more than a given amount of time (by the use of a counter like technique 1), then an asymmetry is recognized and a system shutdown is performed in the same way of the formerly described differential position monitoring technique. This technique is faster in detecting rapid developing asymmetries since it recognizes an asymmetry as soon as right and left ends of the motion transmission exhibit a large speed difference. Thus, the system shutdown procedure can start much before the differential position threshold is reached, with a resulting lower final asymmetry. The measurement of the speed at the end of the transmission can be obtained either from a dedicated speed sensor or as a result of an algorithm that computes the speed as the time derivative of the position measured by the position sensor. In fact, the positions of the two ends of the motion transmission must always be measured and compared to each other to detect asymmetries which could develop 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, but additional sensors are not desirable for cost and reliability problems. 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 more noise sensitive, so the computed speed is less accurate and is provided with some delay to filter out the noise by means of some filtering technique. This partly hinders the quickness of this monitoring technique in detecting fast developing asymmetries and increases the workload of the computer. In general, the asymmetry monitoring technique 2 in the same starting conditions as technique 1 slightly reduces the asymmetry, but in some cases it may have an unreliable behavior producing a nuisance system shutdown. In fact, this monitoring technique detects an asymmetry when either the differential position or the differential speed overcomes its selected threshold and its confirmation time; for example, when the surfaces are subjected to antisymmetric sinusoidal loads or, in case of severe electrical noise regarding the signal lines, the differential speed threshold may persistently be exceeded without any overcoming of the differential position threshold, which is the only true confirmation of the failure condition. In some cases the same trouble may affect also the monitoring technique 1 equipped with a lead-lag filter. To overcome the shortcomings of the previous models, in previous works (Refs. [3, 4]) we proposed four new strategies, derived from the asymmetry monitoring technique 2 and so called 2a, 2b, 2c and 2d.

The **differential position and speed conditioned control monitoring technique** (Also called **2a**) employs the differential speed control just in order to give rise to a warning while only the differential position control is able to confirm the failure condition. It is based on a counter which increases or decreases with a defined time rate when either the differential position or speed exceeds or not an established limit (Threshold): if the only differential speed limit is exceeded, the counter is not able to reach the value beyond which the asymmetry is confirmed, but it is stopped at a slightly smaller value which can be overcome when the differential position threshold is exceeded, so attaining to the actual asymmetry confirmation.

The **differential dynamic position control monitoring technique** (Technique **2b**), marginally derived from the technique 2, employs the differential speed just in order to compute a differential dynamic position, obtained by the sum of the actual differential position with the product between the differential speed and a defined time value (which can be considered as a stopping characteristic time).

Consequently, the model is based on a counter which increases or decreases with a defined time rate when the differential dynamic position exceeds or not an established limit (Threshold). In this technique the selection of the stop characteristic time is critical, because a low value gives to the present technique the same behavior as technique 1, while a high value may cause the same drawbacks as technique 2.

The **differential position and speed proportional conditioned control monitoring technique** (**2c**) employs the differential speed control in the same way as the technique 2a, but it is based on a counter which increases or decreases when either the differential position or speed exceeds or not its respective thresholds with a time rate proportional to the differential speed. If the only differential speed limit is exceeded, the counter is not able to reach the value beyond which the asymmetry is confirmed, but it is stopped at a slightly smaller value which can be overcome when the differential position threshold is eventually exceeded, so attaining to the actual asymmetry confirmation.

The **differential position and speed variable conditioned control monitoring technique** (hereafter referred to as **2d**) is a particular case of the technique 2c: the difference consists of the employment of a counter increase or decrease based on a two levels time rate (not proportional like 2c) as a function of the differential speed.

4. Proposed monitoring techniques

To evaluate possible performance improvements of the previous monitoring techniques, in the present work the authors propose three new monitoring strategies, derived from the asymmetry monitoring technique 2 and so called 2e, 2f and 2g. The common difference between these new techniques and the previously considered ones consists of the employment, in some way, of the absolute speed of the left and right subsystems instead of the comparison of their speeds: when the speed characterizing the left or right subsystem exceeds a defined absolute (2e) or motor-dependent (2f and 2g) value, a specific counter is increased till to a limit above which the respective subsystem alert condition (not failure) is declared. The alert condition does not involve the immediate system shutoff (controlled by imposing $IAs = 1$), but only the specific subsystem stopping command through the engage of the related wingtip brake (actuated by imposing respectively *IAsL* or *IAsR* equal to 1). The complete system shutoff is only commanded as the differential position too exceeds its defined limit, as in the previous cases. All the proposed techniques are characterized by similar architectures (as shown in Fig. 4); the difference between the techniques 2e, 2f and 2g, evidenced in Fig. 4 as algorithms **Alg. #1** and **Alg. #2** (described later in this paragraph), consists of the evaluation method of the respective left or right subsystem speed, as described below. In fact, usually the direct measure of this speed is not performed, generally having no tachometer present on the two mechanical subsystems. The threshold values of the time counters shown in Fig. 4 ($IWrnC = 101$, $IWrn_{new} \geq 100$, $IWrnLC = 80$, $IWrnL_{new} \geq 50$, $IWrnRC = 80$, $IWrnR_{new} \geq 50$) are related to the corresponding monitoring algorithm sample value $\Delta T = 10^{-3}$ [s]. The above-mentioned threshold numerical values represent the number of computational steps required to confirm the failure event; having the computational step ΔT a defined value along the whole simulation run, the aforesaid number of steps is intended as a defined time-delay requested to confirm the failure[1].

The **differential position and absolute speed control asymmetry monitoring technique** (**2e**), as shown in Table 1, employs the absolute value of the surface angular rate obtained by the time derivation of the measured surface position θ_{EL} and θ_{ER}; when these values exceed a defined threshold $\dot{\theta}_{S0}$ the related time counters start evolving as reported above.

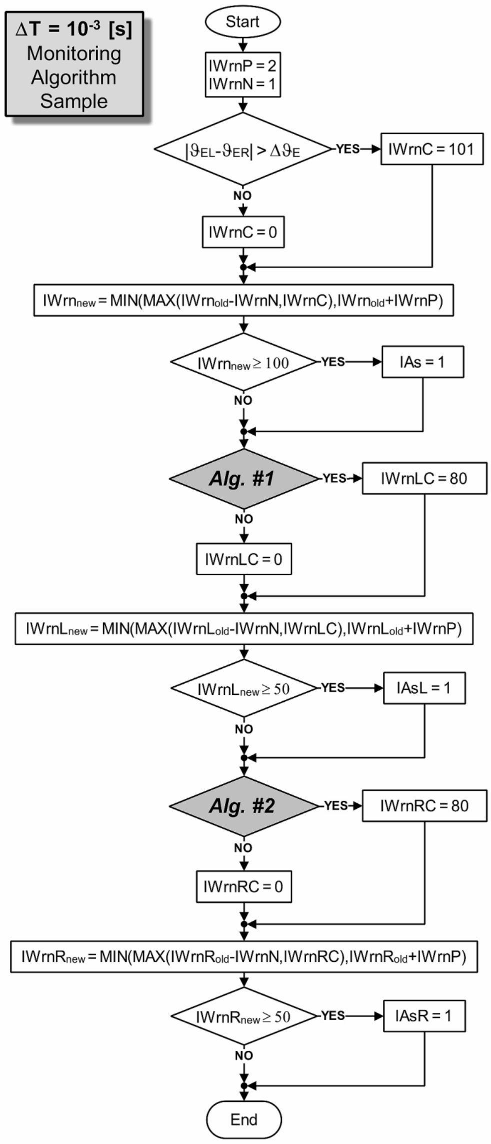

Fig. 4. General flowchart representative of the proposed monitoring techniques 2e, 2f and 2g.

The **differential position and motor referred speed control monitoring technique** (**2f**), as shown in Table 2, employs a differential angular rate again, consisting of the difference between the surface angular rate ($\dot{\theta}_{EL}$ or $\dot{\theta}_{ER}$ respectively) and the product of the hydraulic motor one $\dot{\theta}_M$ and the global gear ratio $ZM \cdot ZS$; if a defined threshold $\Delta\dot{\theta}_E$ is exceeded, the related time counter starts as above.

This technique requires the introduction of a tachometer (and related redundancies) connected to the hydraulic motor to measure the related angular rate; this may be considered as a shortcoming.

The **differential position and simulated motor referred speed control monitoring technique** (**2g**), as shown in Table 3, is similar to the technique 2f: in this case the 2f shortcoming is overcome by the employment of a functional model of the

1 The three statements reported in Fig. 4, giving the values of *IWrn*, *IWrnL* and *IWrnR*, are conceived to produce a progressive variation of the value itself at the increase (decrease) rate of *IWrnP* (*IWrnN*) in the sample time ΔT, pointing to the target value represented by *IWrnC*. For example when $|\theta_{EL} - \theta_{ER}| > \Delta\theta_E$ and *IWrnC* is consequently imposed equal to 101, *IWrn* increases its value of *IWrnP* at any sample till to 101; when $|\theta_{EL} - \theta_{ER}| \leq \Delta\theta_E$ and *IWrnC* is consequently imposed equal to 0, *IWrn* decreases its value of *IWrnN* at any sample till to 0. In this way, the persistent condition in which $|\theta_{EL} - \theta_{ER}| > \Delta\theta_E$ produces the failure declaration ($IAs = 1$), as *IWrn* reaches the value of 100, but, if the above reported condition is verified along a brief time interval (eventual noise or marked oscillations of the mechanical flap transmission), the possible increase of *IWrn* is quickly balanced by its following decrease till to 0, so statistically preventing the growth of *IWrn* till to its critical value of 100.

Table 1. Asymmetry monitoring techniques 2e: employed surface angular rate algorithms.

Alg. #1	$\lvert\dot{\theta}_{EL}\rvert > \dot{\theta}_{S0}$
Alg. #2	$\lvert\dot{\theta}_{ER}\rvert > \dot{\theta}_{S0}$

Table 2. Asymmetry monitoring techniques 2f: employed surface angular rate algorithms.

Alg. #1	$\lvert ZM \cdot ZS \cdot \dot{\theta}_M - \dot{\theta}_{EL}\rvert > \Delta\dot{\theta}_E$
Alg. #2	$\lvert ZM \cdot ZS \cdot \dot{\theta}_M - \dot{\theta}_{ER}\rvert > \Delta\dot{\theta}_E$

Table 3. Asymmetry monitoring techniques 2g: employed surface angular rate algorithms.

Alg. #1	$\lvert ZM \cdot ZS \cdot \dot{\theta}_{MC} - \dot{\theta}_{EL}\rvert > \Delta\dot{\theta}_E$
Alg. #2	$\lvert ZM \cdot ZS \cdot \dot{\theta}_{MC} - \dot{\theta}_{EL}\rvert > \Delta\dot{\theta}_E$

Table 4. Main merits and shortcomings of the proposed techniques.

Technique	Merits	Shortcomings
2e	It assures a significant reduction of the flap asymmetry if compared with 2a monitoring technique.	With respect to 2f and 2g, the 2e technique measures the absolute (not differential) flap angular rate and so requires higher thresholds involving delayed failure declaration.
2f	It assures slightly reduced asymmetry with respect to 2e monitoring technique.	It requests the introduction of a tachometer (and related redundancies) connected to the hydraulic motor in order to measure the angular rate.
2g	It assures similar performance with respect to 2f monitoring technique (if the thresholds are conveniently selected as a consequence of the manufacturing imperfections / load conditions).	It request the employment of a functional model of the servovalve and hydraulic motor assembly able to compute the motor angular rate θ ̇_MC as a function of the servovalve input current.

servovalve and hydraulic motor assembly able to compute the motor angular rate $\dot{\theta}_{MC}$ as a function of the servovalve input current through a first order nonlinear dynamic model. The computing process is performed having a hypothetic average value of load acting on the motor shaft, and this represents an uncertainty of the process, requiring an appropriately wide threshold value. Main merits and shortcomings of the three proposed techniques (2e, 2f and 2g), with respect to reference one (2a), are concisely shown in Table 4.

5. Aircraft numerical test-bench

The performances of the different asymmetry monitoring techniques have been tested by means of a numerical model simulating the dynamic behaviors of a complete aircraft: in particular, the authors conceived an integrated numerical model able to take into account the effects of the flap actuation system on the aircraft lateral-directional dynamics through the action of the autopilot.

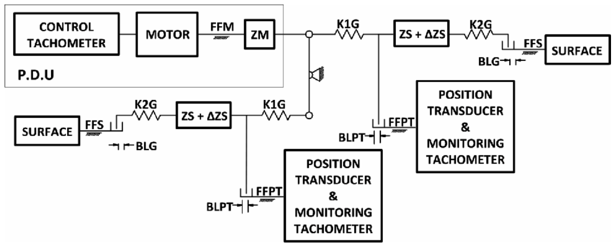

Fig. 5. Actuation system mechanical model.

5.1 Actuation system modelling

To compare the relative merits of the proposed asymmetry monitoring techniques, an actuation system was considered, typical of those currently used for flaps actuation (Fig. 2). The schematic of such actuation system is shown in Fig. 5.

The system consists of a power control and drive unit (*PCDU*), 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 critical torque tubes (*CTT*) between the *PCDU* and the inboard actuators are considered to be the weak link in the power drive system. The wingtip brakes (*WTB*), the position transducers (*PT*) and the flap tachometers (if requested by the considered monitoring technique) are located at the two outer ends of the shaft system. System control is performed by an electronic control unit (*ECU*), not shown in Figs. 1-3, which closes the position control loop. The positions provided by the wingtip transducers are 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, and the eventual tachometers for a continuous actuation speed control (if requested by control law /monitoring technique).

Fig. 5 shows a mechanical model of the actuation system. The model takes into account the hydraulic and mechanical characteristics of all system components [5, 6], including their friction, stiffness 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 (closed loop),
- Errors and temperature effects in the position transducers and backlash (*BLPT*) within the position transducers drive (closed loop),
- Errors in the position transducers electronics and in the A/D conversion,
- Stiffness (*K2G*), backlash (*BLG*) and lead errors (*ΔZS*) of the ballscrew actuators (open loop),
- Third-order electromechanical dynamic model of the servovalve with first and second stage ends of travel and complete fluid-dynamic model [7],

- Dynamic and fluid-dynamic model of hydraulic motor and high speed gear reducer taking into account, beside the above mentioned Coulomb friction, viscous friction and internal leakage [8, 10],
- Efficiency of the actuators both in opposing and in aiding load conditions.

The mathematical model takes into account also activation / deactivation logic of the flap 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 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 to the hydraulic motor by means of the control valve.

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 to depressurize the hydraulic system, thereby avoiding the continuous oil leakage from the supply to the return pressure which affects the pressurized system.

5.2 Aircraft and autopilot modelling

To assess the amount of perturbations induced on the aircraft attitude by the failures of the flap actuation system, also the lateral-directional dynamics of the aircraft and of its autopilot has been simulated. The dynamics characterizing the aircraft lateral-directional behavior is represented by the usually considered model reported in the current literature [9].

The autopilot control laws have been assumed to be of a *PID* type, which is adequate to approximate the actual autopilot control within the objective of the present work. By measuring the aircraft roll angle the autopilot *PID* controller develops the commands to the ailerons and to the rudder. These flight controls have in turn been simulated as second-order systems having speed and position saturations. The aircraft data taken for the simulations are typical of a commercial transport jet aircraft; the purpose of this selection is purely exemplifying, because the aircraft behavior following the failure is substantially similar for all the types of aircrafts.

6. 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 has been prepared. The computer code contains the models of the different asymmetry monitoring techniques considered in the work. Several simulations have been run reproducing a mechanical failure of the transmission shaft with a resulting asymmetry between right and left surfaces. As it results in Ref. [3], the asymmetries in case of large loads are always higher than they are under low loads, and therefore

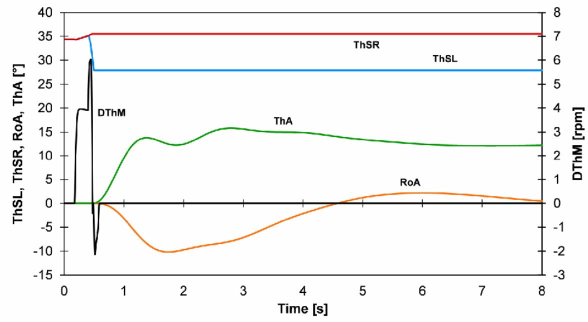

Fig. 6. Flaps deployment under high load: technique 2a.

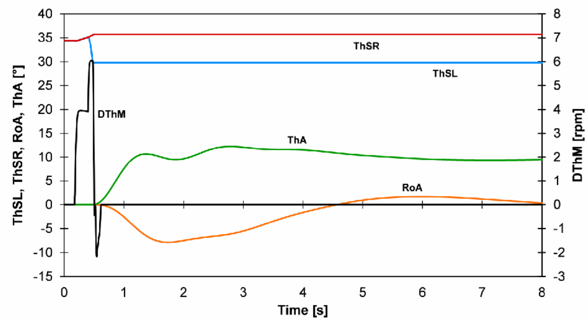

Fig. 7. Flaps deployment under high load: technique 2e.

these load conditions are more significant for evaluating the efficiency of the monitoring techniques: therefore, in the present work, only loaded servomechanism actuations are considered. 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.

Figs. 6-9 show the simulation results in case of deploying flaps with reversible actuators in the final part of their stroke (high flap deflection) under high loads (50% of the stall load), that act as opposing to the flap deployment.

The simulation results shown in these figures refer, respectively, to the cases of monitoring techniques 2a, 2e, 2f and 2g, in which the technique 2a is employed as a reference for comparison. In 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 system start up time.

In this case of high opposing loads, the portion of flap system downstream the failure is interested, under the load action, by a sudden retraction consequent to a high forward deceleration followed by a high backward acceleration 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. In all these figures the asymmetry is given by the differences between the two state variables *ThSR* and *ThSL*. As expected, the asymmetry monitoring techniques 2e, 2f and

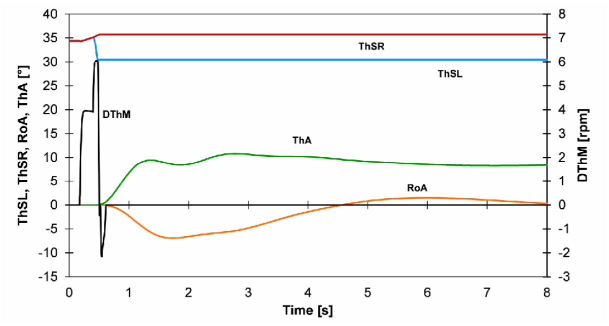

Fig. 8. Flaps deployment under high load: technique 2f.

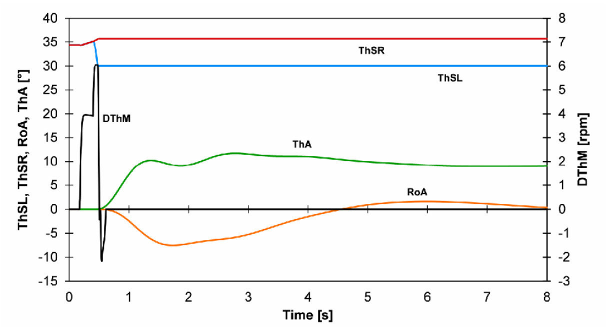

Fig. 9. Flaps deployment under high load: technique 2g.

2g (Figs. 7-9) allow a faster detection of the developing asymmetry and thus lead to a final asymmetry lower than monitoring technique 2a (Fig. 6).

The proposed techniques 2e, 2f and 2g under large aerodynamic loads perform a lower detection time delay in comparison with the technique 2a. The effects of the asymmetry monitoring techniques on the aircraft attitude are shown by the curves *RoA* and *ThA*. As the same figures show, the roll angle *RoA* increases as the asymmetry develops; at the same time the autopilot performs a command to the ailerons to realign the aircraft through a dynamic response including a Dutch roll mode. The employment of techniques 2e, 2f and 2g generally reduces the maximum roll perturbation and the related aileron command in comparison with the technique 2a.

Figs. 10-13 (respectively monitoring techniques 2a, 2e, 2f, 2g; failure time as before) show the simulations results in case of retracting flaps with reversible actuators in the final part of their stroke (high flap deflection) under high loads (50% of the stall load), that act as aiding to the flap retraction. Since these simulations have been run for large aiding loads, the portion of the flap system downstream the failure quickly accelerates, developing an excessive and uncontrolled retraction, with a resulting asymmetry until the system shutdown occurs, stopping it.

As for the case of large opposing loads of Figs. 6-9, the monitoring techniques 2g and particularly 2e and 2f provide, with respect to the technique 2a, a faster response and a final lower asymmetry with a resulting lower rolling perturbation of

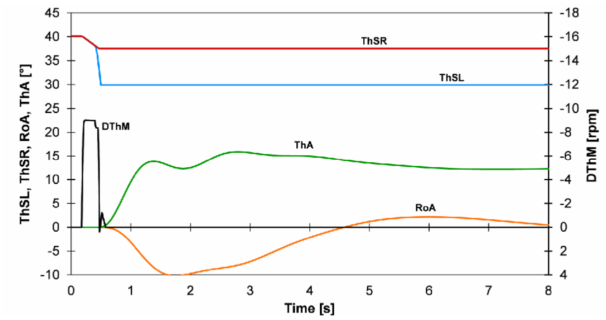

Fig. 10. Flaps retraction under high load: technique 2a.

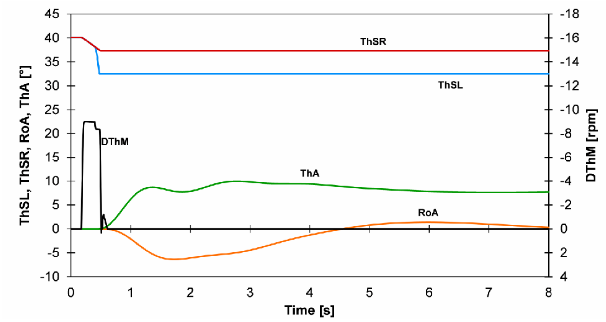

Fig. 11. Flap retraction under high load: technique 2e.

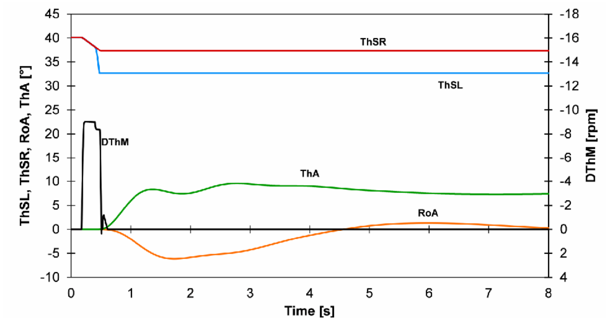

Fig. 12. Flap retraction under high load: technique 2f.

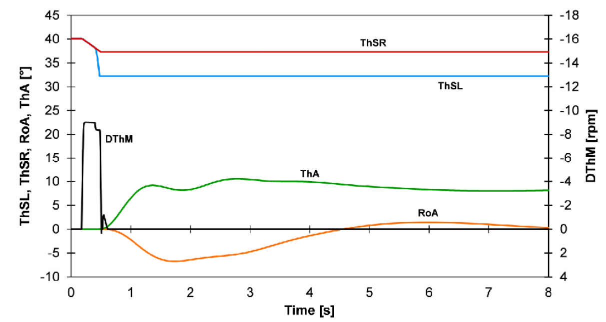

Fig. 13. Flap retraction under high load: technique 2g.

the aircraft.

Figs. 14-17 (respectively monitoring techniques 2a, 2e, 2f, 2g; failure time as before) show the simulations results for the

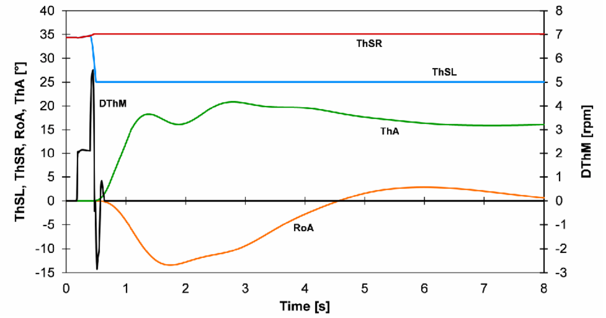

Fig. 14. Flap deployment under very high load: technique 2a.

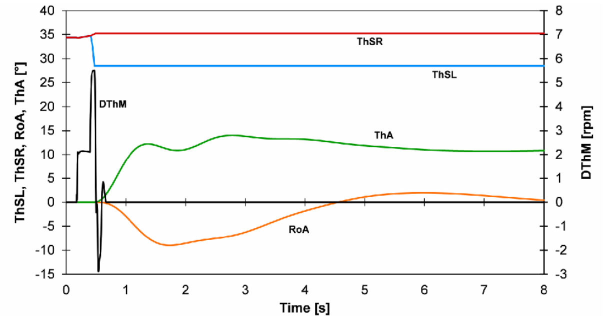

Fig. 15. Flap deployment under very high load: technique 2e.

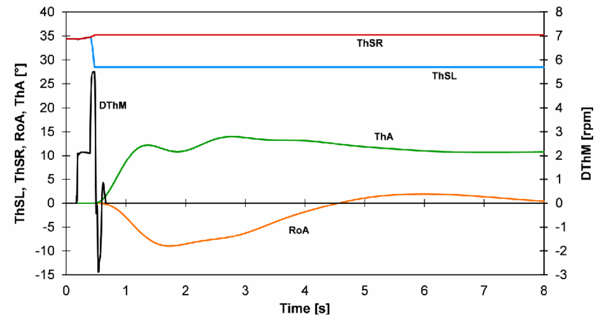

Fig. 16. Flap deployment under very high load: technique 2f.

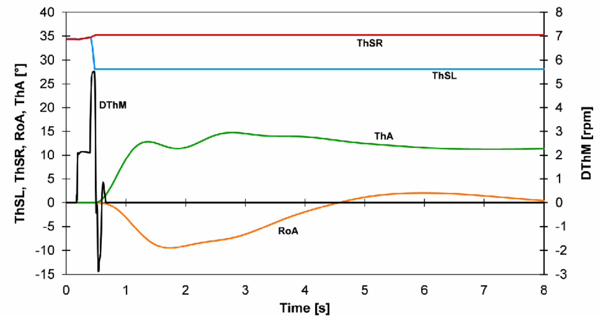

Fig. 17. Flap deployment under very high load: technique 2g.

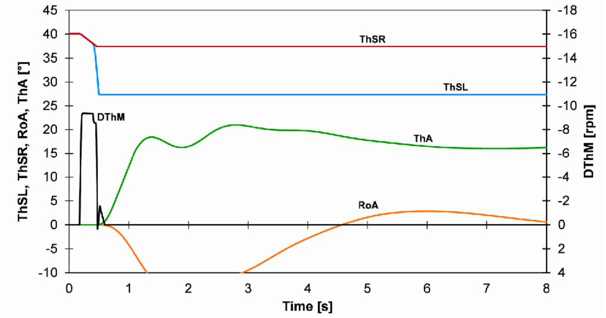

Fig. 18. Flap retraction under very high load: technique 2a.

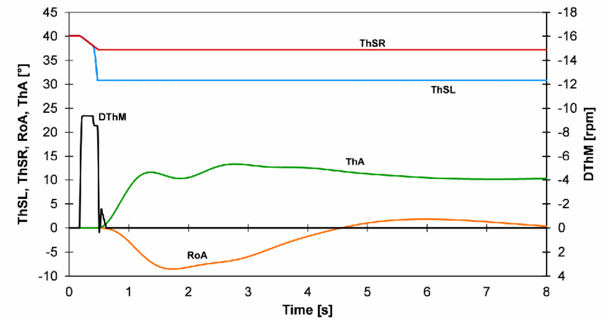

Fig. 19. Flap retraction under very high load: technique 2e.

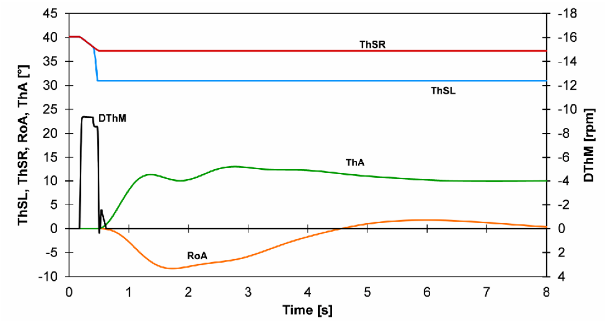

Fig. 20. Flap retraction under very high load: technique 2f.

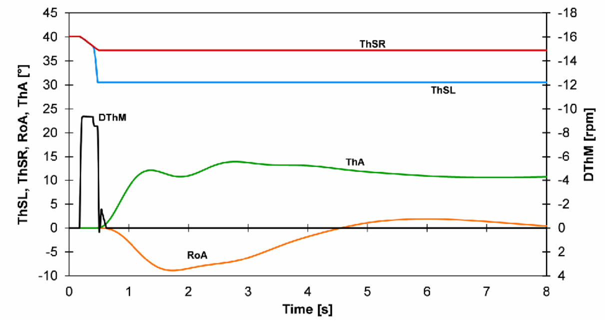

Fig. 21. Flap retraction under very high load: technique 2g.

cases of deploying flaps with reversible actuators under very high opposing loads (it is defined as "very high load condition" the situation in which the actuation system is subject to an aerodynamic load equal to 75% of the stall load 75% of servomechanism stall load).

With respect to the cases of deployment under high loads (previously shown in Figs. 6-8) larger asymmetries and perturbations occur.

The maximum flap asymmetry with the resulting roll perturbation and aileron commands progressively decreases moving from monitoring technique 2a to techniques 2g, 2e and 2f.

Similar considerations must be done for the cases of Figs. 18-21 (respectively monitoring techniques 2a, 2e, 2f, 2g; failure time as before) showing flap retraction under very high aiding loads (75% of the stall load) in comparison with Figs. 10-13 (flap retraction under high aiding loads).

7. Conclusions

Although the asymmetry monitoring technique based on the differential position surveying is generally used and considered sufficient to maintain aircraft control after a failure, the results of this study clearly show that a careful analysis is recommended to verify the actual safety margins under a combination of adverse conditions, as in case of failure occurring under very high loads (e.g., aircraft maneuvering during flap actuation). In this case the proposed monitoring techniques (differential position and absolute speed control, differential position and motor referred speed control, differential position and simulated motor referred speed control or, eventually, their integration, not considered in the present paper) should be strongly considered to improve aircraft handling and safety level after a flap transmission shaft failure. However, the techniques based on differential position and absolute speed control, differential position and motor referred speed control show better behavior in limiting the flap asymmetry and, consequently, in improving the aircraft handling following a flap transmission shaft failure. The criticality of the flap system asymmetry failure may be higher or lower as a consequence of the characteristics of the considered aircraft type. In fact, the failed flap acceleration is usually higher and the aircraft dynamic response to an asymmetry is generally faster for small or medium aircraft; so the criticality of the considered failure is usually smaller for large aircrafts because the time required to produce a critical flight condition is longer. In these conditions the quickness required of the monitoring system is slightly lower. However, this event is always considered as a possible cause of catastrophic accidents. Apart from the specific characteristics of the aircraft, its dynamic behavior following the failure strongly depends on the quickness of the corrective action performed by the monitoring system.

The proposed monitoring techniques are specifically conceived to enhance the aforesaid quickness. So, the considerations performed applying the dynamic simulations to a specific type of aircraft are substantially generalizable, even if the failure effects may be more or less critical depending on the behavior differences between the aircraft types.

A possible future work could envisage the advantages offered by some proper integration of the different techniques previously considered.

Nomenclature

BLG : Ballscrew actuator backlash
BLPT : Position transducer driver backlash
BS : Ballscrew actuator
BSN : Ballscrew actuator with irreversibility brake
CTT : Critical torque tube
DThM : Motor angular rate
FFM : Motor Coulomb friction torque
FFPT : Position transducer Coulomb friction torque
FFS : Surface and actuator Coulomb friction torque
IA : Irreversible actuator
IAs : Asymmetry declaration (*IAs* = 1)
IAsL : Left wingtip brake engage command (*IAsL* = 1)
IAsR : Right wingtip brake engage command (*IAsL* = 1)
$IWrn_{old}$: Generic differential position counter value (old computational step)
$IWrn_{new}$: Generic differential position counter value (new computational step)
IWrnC : Differential position time counter target
$IWrnL_{old}$: Generic left flap counter value (old computational step)
$IWrnL_{new}$: Generic left flap counter value (new computational step)
IWrnLC : **Alg. #1** time counter target (left flap)
$IWrnR_{old}$: Generic right flap counter value (old computational step)
$IWrnR_{new}$: Generic right flap counter value (new computational step)
IWrnRC : **Alg. #2** time counter target (right flap)
IWrnN : Time counter decrease rate
IWrnP : Time counter increase rate
K1G : Torque tube stiffness
K2G : Ballscrew actuator stiffness
PCDU : Power control and drive unit
PCU : Power control unit
PDU : Power drive unit
PT : Position transducer
RoA : Aircraft roll angle
ThA : Actual value of aileron angle
ThSL : Left flap deployment angle
ThSR : Right flap deployment angle
WTB : Wingtip brake
ZM : Motor gear reducer or its gear ratio
ZS : Actuator gear reducer or its gear ratio
ΔZS : Ballscrew lead error
ΔT : Monitoring algorithm sample value
θ_{EL} : Left flap transducer measured position
θ_{ER} : Right flap transducer measured position
$\Delta\theta_E$: Measured flap differential position threshold
$\dot{\theta}_{S0}$: Measured absolute flap angular rate threshold
$\dot{\theta}_{EL}$: Left flap transducer measured angular rate
$\dot{\theta}_{ER}$: Right flap transducer measured angular rate
$\dot{\theta}_{M}$: Measured hydraulic motor angular rate
$\Delta\dot{\theta}_{E}$: Measured flap differential speed threshold

$\dot{\theta}_{MC}$: Computed hydraulic motor angular rate

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Lorenzo Borello received the M.S. degree from the Politecnico di Torino in 1973. He is a retired full professor and continues to cooperate with other researchers of the Department of Mechanics and Aerospace Engineering His research activity is mainly focused on aeronautical systems engineering and, in particular, is dedicated to design, analysis and numerical simulation of on board systems, study of secondary flight control system and conception of related monitoring strategies and developing diagnostic algorithms for aerospace servomechanism and flight controls.

Giuseppe Villero received the M.S. degree from the Politecnico di Torino in 1974. He is an assistant professor at the Mechanical and Aerospace Engineering Department of Politecnico di Torino, that joined in 1982. Since 2003 he is also an aggregate professor in the same Department where he teaches aerospace structural engineering. His research activity is mainly focused on the aeronautical systems engineering and, in particular, is dedicated to design, analysis and numerical simulation of on board systems, and conception of related monitoring strategies.

Matteo Davide Lorenzo Dalla Vedova received the M.S. and the Ph.D. degrees from the Politecnico di Torino in 2003 and 2007, respectively. He is currently assistant researcher in the Department of Mechanics and Aerospace Engineering. His research activity is mainly focused on aeronautical systems engineering and, in particular, is dedicated to the design, analysis and numerical simulation of on board systems, study of secondary flight control system and conception of related monitoring strategies and developing of prognostic algorithms for aerospace servomechanism.