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Robust simulation model approach to evaluate innovative asymmetry monitoring and control techniques in critical flap failure and aircraft controllability

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Abstract - Asymmetry limitation requirements between left and right wing flap surfaces are the most important in the design of the actuation of secondary flight control system, both in civil and military aircraft, due to the severity of the consequences. In case the position asymmetry would exceed a defined critical value it must be detected and limited by a dedicated monitoring equipment using a suitable and effective control algorithms. The development of the asymmetry monitoring feature plays a very important role in the design of innovative flap control systems, especially to improve the operating performances of secondary flight control systems installed on board of a modern aircraft. The current monitoring techniques are based on the differential position detection between left and right surfaces and, generally, their application slightly reduces the asymmetry. Nevertheless, in some cases these techniques may have an unreliable behavior in case of torque shaft fracture or major structural failures. When these particular mechanical failures appear special monitoring techniques can improve the control systems performances to overcome the typical shortcomings of the standard methods. In this paper a simulation model is proposed to evaluate, with an acceptable level of accuracy, the real behavior of a standard flap system using different monitoring and control algorithms. A reference control flap architecture, usually applied in military aircraft, is used to validate the model in the same operative conditions. By the proposed simulation model it is possible to evaluate the performances of the asymmetry detection and reduction algorithms with a comparison between different flap control system.

Key-words: - Flap Actuation System, Control and Monitoring Algorithms, Flap Asymmetry.

1 Introduction

Secondary flight controls are a critical feature of the aircraft system as they actuate flap and slat surfaces fulfilling these main specifications:

- on-off command type (not continuous operating mode);
- modification of wing aerodynamic coefficients like: C_D (Drag Coefficient); C_L (Lift Coefficient);
- actuation during take-off and landing phases, keeping the surfaces on a stable extracted position.

In this work only a flap actuation systems configured on standard civil aircraft, using hydraulic driven motor, are consider. Based on the main specifications flap flight control systems must satisfy many types of requirements in terms of performance, accuracy, reliability and specified interface with other aircraft systems and primary structure. The asymmetry limitation between left and right wing flaps is one of the most critical design requirements as regards actuation, monitoring and position control of standard configuration of the flap actuation system. During normal operating conditions the typical asymmetry between right and left flaps is generally very small. Some physical non-linear phenomena as the backlash and the elastic deformation of the mechanical transmission (actuators and cinematic shaft unit) contribute to this asymmetry during the actuation under non symmetrical loads; referring to the percentage of the full travel of the flap surface this asymmetry usually produces a value lower than 0.05%, as regards the backlash, and lower than 0.5%, for the elastic deflection. These asymmetry angles are not able to damage maneuverability and controllability of the aircraft, but many types of failures can affect secondary flight controls: they are designed with a conservative safe-life approach, which imposes to replace the related components after a fixed amount of flight hours (or operating cycles).

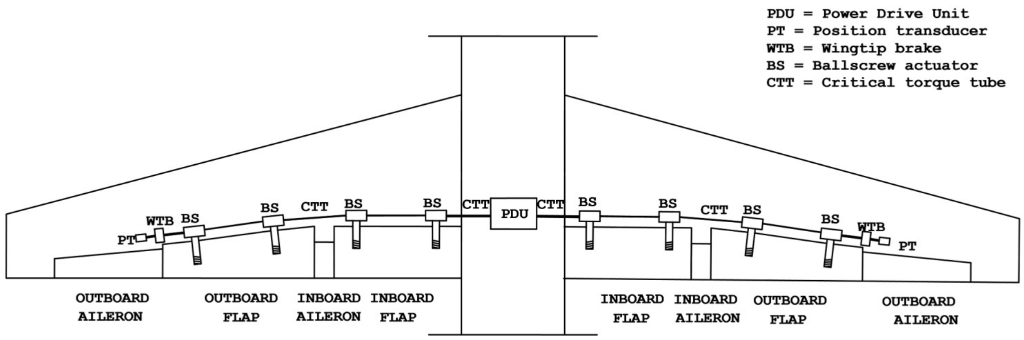

Fig. 1: Wing tip Brakes (WTB) Flap Architecture.

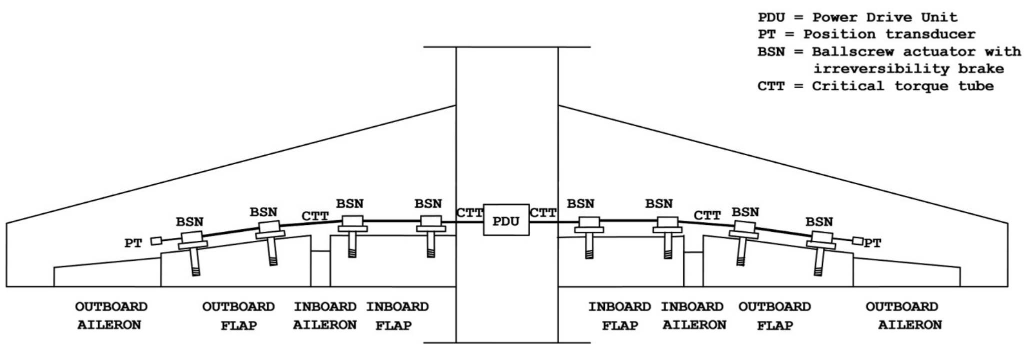

Fig. 2: NoBack Irreversibility Brakes (NBB) Flap Architecture

The safe-life design approach lacks the possibility to evaluate possible initial flaws (occurred during manufacturing) that could generate a sudden fault which could compromise the safety of the aircraft; moreover, such method does not allow to individuate a specific failed unit component to be replaced alone, instead to intervene to the whole unit (with the related inefficiencies and additional costs).

A mechanical failure may occur in any component of the actuation control system (shafts, sensors, PDU, actuators), but these types of failures can result in the inability to operate the affected flap system without any effect on the system symmetry.

Considering a general flap control system configuration, if a shaft fracture occurs the segment of the actuation system upstream the fracture point keeps rotating with the PDU (Power Drive Unit) until a shut-off is not given by the control system. Otherwise, the shaft system downstream the fracture point is at the mercy of the aerodynamic load operating on flap surfaces to drive it, in reaction mode, until the end of travel.

Therefore, a sudden fracture of the mechanical transmission generates, in a very short time, an increasing asymmetry builds up between left and right flaps surfaces, which may become excessive and safety critical without an appropriate corrective action operated by the monitoring and control system.

The 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. Only the shaft failure must be considered potentially critical because of it involves large asymmetry angle between left and right surfaces, resulting in an uncontrolled roll-rate and sideslip of the aircraft under particular flight conditions. Indeed, as example of critical Incident related to large asymmetry flap control system, it is possible to note that on January, 27th 2009 an aircraft model ATR42-320 of the Empire Airline at the airport of Lubbock, Texas, USA had a crash during landing phase; other similar incidents are archived within FAA archives. The actuation systems of the flap surfaces are classified within main three types based on mechanical reversibility with different behavior in case of fracture of transmission shaft:

- Irreversible Actuator: this system performs high deceleration followed by a standstill, because the aerodynamic load cannot drive back the actuators and the small kinetic energy of the shaft system is quickly dissipated by the losses of the rotating shafts;
- Reversible Actuator: the aerodynamic load can develop high acceleration in retracting the failed part of the actuation system. In this case the stop of the surfaces can only be obtained by means of wing-tip brakes (Fig. 1) or irreversibility brakes (Fig. 2).

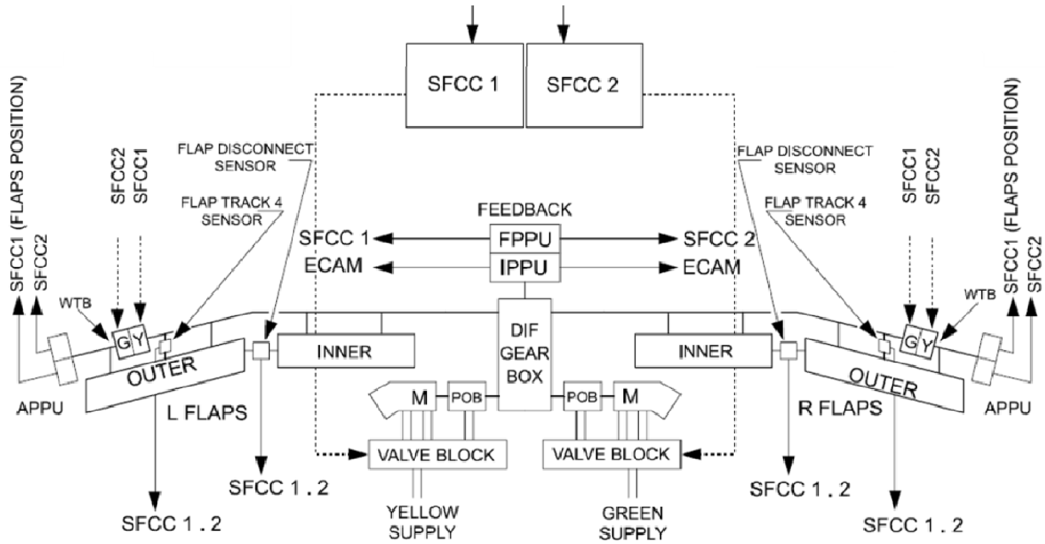

Fig. 3: Schematic Diagram for A330 Secondary Flap Actuation System.

In this paper only a system with reversible actuators is considered because of irreversible actuators requires higher hydraulic power associated to lower efficiency; the reversible solutions are used on-board of a wide types of aircraft.

In particular, the wing-tip brakes (WTB) is the most used solution on flap control systems of civil aircraft: it exhibits a greater value of maximum asymmetry in the considered types of critical failure conditions, but easily permits the pre-flight checks to verify the correct operating status. Moreover, it is also the most economical solution, compared with the irreversible brakes solution, often used on high performance military aircraft.

The last one solution is called No-Back Brakes (NBB) and is based only on mechanical systems, if load torque applied to actuator mechanism is greater than the torque applied by control systems the No-Back system brakes the actuator exhibiting best asymmetry performances in the same operating failure scenario without using any electronic control device.

A dedicated numerical simulation model is developed to compare WTB and No-Back performance in the same operating critical conditions with high aerodynamic loads acting on the flaps in case of fracture shaft failure. The flap actuation and control system model presented in this work allows to evaluate several monitoring techniques, proposed by Borello et al. in [1-3], able to prevent potentially critical asymmetries, and to test innovative hardware solutions (that will be presented in authors' future works) capable to reduce, with respect to the more expensive No-Back solution, the asymmetry produced as a consequence of a shaft failure.

2 Aim of the work

The aim of this work is to propose a numerical algorithm capable to simulate the dynamic behavior of a typical flap actuation system, with an acceptable level of accuracy, considering the effects due to the fracture shaft failure and non-linear physical phenomena. Once completed the Matlab/Simulink simulation model, different monitoring strategies are evaluated.

3 Secondary Flight Control System

Secondary flight control systems are typically servomechanism able to drive flap or slat surfaces in discrete extracted positions, keeping them during all the takeoff and landing flight phases. Usually, the secondary flight control system modifies the aerodynamic behavior of a geometric wing section increasing lift (C_L) and drag (C_D) and camber line profile that changes the zero lift angle (α_0). The purpose of flap surfaces is reducing aircraft velocity during landing and takeoff, increasing needed lift to complete these critical flight phases. There are many flap configurations, but in this work only the Fowler flap has been considered. This is why this type is the most used in civil liner aircraft, and it is capable to give a maximum lift coefficient increase ($\mathbf{\Delta C_{Lmax}}$) up to 30% and the best profile camber. Then, if flap surfaces are slotted, as shown in Fig. 5, it is possible to increase locally the boundary layer adherence, and globally the aerodynamic efficiency of the wing. Differently from the primary flight controls, flap actuation system can drive surfaces only on discrete positions, generally at 0°, 15°, 25°, 35° extraction degrees with angle velocity from 6° to 8° degrees to second.

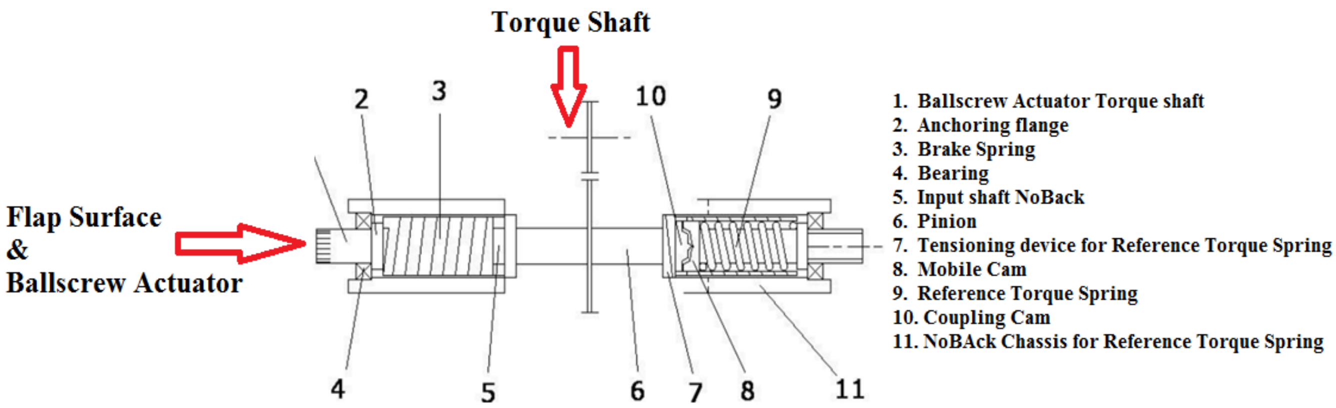

Fig. 4: Schematic Diagram for NBB NoBack Irreversible Brake.

In order to elaborate a numerical simulation model with an acceptable accuracy a physical actuation systems has been considered as a reference model commonly used on-board of modern aircraft.

The physical model proposed as a reference is the actuation system for secondary flight control installed on the Airbus A330, shown in Fig. 3. As previously indicated in this work the flap actuator control system has only been considered.

The proposed reference actuation system architecture is composed by the following main components:

- **SFCC:** Slats , Flaps Control Computer
- **PDU:** Power Drive unit for hydraulic power transformation to mechanic power ;
- **POB:** Pressure Off Brakes stopping PDU shaft to Differential Gearbox in case of major failures;
- **SVALVE:** Solenoid Valve regulating Power to PDU;
- **APPU:** Asymmetry Position Pick Off Unit for angular position at the end of cinematic line;
- **FPPU:** Feedback Position Pickoff Unit for angular position of hydraulic motor shaft ;
- **IPPU:** Indicator Position Pickoff Unit for extraction angle of Flap surfaces;
- **WTB:** Wing Tip Brakes;
- **ECAM:** Electronic Centralized Aircraft Monitoring;
- **RELIEF-VALVE:** shutoff valves to avoid over pressure due to thermal and external loads and activate POB Power off brakes.

The PCU Power Control Unit transform hydraulic power supply to mechanical power to drive flap surfaces by cinematic line composed by torque shafts, gear box, and universal joints. Every PCU have two different specific hydraulic supply, to give a hot redundancy for aircraft safety, and is composed by PDU (Power Drive Unit), SVALVE (Solenoid Valve), POB (Pressure Off Brakes) and Relief Valve.

In this work reversible actuators are considered, where the aerodynamic load can develop high acceleration in retracting in case of shaft fracture stopped only by means of the systems irreversibility. In order to satisfy the following functional requirements a secondary actuation system involves irreversible systems:

- Keeping in position flap or slat surfaces driven by monitoring and control system;
- Promptly stopping flap or slat surfaces in case of asymmetry due to failure actual system;
- Limiting actuation velocity in retracting in case of aerodynamic load in aiding configuration (the surface motion is concordant with external load direction);

We consider as reference performances for irreversibility systems the NBB NoBack brakes solution is used on board of many military aircraft. This brakes solution is present in each surface actuator within actuation system architecture and a schematic diagram for a NBB NoBack system is showed in Fig. 4.

This particular system can break the flap surface, without any electromechanical command, every time that load torque is major than Reference torque fixed by Reference Torque Spring of the NoBack system. The most common irreversibility breaks used in civil aircraft is the WTB Wing Tip Brakes solution where at the end of each cinematic line is present a friction system driven by SFCC: Slats, Flaps Control Computer.

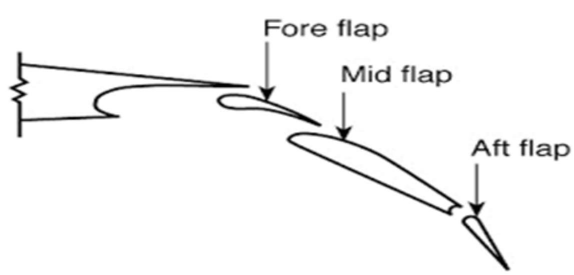

Fig. 5: Schematic Diagram for Triple Slotted Flap.

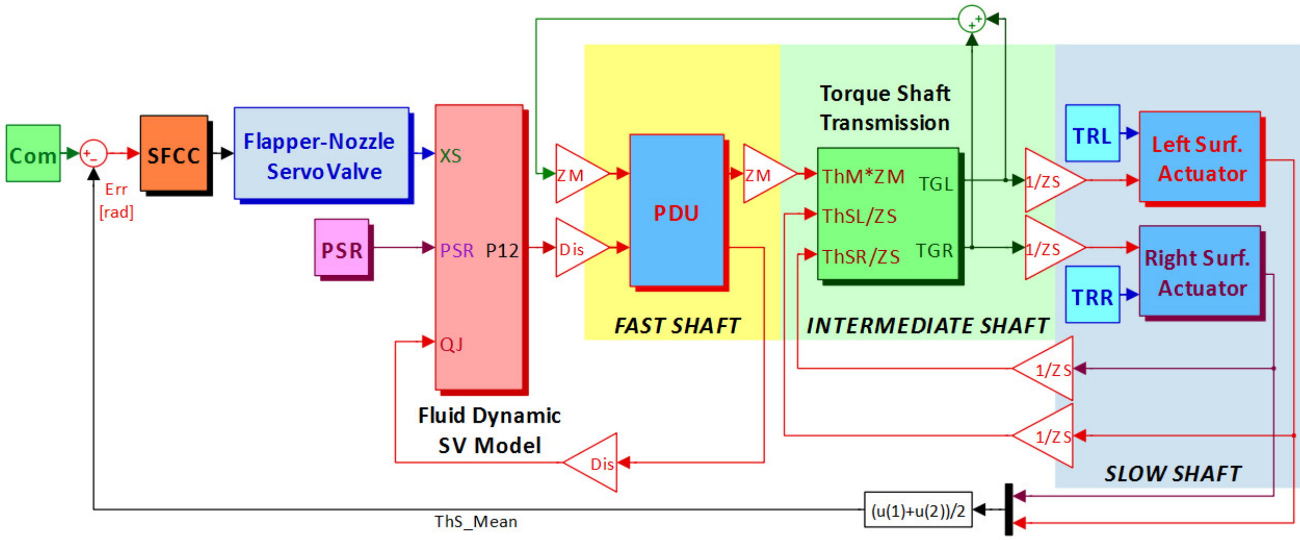

Fig. 6: Proposed MATLAB/SIMULINK® simulation model of flap actuation system.

If it is necessary to stop the flap surfaces for each wing, the monitoring and control system engages friction disks of the WTB reducing input pressure of hydraulic Power Supply to the brake system. Although the WTB is the common used irreversibility system, its asymmetry performances in case of major failure of torque shaft fracture couldn't result reliable under particular flight conditions using simple asymmetry control based on differential position monitoring. WTB performance could be improved applying enhanced monitoring techniques characterized by increasing complexity [1-3].

4 Proposed Numerical Model

As previously described, the primary goal of this work is to define a numerical simulation model developed in the Matlab/Simulink® environment in order to simulate, with an acceptable accuracy, a modern flap actuation control systems, described in above paragraphs, improving WTB Wing tip brakes architecture with innovative monitoring and control algorithm in comparison with specific customized NBB No-Back solution. The robustness of the proposed simulation model allows to simulate different operative conditions and flap actuation system configurations.

Moreover, it evaluates different solutions and effective new monitoring techniques using the model as a suitable test simulation bench in order to support decision making process during design activities. Therefore, for this work a specific aircraft an ATR42 is considered as a reference flap actuation system, with specific operative flight conditions, in order to define a set of simulation parameters and boundary condition for simulation model runs.

A reference flap actuation system allows to define technical information improving simulation model accuracy, related to:

- **Geometries** of main components for example: flap surfaces, torque shafts, irreversibility breaks, gear boxes;
- **Operative flights conditions** during takeoff and landing phases for example: using to define aerodynamics loads working on the flap system;
- **Operative parameters** of main actuation system components for example: backlash, material characteristics, friction coefficients;

Furthermore dedicated design algorithm are developed to customize NBB solution for different civilian aircraft configuration as reference system to evaluate classical WTB solutions improved by innovative monitoring and control techniques.

The numerical simulation model reported in Fig. 6 is consistent with physical model described in previous paragraph and illustrated in Fig. 3. It is composed by nine main different sub systems:

1. **Com:** an input block that generates surfaces position commands (Com);
2. **SFCC:** subsystem simulating Slats-Flaps Computer control functions as PID controller and the Monitoring and Asymmetry Control Algorithms generating command signals for control system of servovalve (SV);
3. **Flapper-Nozzle SV:** third order electromechanical model to calculate SV spool displacement as function of SFCC command signals [4];
4. **Fluid Dynamic D:** Fluid Dynamic model to correlate Spool displacement **XS** to Differential Pressure **P12** and Flow Rate **QJ** managed by SV [5];

5. **PSR:** Power Supply Pressure generated by electrohydraulic pump;
6. **Hydraulic Motor:** Second order simulation model for hydraulic motor to transform hydraulic power to mechanical power evaluating, inertia, elastic torque of each transmission line shaft, viscous damping and internal friction phenomena;
7. **Transmission Model:** motion transmission model evaluating backlash and stiffness of torque shaft and universal joint and gear boxes, detailing specific parameters for left and right line;
8. **TRL,TRR:** Value of aerodynamic load acting both left and right flap surfaces;
9. **Left/Right Surface-Actuator:** second order model block for flap surfaces and ball screw actuators evaluating static and dynamic friction phenomena and main features of WTB and NBB systems.

Some nonlinear phenomena need to be managed by simulation numerical model in order to improve accuracy state by means of particular dedicated simulation algorithms. In our proposed simulation model we manage different nonlinear physic phenomena as static and dynamic Coulomb's friction, backlash, elastic viscous dumping, transient hydraulic behavior [6].

For each nonlinear phenomenon a specific numerical approach is defined and integrated within some model subsystems, leaving aside, where is possible, a massive integration related to a more complex numerical effort avoiding a negligible effects on model behaviors.

Among model subsystems showed in Fig. 6 we propose in this work two subsystems models: "Transmission subsystem" and "Surface Actuator subsystem" models which are critical for the accuracy of whole simulation model using different configurations related to each irreversibility brakes types.

The mechanical transmission subsystem shown in Fig. 7 simulates the behavior of the transmission torque shafts liking together by universal joints and the speed reducer gearboxes. The whole cinematic line is divided in the proposed architecture, in three main line components: motor model as fast shaft, mechanical transmission model as intermediate shaft and surface-actuator as low shaft. By means of convention all torque calculation are elaborated within intermediate shaft so we consider these gear ratio related to speed reducers: $\mathbf{Z_M}$ from fast shaft to intermediate shaft, $\mathbf{Z_S}$ from intermediate shaft to low shaft.

All cinematic lines are affected by backlashes simulated using **BLG** parameter to identify Zero Band of torque as function of deformation angle $\boldsymbol{\theta_{Trasm}}$ in (1) with specific values for left and right wing to improve accuracy of the model.

The mathematical model of backlash is based on θ_M motor shaft angle and $\boldsymbol{\theta_S}$ deflection surface angle, within the model this angle is indicated as **ThSL** for left surface and **ThSR** for right surface:

$$\theta_{Trasm} = \theta_M Z_M - \frac{\theta_S}{Z_S} \mp BLG \tag{1}$$

$$\theta_{Trasm} = 0 \quad \text{if} \quad -BLG \leq \theta_{Trasm} \leq BLG \tag{2}$$

The torque transmitted $\mathbf{C_{Trasm}}$ by transmission line is based on **KG** elastic stiffness coefficient and CG viscous elastic dumping coefficient which represents hysteresis behavior of the material used for transmission components when deformation speed is different than zero:

$$C_{Trasm} = IRG\left(C_{elast} + C_{visc}\right) \tag{3}$$

$$C_{elast} = KG\,\theta_{Trasm} \tag{4}$$

$$C_{visc} = CG\,\dot{\theta}_{Trasm} \tag{5}$$

The parameter **IRG** simulate the fracture line failure bringing to the transmitted torque (3) as sum of elastic (4) and viscous momentum (5). In particular the KG stiffness coefficient is composed by a series of different tarms considering an arbitrary division of cinematic line useful to introduce the effects of NBB NoBack system within transmission model.

$$KG = \left(\frac{1}{KMin} + \frac{1}{KMout}\right)^{-1} \tag{6}$$

The arbitrary division considers KMin the stifness coefficient from Motor to input line of NBB position and KMout form outline of NBB position to actuator. In the same way is simulated the CG viscous elastic coefficient as indicated in (7).

$$CG = \left(\frac{1}{CMin} + \frac{1}{CMout}\right)^{-1} \tag{7}$$

The arbitrary division considers CMin the viscous elastic coefficient from Motor to input line of NBB position and CMout form outline of NBB position to actuator. Therefore transmission model for classic flap actuation system with WTB is simulated as indicated in Fig. 8. Simulating a flap actuation system with NBB system it is necessary consider effects of this irreversibility brakes type on stiffness and viscous elastic dumping for the transmission system.

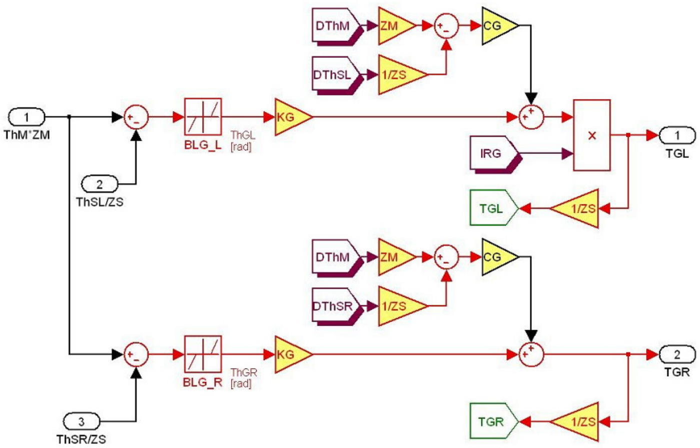

Fig.7: Diagram for Transmission Model with WTB.

The NBB increases stiffness of the transmission cinematic line adding a term KNB related to stiffness between input and output of mechanical NBB component, as reported in (8).

$$KG_{NBB} = \left(\frac{1}{KMin} + \frac{1}{KMout} + \frac{1}{KNB}\right)^{-1} \tag{8}$$

$$C_{elast1} = KG_{NBB}\,\theta_{Trasm} \tag{9}$$

Furthermore the elastic torque is defined for NBB architecture by two elastic torque components the first is illustrated in (9) the second considers internal stiffness of break spring and input and output shaft of NBB component illustrated in (11) where KNBF coefficient is NBB internal spring stiffness.

$$KGF = \left(\frac{1}{KMin} + \frac{1}{KMout} + \frac{1}{KNBF}\right)^{-1} \tag{10}$$

$$C_{elast2} = KGF\,\theta_{NBB} \tag{11}$$

Similarly the viscous elastic dumping coefficient **CG** is modified by the presence of NBB system introducing an additional term CNB related to viscous elastic dumping between input and output of NBB component.

$$CG_{NBB} = \left(\frac{1}{CMin} + \frac{1}{CMout} + \frac{1}{CNB}\right)^{-1} \tag{12}$$

$$C_{visc} = CG_{NBB}\,\dot{\theta}_{Trasm} \tag{13}$$

Another effect due to introduction of NBB system within flap actuation systems is the internal backlashes of NBB mechanism simulated with **ThTF1** which indicates a zero functional band linked to $\mathbf{C_{elast2}}$ function of $\boldsymbol{\theta_{NBB}}$ internal springs deformation angle (11) within this band also $\mathbf{C_{elast1}}$ has zero value. Therefore the backlash simulation of transmission model with NBB considers two backlash type as indicated in Fig. 8.

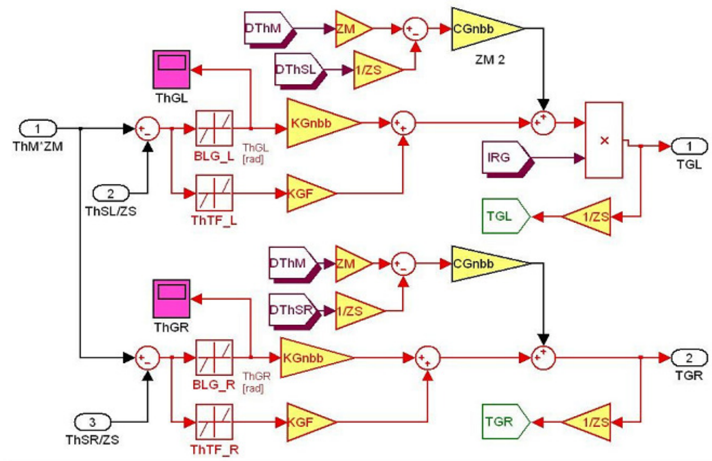

Fig. 8: Block Diagram for Transmission Model with NBB.

$$-BLG \le \theta_{Trasm} \le BLG \tag{14}$$

$$-ThTF1 \le \theta_{NBB} \le ThTF1 \tag{15}$$

An important nonlinear physics behavior simulated in this numerical model is related to the Coulomb's friction phenomena. Many authors have developed models to simulate static and dynamic Coulomb's friction forces as Stribeck, Karnopp, and Quinn [7-9]. All these models give simulation not corresponding to the real behavior, manifesting the problem of "zero crossing" between static and dynamic friction, or using the values of the main parameters arbitrarily defined by the users which make these models not reliable [10].

In this work the main friction model proposed by Borello et al. [11] (shown in Fig. 9) is applied avoiding the numerical simulation problems of the above mentioned friction models (especially "zero crossing" numerical oscillation) by stopping mechanical system for one integration time step when the relative speed between sliding surfaces changes sign. The proposed friction model is based on these variables:

- **FSJ:** Static Friction Force;
- **FDJ:** Dynamic Friction Force;
- **FF:** Resultant Friction Force;
- **DThSL:** Speed Transmission Line;
- **DThSL SP:** Reference value (not reset) of Speed Transmission Line;
- **ActTh**: Active Force on actuator surface system;

As shown in [11], the Borello dry friction model is integrated into the dynamic models of the components in order to guarantee a suitable accuracy and fidelity. This reference friction model is integrated within hydraulic motor model and, a dedicated actuator surface model for left and right wing in order to improve accuracy allowing different aerodynamic load configurations.

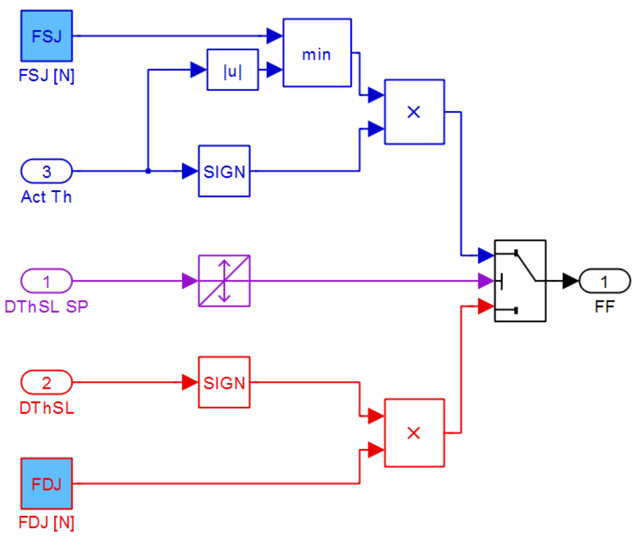

Fig.9: Block Diagram of Reference Friction Model.

The actuator surface model considers dynamic equilibrium equation (16) among **Act** active torques, $\mathbf{C_{res}}$ resistant torques, $\mathbf{C_{IN}}$ inertia component as function of θ_S angle, $\dot{\theta}_S$ speed, $\ddot{\theta}_S$ acceleration of flap surface.

$$Act - C_{Rev} + C_{In} = 0 \tag{16}$$

$$C_{disp} - C_{Visc} - C_{Est} = Act \tag{17}$$

$$C_{Attr} - C_{Irrev} = C_{Res} \tag{18}$$

In the Simulink Block Model we have implemented the WTB and NBB irreversibility brakes within a customization of friction model because their physical behaviors are similar to the friction torques. But the proposed brake systems are different so the related simulation models present many differences. A design process to define breaking torques of irreversibility breaks gives the operating parameter of the simulation model. The NBB NoBack breaks are simulated by "Simulink Lookup Table" where breaking torque $\mathbf{FF_{noback}}$ is a function of **ΔTG** difference between available torque **TGL** (for left wing) and **TRL** aerodynamic external load. The NBB apply for positive values of **ΔTG** a minimum constant torque value **FF_NBBmin** in every motion conditions.

When **ΔTG** get negatives values the breaking torque gain magnitude as indicated in Fig. 10. The WTB Wing Tip brakes are similarly simulated within the reference friction model but breaking torque has different designed value as function of **PSR** pressure supply value within driver hydraulic circuit of WTB. The friction discs of WTB begin to apply breaking torque when flap control system activates the break closing dedicated Relief valves.

When flap control system activates the WTB the **PSR** time transient is simulated by first order model transfer function from nominal value of **PSR** to **PSVc** minimum hydraulic pressure to apply a breaking torque, as indicated in Fig. 11.

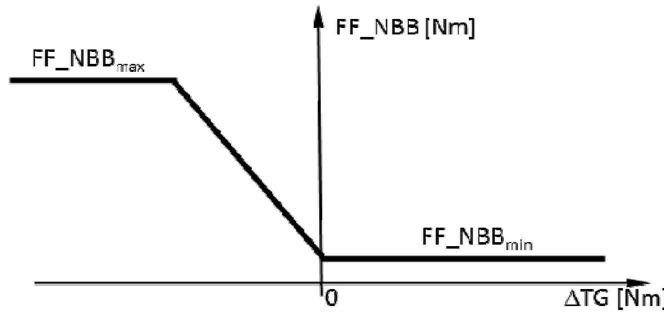

Fig.10: NBB Breaking Torque as a function of ΔTG.

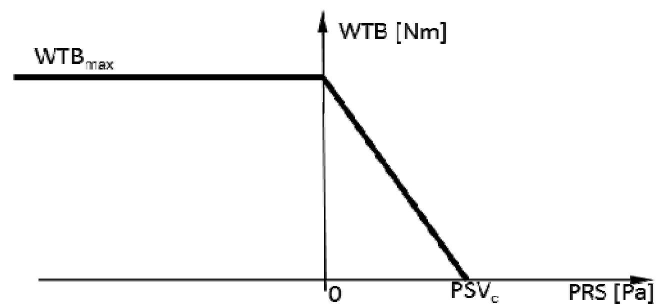

Fig.11: WTB Breaking Torque as a function of PSR.

4.1 Aircraft and autopilot modelling

In order to assess the amount of perturbations induced on the aircraft attitude by the failures of the flap actuation system, 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 [12].

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 [3].

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.

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4.2 Monitoring Asymmetry Techniques

The current monitoring technique is based on the detection of the differential position between left and right flap surfaces. Its use generally slightly reduces the asymmetry, but in some cases it may have an unreliable behavior [1]. To overcome these shortcomings different monitoring strategies have been developed by the authors in [2]. The assessment of their effectiveness has been performed using the aforesaid Simulink test bench, evaluating the ability of the different techniques to limit the asymmetry following a torque shaft fracture.

To this purpose, the standard PID controller has been integrated with a numerical algorithm that implements several asymmetry monitoring techniques, characterized by an increasing complexity and performances:

- Differential position control (type 1).
- Differential position and speed control (type 2).
- Differential position and speed conditioned control (type 2a).
- Differential position and speed proportional control (type 2c).
- Differential position and speed variable conditioned control (type 2d).

The differential position control technique, referred as asymmetry monitoring technique *type 1*, performs the flap asymmetry detection by comparing the electrical signals of the position transducers placed at the ends of left and right shaft subsystems. If this difference is greater than a defined limit $\Delta\theta_{Lim}$ persisting for more than a given evaluation time, an asymmetry failure is recognized and shut-off command procedure is activated to engage the WTB wingtip brakes.

The improved asymmetry monitoring techniques, which are belonging to the type 2 monitoring family, are based on detecting both position and speed differences of the two ends of the transmission line [1-3]. If either the position or the speed differential exceeds its established reference threshold for more than a given evaluation time, then an asymmetry is recognized.

5 Simulation Results

In order to evaluate the performance of the proposed numerical model and its ability to test the aforesaid monitoring techniques, several simulations have been run simulating a mechanical failure of the transmission shaft with a resulting asymmetry between right and left surfaces. It must be pointed out that the asymmetries obtained in case of large loads are always higher than the low load ones [1]; 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.

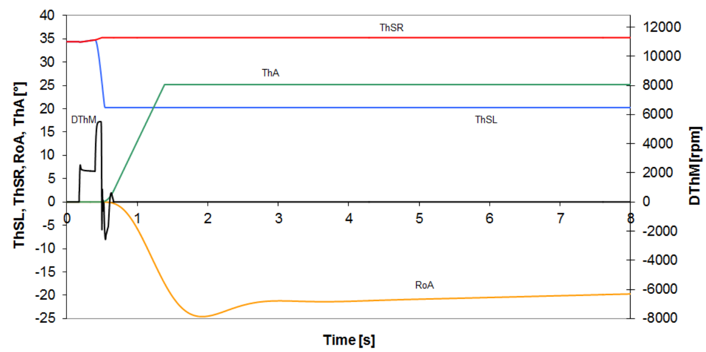

Fig.12: Flaps deployment under very high load – technique 1.

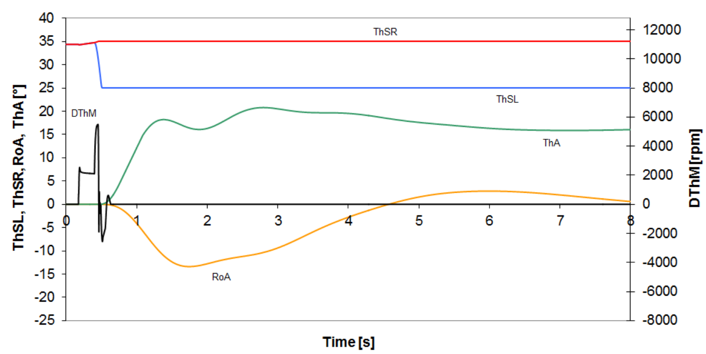

Fig.13: Flaps deployment under very high load – technique 2a.

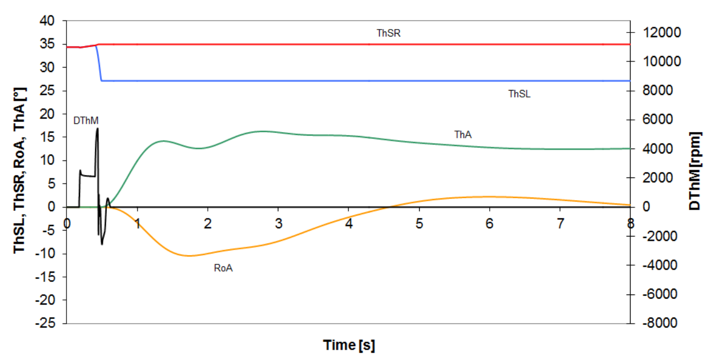

Fig.14: Flaps deployment under high load – technique 2c.

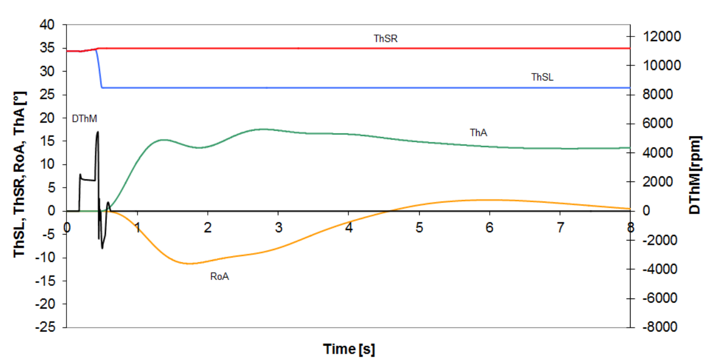

Fig.15: Flaps deployment under high load – technique 2d.

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Figures 12, 13, 14 and 15 (respectively monitoring techniques 1, 2a, 2c, 2d; failure time as before) show the simulations results for the 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 servomechanism stall load); this load act as opposing to the flap deployment.

For all the simulations the transmission shaft failure occurs at time = 0.4 s, while the actuation system is running at the rated speed, following the system start up time. The portion of flap system downstream the failure decelerates very fast under the action of the very high opposing load and then it 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. 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 12 puts in evidence that the technique 1 leads to an uncontrollable flight condition, because the aileron efficiency is not sufficient to balance the flaps asymmetry. According with the results shown in [2], the maximum flaps asymmetry with the resulting roll perturbation and aileron commands progressively decreases moving from monitoring technique 1 to the *type 2* techniques 2a, 2d and 2c (Figg. 13, 14 and 15). It must be noted that the proposed techniques 2c and 2d, in case of very large loads, perform a slightly lower detection time delay in comparison with technique 2a.

6 Conclusion

The proposed numerical model it is capable to perform, with an acceptable accuracy, a robust simulation algorithms in order to evaluate within a virtual environment the behavior of a wide range of flap actuation system configurations as a support for the decision making process throughout the pre-design activities. As concern the monitoring and control techniques the proposed simulation model allows to evaluate the effectiveness of each of them on reference architecture under analysis making as reference the NBB No-Back irreversibility brakes specifically designed by boundaries conditions of the model. It is also possible to use this "virtual bench" to develop, test and evaluate innovative monitoring and control techniques and conceive/develop new layouts able to improve the performances and the safety of the whole actuation system (e.g. centrifugal or nonlinear viscous brakes, innovative PDU conception or innovative actuators).

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