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Abstract. This paper proposes an active monitoring strategy to control aircraft trailing-edge high-lift devices (flaps) asymmetry. A variety of system failures can cause asymmetry in the control surfaces, including the transmission torsion bar break down and control surface actuator wear and tear. The authors' novel asymmetry active monitoring approach detects and identifies flaps position asymmetry. Once the failure side has been identified, the active control activates the wingtip brakes to stop the uncontrolled flap surface. The still controlled flaps are driven to the damaged surface braking point to reduce flap asymmetry. As a result, the undesired aircraft roll moment (due to flaps asymmetry) will be controlled, and the aircraft maneuverability after failure will be (partially) restored. The proposed asymmetry active monitoring technique has been widely tested in different operational and failure conditions, using wear-free or worn-out actuators and considering every failure side scenario. The behavior of the proposed active model is evaluated in terms of time response and stability margin under certain operating conditions.

1. Introduction

High-lift devices on wing trailing edges (i.e. flaps), along with slats (their counterpart on the leading edges), are a pivotal part of the secondary flight controls set in a commercial aircraft. Despite not being essential for manoeuvring the airplane, flaps increment the maximum lift coefficient, hence they are useful in landing and take off phases [1]. In fact, in these flight phases the low aircraft speed, combined with a high incidence, would lead the aircraft to a stalled aerodynamic condition. As far as commercial aircrafts flight controls are concerned, flaps deflections are discrete and they may be selected by the pilot with a limited positions knob. In fact, only a limited number of final positions are considered for these devices, unlike the primary flight controls, which admit a continuous control surface deflection.

Even though they are not safety-critical elements, as a failure would deteriorate the aircraft performances but neither the flight safety nor the aircraft controllability, one of the most strict and demanding safety design requirements involves the actuation symmetry of each mobile surface. The measurable asymmetry between right left flaps is often extremely low under nominal conditions. This occurs because the transmission line has very strict transmission backlash requirements. Mechanical transmission (actuators and shaft system) deflection under non-symmetrical loads, on the other hand, is often only a small part of total travel by design (backlash less than 0.05%, deflection less than 0.5% of the full flap travel [2]). However, if the mechanical transmission fails [3], an increasing asymmetry between the left and right flap surfaces may occur. If no corrective action is envisaged, this asymmetry could become significant and jeopardize flight safety.

The results of a non-controlled flap asymmetry would be really hazardous indeed [4]. In fact, a non symmetrical flap configuration would inevitably lead to excessive and probably uncontrollable roll and yaw moments on the aircraft.

This is why additional safety procedures must be put in place to guarantee the expected safety standards. A solution to this problem may be found in flaps asymmetry monitoring techniques [5, 2, 6], which try to identify the non nominal condition and, depending on the complexity of the monitoring framework, even try to minimize the detrimental effects the flap asymmetry may produce on both the aircraft controllability and maneuverability after a potential failure.

The current state-of-the-art monitoring techniques can be divided in active and passive ones. The authors developed a new active monitoring technique which is proved to solve other strategies issues [6] and manages to identify the correct failure side, improving the overall accuracy and behaviour.

After a brief introduction of widespread flaps configurations and a description of possible failures in the system, an overview of the existing monitoring techniques is reported. Finally, the innovative technique developed by the authors is presented along with some simulations and results.

2. System Overall Configurations and Design

The flaps overall configuration is quite standardized and it comprehends several sub-units. The description of the overall system goes beyond the scope of this work. The interested reader should consider looking for [7]. However, a brief summary of the components and functioning principles is reported below for the ease of understanding.

- *Power Drive Unit (PDU).* This is the mechanical power unit, usually powered by hydraulic motors, connected to the aircraft hydraulic system. There is an ongoing effort to shift to electric ones, following the MEA (More Electric Aircraft) paradigm [8].
- *Power Control Unit (PCU)* It controls the actuation and, in general, it is integrated together with the PCU, thus creating the single PDCU.
- *Drive shafts and torsion bars.* They are used to transfer the motion form the motor output shaft to the user (i.e. flaps surfaces) through the actuators [9].
- *Actuators.* They are placed between the torsion bars and the flight surfaces themselves. They are usually ballscrews or screw-and-nut ones [7].
- *Servovalves, solenoid and shut-off valves*, which regulate the hydraulic power going into the PDU.
- *Mechanical links and components.*

2.1. PDCU

More in details, the most advanced PDCUs may consist of two internal power units. In this case, on commercial aircrafts, the employed technology is the so-called speed summing architecture: this configuration outputs an average velocity between the two motors and a final torque equal to a single motor torque.

2.2. Drive Shaft Design

The drive shaft system mainly consists of the torsion bars. In general, the high lift devices drive shaft bars present a certain degree of torsional flexibility on commercial aircrafts.

2.3. Actuators and Braking Architecture

Normally, the actuators used on high-lift devices drive systems are linear and the overall actuator architecture can hence be divided into:

- Irreversible actuators (screw-and-nut actuators);
- Reversible actuators (ballscrew actuators).

The actuators internal friction forces is strictly linked to the actuators performance in terms of reversibility. As better explained later, the significant internal friction forces irreversible actuators are subjected to prevent the inoperative surface retraction after failure when operating under high aerodynamic loads. On the other hand, reversible actuators allow the failure surface retraction on high aerodynamic load conditions, due to their inherent low friction.
Nonetheless, the reversible actuators are more efficient than irreversible ones in terms of energy dissipation before failure.

In the reversible case, further measures must be implemented to address safety issue and to prevent flaps surfaces uncontrolled movement. There are two options to stop the uncontrolled flaps: wingtip brakes or irreversibility (self acting) brakes. These solutions are typically employed in different aircraft categories [9, 2].

Due to their cost-effectiveness and, more crucially, ease in executing pre-flight checks, reversible actuators with wingtip brakes represent the most commonly employed architecture for commercial high-medium performance aircraft. Wingtip brakes are installed on the transmission line, close to the electrical flap position transducer (one per flap). The wingtip brakes are then controlled by the asymmetry monitoring techniques.

3. Failure Analysis

Possible failures in the transmission line may be caused by a wide variety of components, being the flap system quite complex indeed. According to [10, 11], the most probable failure points in a secondary flight control subsystem may be linked to:

- Torque tubes or torsion bars (e.g. corrosion, micro-damage due to friction between rivets, fretting, jamming [12] on the transmission line).
- Rotary actuators (e.g. fatigue cracks, galling, jamming, loss of precision due to wear and corrosion).
- Flap tracks, slider and mechanical links.

However, in this case only the transmission failure involving torque shaft has been considered, as already done in [2]. In fact, due to the significant asymmetries between the left and right surfaces involved with this failure, the shaft failure is regarded as the sole potentially safety-critical event. All other failures only inhibit nominal operations and have a minor impact on the system symmetry. De facto, in the event of a shaft failure, the part of the actuation system upstream of the fracture point would continue to rotate with the PDU, while the downstream section of the shaft system (and the flap surface itself) would no longer be controlled. Depending on how the flap is configured and the aerodynamic loads it is subjected to, the behaviours vary. As, stated before, the overall system can be reversible on non-reversible depending on the mechanical transmission and the actuator. If the actuators are non-reversible, a failure would result in a rapid slowdown followed by a full halt of the mechanical system.

In fact, due to the system irreversibility, the aerodynamic loads would be unable to drive the mechanical assembly backwards and friction forces would be quickly dissipated. As a result, the control surface would remain halted almost instantaneously after a failure, providing a sort of fail-safe system. On the other hand, if the actuators are reversible, the failed part of the actuation system would experience significant accelerations due to the aerodynamic loads which are free to put the surface in motion (especially considering the low rotational inertia of the high-lift device system). In this case, wingtip brakes or irreversibility (self acting) brakes must be employed to guarantee the flap safety requirements.

Following the aforementioned explanation and the fact that the worst cases in terms of asymmetry criticality concern the behavior of one specific architecture, the examined configuration for this work considers a transmission line with torsion bars, velocity summing PDCU, ball screw actuators (i.e. reversible configuration) and wingtip brakes.

4. Monitoring Techniques

There are several types of control surfaces asymmetry monitoring techniques [12, 13, 6] which can be classified according to the type of response (active or passive), to the ways asymmetry is measured (differential between the two flaps or relative to a third common position) etc. However, the two main categories of these techniques are:

- *Passive asymmetry monitoring techniques.* A passive asymmetry monitoring technique only detects the position asymmetry failure condition, after which it brakes both flaps, regardless of their position.
- *Active asymmetry monitoring techniques.* An active asymmetry monitoring technique both detects the position asymmetry failure, identifying the failure side, and corrects it. Once the asymmetry failure arises, the failure surface is braked as soon as possible while the operative flap tries to reach the position of the faulty surface. As a result, the control surface position asymmetry on steady state will be minimal, with a drastic increase in stability, controllability and manoeuvrability after failure. These models are more complex than the previous ones but preserve the dynamic system response stability.

In general, every position asymmetry monitoring technique follows a similar logic both to detect the asymmetry failure condition and to brake the damaged surface. Firstly, the asymmetry failure is detected by comparing the signals coming from each actuator. Should the aforementioned comparison exceed a certain asymmetry threshold for a certain time, the position asymmetry failure is declared. Once the asymmetry failure is detected, the hydraulic unit is depressurized and, consequently, the wingtip brakes will stop the failure surface.

5. Proposed Active Control Technique

The proposed strategy is an active, relative position driven, step-input control technique [14]. In fact, the algorithms always use the surface relative electrical position in relation to a common position reference to detect eventual asymmetry failure conditions. This is done comparing the relative position reference of either the left or right surface with a angular position threshold Δ_{θ_E}, empirically set as $\Delta_{\theta_E} = 0.02rad$. As described further on, whenever the position threshold is exceeded for a specific amount of time, the asymmetry is declared.

The strategy was developed to both detect the failure surface and to activate the braking system of the inoperative surface when a failure happens. Firstly, the partial asymmetry detection is able to distinguish between left and right failure thanks to Eq. 1.

$$|\theta_M Z_M Z_S - \theta_{E,i}| > |\theta_M Z_M Z_S - \theta_{E,j}| \ \wedge \ |\theta_M Z_M Z_S - \theta_{E,i}| > \Delta\theta_E \tag{1}$$

Where θ_M is the motor position, Z_M and Z_S represent the motor and actuator gear ratio, $\theta_{E,i}$ is the electrical position of the $i-th$ surfaces with $i = L, R$ for left and right flap.

Whenever this condition is met (with a cycle running at the program sample time), either for the left or the right surface, the partial asymmetry counter $I_{W_{rn,i}}$ increases. When it reaches $I^{thr}_{W_{rn,i}}$, the partial asymmetry indicator $I_{A,i}$ is activated. This is a boolean variable set as 1 or 0 whether there is a failure or not. On top of that, a second general logic is added: this further detection logic was conceived to solve the eventual multiple failure problem (i.e. when the failure is present on both sides). This general asymmetry detection logic is independent from the partial asymmetry logic and brings benefits in terms of system stability and robustness.

This relevant logic states the following:

$$|\theta_M Z_M Z_S - \theta_{E,i}| > \Delta\theta_E \ \wedge \ |\theta_M Z_M Z_S - \theta_{E,i}| > \Delta\theta_E \tag{2}$$

This algorithm manages the general asymmetry scenario as independent from both partial asymmetry cases, which makes the model more robust and reliable. Similarly, whenever this condition is met, the general asymmetry counter $I_{W_{rn}}$ increases and, when it reaches $I_{W_{rn}}^{thr}$, the general asymmetry indicator I_A is activated. Additionally, the developed monitoring logic is able to detect further system failures apart from flap asymmetry, such as wingtip brakes failure and a general power plant failure or hydraulic system depressurization. These will not be studied in detail in this project. Nonetheless, a general overview can be found in [14].

6. Modelling Framework

The flap system modeling and simulation has been carried out through a FORTRAN computer program that reproduces the system behaviour when commanded. In addition, both the aircraft roll dynamics and the autopilot behaviour are also included. The aircraft lateral-directional modelling reproduces the vehicle roll dynamics considering the flap position asymmetry and the autopilot controls the aircraft rolling moment [1]. A thorough explanation of every single block and equation, along with the description of the hydraulic and mechanical components modelling can be found in [14] and [2]. The aerodynamic surfaces are considered infinitely rigid (i.e. no aeroelastic effects such as divergence, control reversal and flutter are considered). Nonlinear aerodynamic effects, such as stall or wing-tip vortex, and the nonlinear formulation are also dismissed. In addition, as explained later on, the resistive torque T_{RC} is considered as a constant.

7. Results & Simulation

Several tests were performed to study the system behaviour and detecting the main advantages and disadvantages of each active monitoring technique. To that end, a simulation and testing campaign, which consisted in testing the following variables on each model, was carried out:

- *Failure side*: each test was performed considering the failure either on the right or the left surface.
- *Aerodynamic constant torque* T_{RC}: the torque caused by aerodynamic forces on the flap notably affects the test results. Thus, different flight phases could be tested in a first approximation varying T_{RC}.
- *Flap extension or retraction*: the motion sense, combined with the aerodynamic constant torque T_{RC}, might be decisive when detecting and controlling the asymmetry.
- *Extraction/retraction magnitude.*
- *Presence of friction* The worn-out cases study the system time response considering worn-out actuators. This increases the friction forces inside the actuators, seriously affecting their performances and, therefore, the surface deflection.

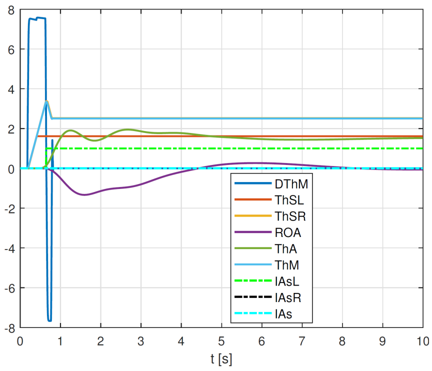
The failure injection time is set for all the tests: $t_f = 0.4s$. A wide variety of simulations has been performed in very different conditions. For reasons of brevity, only some of them are reported in this paper, all of them with failures on the left flap. The behaviour, however is similar for the right semi-wing too. A more in depth analysis with more results can be found in [14]. Therefore, the following simulations were performed, with left faulty flap:

- Extraction from 0 to 0.07 rad $(around\ 4°)$ at $T_{RC} = 0Nm$.
- Retraction from 0.07 to 0 rad at $T_{RC} = 0Nm$.
- Extraction from 0.4 rad $(around\ 23°)$ to 0.5 rad $(around\ 28°)$ at $T_{RC} = 10000Nm$.
- Retraction from 0.5 to 0.4 rad at $T_{RC} = 10000Nm$.

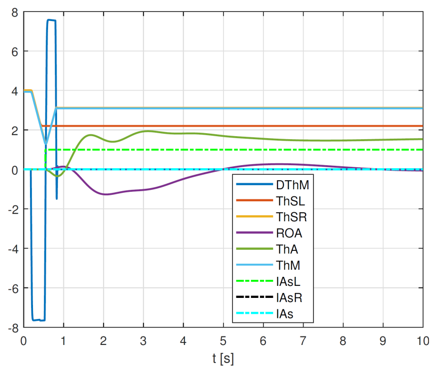
The first two cases are simulations of maneuvers at low aerodynamic load. On the other hand, the last two cases are considered to be maneuvers at high aerodynamic load, which are more significant [9] since every phenomenon is more evident. The same set of simulations has been carried out in worn out conditions; thus a total of 8 cases have been reported.

In the following plots $DThM$ refers to the motor speed, $ThSL$ and $ThSR$ highlights the left and right flaps angular positions, ThA is the ailerons deflection angle, ThM is the motor position and RoA shows the aircraft roll angle behaviour. Every angle is expressed in degrees on the y-axes. $IAsL$, $IAsR$, IAs are the anomaly indicators (Left, Right and General respectively) which may assume a value of boolean 0 or boolean 1. As stated before, the authors' monitoring technique uses the relative position with respect to the motor angular position which is the reference for all the step input models.

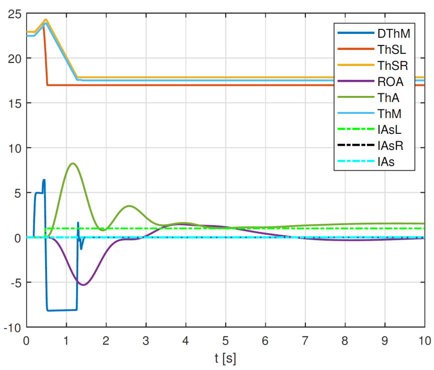
The failure side is correctly detected, regardless of whether the surface is extending or retracting. The asymmetry can be noticed at 0.4s when the two signals $ThSL$ and $ThSR$ are not coherent anymore: the red signal (representing the left flap position) at 0.4s does not follow



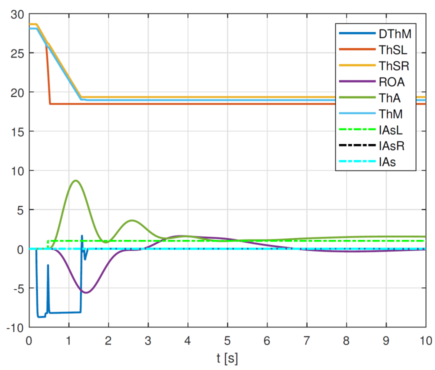
(a) From 0 to 0.07 rad (E) $T_{RC} = 0\,Nm$



(b) From 0.07 to 0 rad (R) $T_{RC} = 0\,Nm$

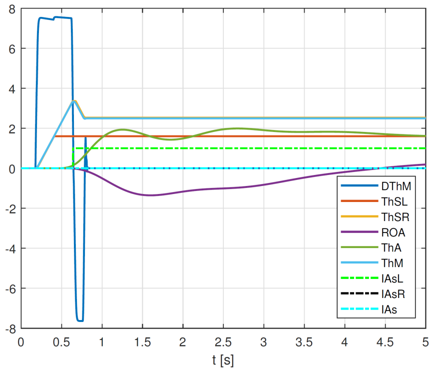


(c) From 0.4 to 0.5rad (E) $T_{RC} = 10000Nm$

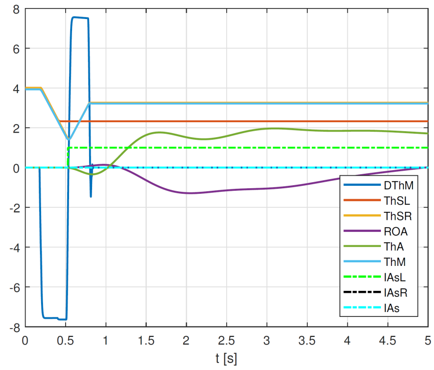


(d) From 0.5 to 0.4 rad (R) $T_{RC} = 10000\,Nm$

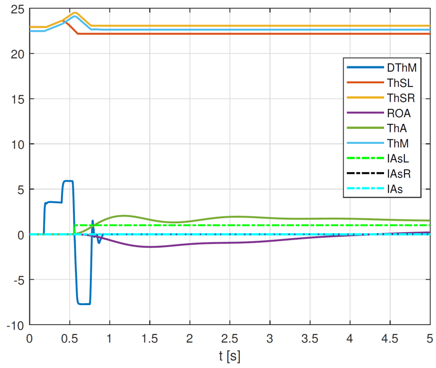
Figure 1: Simulation of nominal (wear-free) flap extraction and retraction in different operational scenarios.



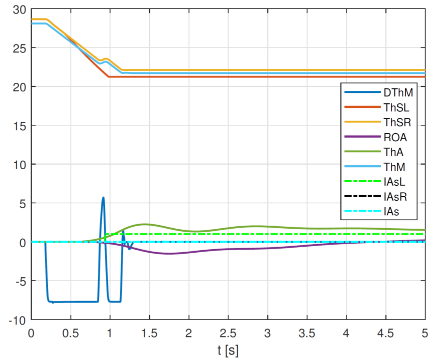
(a) From 0 to 0.07 rad (E) $T_{RC} = 0\ Nm$ worn-out



(b) From 0.07 to 0 rad (R) $T_{RC} = 0\ Nm$ worn-out



(c) From 0.4 to 0.5 rad (E) $T_{RC} = 10000\ Nm$ worn-out



(d) From 0.5 to 0.4rad (R) $T_{RC} = 10000 Nm$ worn-out

Figure 2: Simulation of worn-out flap extraction and retraction in different operational scenarios.

the actuator position anymore because the transmission is broken. As a result, the motor is subjected to very high speed since it tries to regain the position. After a while, the system recognizes the failure and sends a signal to the PDU. As the counter reaches the set threshold, the anomaly indicator shifts to one (dotted green line) and the failure is recognised. Thanks to this signal, the operative surface (the right one) is able to minimize the roll torque by its slight retraction. Nevertheless, the aircraft dynamics is influenced by this change and the aircraft experiences a roll moment: this can be seen as the roll angle changes. The autopilot reacts by modifying the aileron position (green line) but, thanks to the monitoring strategy its change in position is reduced. The operative flap, however, does not get to the same extraction magnitude as the faulty one. In fact, the authors considered a worst-case-scenario in which the electric transducers are affected by offset and errors. The entity of this effect is different whether the aerodynamic load is applied or not and it is less visible when high aerodynamic torque is simulated since every torque is higher.

In the case of high opposing torque, after the transmission failure, the flap system section after the breakdown is subjected to a sudden retraction due to the aerodynamic load, which pushes the surface back. This can be seen in the abrupt change in the flap position as well as in the motor high speed and acceleration. The failure is then recognized by the monitoring system and the wingtip brake provides a full stop to the system. At the same time, the motor quickly sets the operative surface to a position similar to the faulty one to minimize the asymmetry effects. Even here, the effects of unbalanced surfaces can be noted as the roll angle and the autopilot response on the aileron is clearly visible.

In Fig. 2 the same extraction and retraction patterns are reported. However, in this case, the actuator is affected by friction. Both the aiding and opposing friction efficiencies in dynamic conditions are considerably reduced, thus reducing the actuator reversibility too [14]. Moreover, kinetic energy is loss during the motion transmission and the actuators and overall system reliability is significantly reduced. As a result, paradoxically, the effects of a high friction force due to the worn out actuators helps the asymmetry control algorithm to detect eventual asymmetry failures, which improves the system performance after failure. This can be explained by the fact that an higher friction contributes to prevent the surface from moving. However, these "positive" outcomes must not mislead the reader as the presence of friction has an overall detrimental effect on the system. The effects of the increased friction on the overall dynamics are quite limited indeed (Due to the high friction force, worn-out actuators shorten $t_b r$, increase roll angle time-to-peak and reduce the overshoot) as the monitoring strategy goal is trying to reduce the impact on the aircraft dynamics. Finally, the torque resulting from the friction acting on the components is limited as the gear ratio is quite high [14].

8. Conclusions

A new strategy able to actively monitor flaps asymmetry has been developed and successfully tested on aircraft models. The results show that the control technique is able to recognize correctly the presence of a failure as well as the malfunctioning side. The methodology has been tested in nominal conditions as well as in the presence of increased friction showing satisfactory results as the impact of the failure on the aircraft dynamics is contained. Moreover, this advanced strategy allows to limit the controllability and stability issues deriving from the aerodynamic surfaces unbalance leveraging the active surface realignment in order to match the position of the damaged flap. In this way, the roll angle spikes are limited and the overall safety is significantly increased. Further studies can be approached, considering more advanced algorithm taking into account speed, dynamic position sensing as well as different input (commanded) waveforms.

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