Preliminary study and modeling of a fly-by-wire rudder control system for STOL applications on the ATR 42-600

Gianluca Lombardo
Intern at ATR Aircraft – Engineering Divison, Blagnac (Toulouse), France, 31712

Many airlines operating on short-haul routes in remote areas of the world have lately expressed their urgent need for new aircraft, capable of being operated in very small airports and with low operating costs. As of today, turboprops are the most efficient aircraft for this type of operations and ATR, in order to address the emerging needs of its customers, launched the STOL program, whose basic idea is to improve the short runways capabilities of the ATR42-600. This study deals with an evolution of the rudder control system of the aircraft, concerning the introduction of the hydraulic actuation and the implementation of a fly-by-wire architecture. A proposal for a new and unconventional type of actuator is made: the kick/reaction link actuator, which proved to be suitable for the ATR 42-600 as it can be optimized to reduce significantly the loads on the vertical tail plane. Moreover, the design of a Direct Law is introduced, followed by a preliminary and qualitative analysis of the dynamic response of the system to different inputs.

Nomenclature

CAS	=	calibrated airspeed
OEW	=	operative empty weight
RTL	=	rudder travel limiter
TAS	=	true airspeed
TOFL	=	take-off field length
V1	=	decision speed
VMC	=	minimum control speed
VMCG	=	minimum control speed on ground

I. Introduction

THE basic idea behind the Short Take-Off and Landing program is to address the needs of the airlines operating the ATR42-600 in remote areas of the world and in airports with very low equipment on ground by improving the short runways capabilities of the aircraft in terms of *Take-Off Field Length* and *Landing Distance*.

The new performances would allow these airlines to access difficult airports and to increase the number of routes offered to their customers. Moreover, the improved STOL capabilities would permit a more flexible use of the aircraft, meaning that airlines would be able to address more specific categories of travelers.

The absence, in today's market of regional aviation, of alternatives from ATR's direct competitors, brings a strong added value to this project.

The ATR 42 STOL is intended for airlines operating on short-haul routes with a demand that ranges between 30 and 40 passengers per flight. Thus, the new performances of the aircraft are calculated at a MTOW lower than the current one and corresponding to 30/40 available seats and a range of 100 nm.

The reduction of the TOFL will be reached by lowering the Decision Speed of the aircraft (V1), whereas the reduction of the Landing Distance will be achieved by implementing the Ground Spoilers function and the Automatic Brake function.

The modifications on the design of the aircraft and its systems shall affect mainly the take-off and landing phases, minimizing the impact on the whole aircraft flight envelope. All technical solutions selected for low speed performances shall have minimum consequences on high speed performances, meaning that:

- The increase in OEW shall not modify significantly the payload/range diagram;
- The increase of loads shall be limited to low-speed flight envelope;
- The aerodynamic modifications shall not have an impact on drag polars.

In the frame of the STOL program it is a key element to have a smooth transition between the current ATR 42 and its STOL version. Modifications, limited to specific areas of the aircraft, must not impose any major revisions of the structural design, nor changes on systems that are not directly related to the STOL performances.

A. Impact on flight controls

The STOL performances impose two main modifications at the flight controls level:

- The introduction of the Ground Spoilers function;
- The increase of the yawing capabilities of the aircraft through a greater rudder surface.

The introduction of the Ground Spoilers is necessary to completely *spoil* the lift at touch-down and to further decelerate the aircraft. On an ATR today, spoilers are hydro-mechanically powered in an anti-symmetrical way in order to assist a roll maneuver. The introduction of the Ground Spoilers function will impose a revision of the current architecture to implement both the anti-symmetrical actuation in flight and the symmetrical actuation on ground.

As regards the increase of the yawing capabilities of the aircraft, a great constraint is posed by the EASA CS25[1] regulation on Minimum Control Speed (VMC). In the case of an engine failure, in fact, the aircraft needs to be always controllable, meaning that it must be possible for the pilot to act on the rudder and ailerons in order to counterbalance the moment resulting from the unbalanced thrust and maintain a proper bank angle (EASA CS25.147).

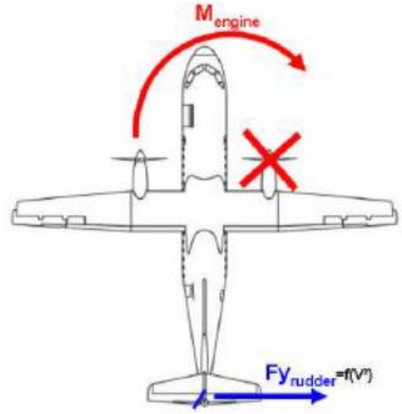

Figure 1. Unbalanced thrust after an engine failure

In particular, given that an engine failure can occur on ground during the take-off run, it must be proven that, before the V1 is reached, it is possible to "*maintain control of the aeroplane using the rudder control alone [...] to enable take-off to be safely continued using normal piloting skills*". In this case, the Minimum Control Speed, normally defined as the calibrated airspeed necessary to maintain straight flight with one engine inoperative and an angle of bank of not more than 5°, is called Minimum Control Speed on Ground (VMCG) and it is certified to ensure that the lateral deviation of the aircraft path during the take-off acceleration, from the moment the critical engine becomes inoperative, does not exceed 9.1m from the original trajectory.

In the frame of the STOL project, a reduction of the V1, necessary to attain a lower TOFL, leads to a reduction of the VMCG, the latter being always lower than the Decision Speed. As such, an increase of the rudder surface is deemed necessary to attain the required yawing performances at low speed and satisfy the regulation.

B. A Fly-by-Wire architecture

The new rudder will derive from the current one (same aerodynamic profile) through an increase of its span and chord. The tab on the trailing edge, today used as a spring tab to reduce the efforts of the pilots, will be converted into an anti-tab, meaning that its deflection would happen towards the same direction of the rudder and will contribute to increase the lateral force and the yawing moment of the aircraft.

Such modifications, however, cause a dramatic increase of the hinge moment, making it impossible for the pilot to withstand the efforts with the current mechanical controls made of rods, cables and pulleys. Thus, an evolution of the rudder control system towards a fly-by-wire architecture with hydraulic actuation is a necessary step of the program.

Given the absence of a force feedback in the cockpit whenever the interface between the pilots and the control surfaces of an aircraft is achieved by means of an electric loop, a Pedal Feel and Trim Unit (PFTU) will be also installed to provide the trim function and an artificial feeling of effort proportional to the deflection of the pedal legs.

A second element, called Pedal Damping and Friction Unit (PDFU) will damp out the pedals' oscillations in the case of a sudden release and will prevent them from "falling" in the case of rupture of the PFTU rod.

As regards the hydraulic actuation, one of the key aspects to take into account is the significant increase of the loads on the rear spar of the vertical tail plane, where the actuators would be fixed. Since the structure of the vertical tail plane of the ATR 42-600 was not initially designed to withstand the increased loads deriving from the STOL performances, the possibility to install a new and unconventional type of hydraulic actuators, the reaction/kick link, has been taken into consideration.

II. Reaction/Kick link actuators

Reaction/Kick link actuators are relatively new in the industry, some examples being the Boeing 787 and the Bombardier CSeries for the actuation of the rudder.

The reaction link is used as a constituent component of an actuator for driving a control surface of an aircraft and it can be coupled to a hydraulically driven cylinder whose one end is attached pivotably to the control surface or to a horn arm member on the control surface. The objective is to achieve secure strength and rigidity equal to or higher than those achieved by conventional technology, while reducing the weight and ensuring sufficient rigidity against multi-directional loads.[2]

Primary flight controls are suitable for this type of actuators, which can be used also on flaps and spoilers. For the STOL program, the reaction/kick link actuator has been taken into consideration because of its compact dimensions with respect to a conventional pin-to-pin actuator, which makes it possible to install it in the narrow space between the vertical tail plane and the rudder. The installation of the actuators between the two parts of the vertical empennage, in fact, is quite conventional and prevents problems with the global stiffness of the control chain, typically encountered when using a torque tube.

In addition to that, the specific configuration of a reaction/kick link actuator allows the distribution of almost 80% of the loads of the cylinder on the reaction link (which is connected to the control surface) and the remaining 20% on the rear spar of the vertical tail plane, thus limiting the loads on the fixed part of the empennage and avoiding the need to modify its structural design.

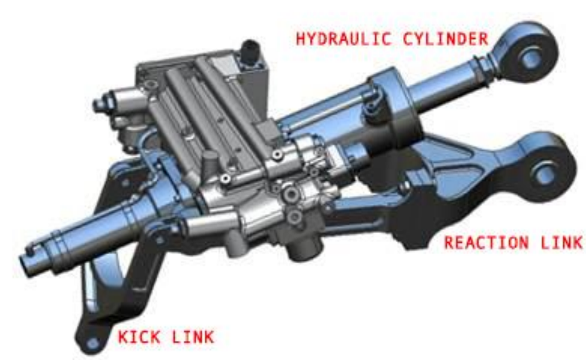

Figure 2. Example of reaction/kick link actuator

The main elements of a reaction/kick link actuator are:

- The hydraulic cylinder;
- The reaction link;
- The kick link;
- The bearings and other elements.

C. Installation on the ATR 42

The studies performed by a Flight Controls Integration specialist together with the Head of Conceptual Design led to the baseline configuration shown in Figure 3.

The reaction link and the kick link are connected by a bearing and the hydraulic cylinder is pivotably attached on the reaction link.

Due to the very limited space, the actuator body could be forced to move inside a hole in the rear spar of the vertical tail plane, depending on the final dimensions of each element.

This kinematic constraint was carefully considered during the sizing of the system as the freedom for the actuator to move withouth any mechanical limitations for the whole rudder deflection shall be absolutely guaranteed.

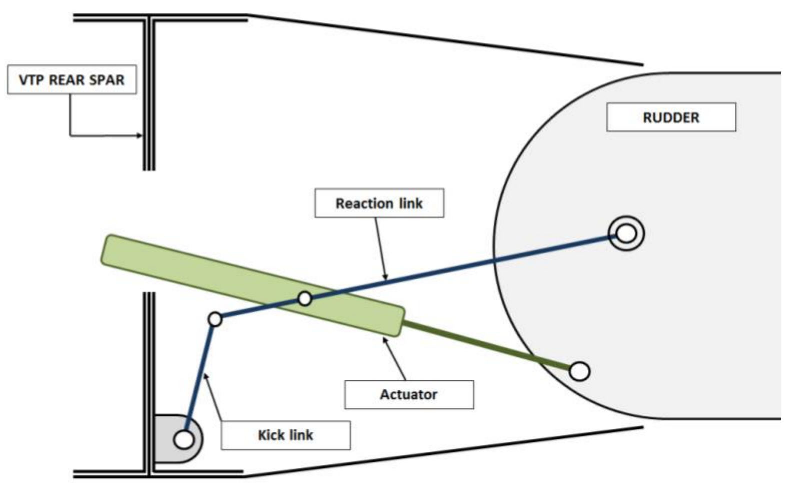

Figure 3. Baseline configuration for the ATR 42 STOL

D. The kinematic model

In order to perform a feasibility analysis and proceed with a preliminary optimization of the system, the kinematics of the actuator has been calculated through a simple 2D model.

With reference to the scheme in Figure 4 and considering as positive the rudder positions corresponding to a nose-left demand for the aircraft, the following relations hold, where $\overline{DR_0}$ is the length of the actuator when the rudder is in neutral position and θ is the rudder angular position:

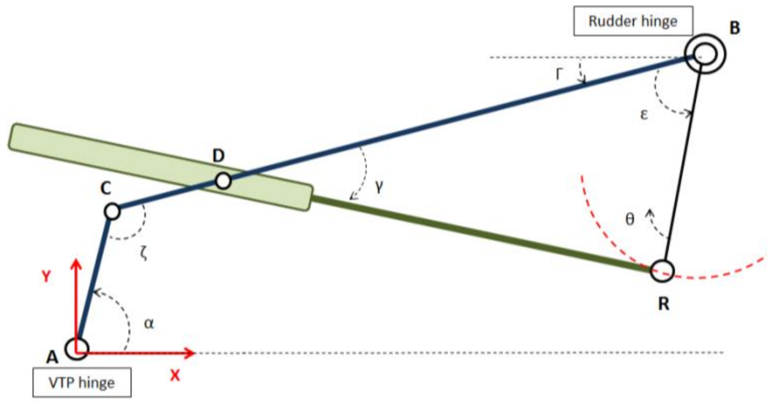

Figure 4. 2D kinematic scheme of the reaction/kick link actuator

$$\epsilon = arccos\left(\frac{\overline{BD}^2 + \overline{BR}^2 - \overline{DR_0}^2}{2 \cdot \overline{BD} \cdot \overline{BR}}\right) \tag{1}$$

$$\overline{DR} = \sqrt{\overline{BD}^2 + \overline{BR}^2 - 2 \cdot \overline{BD} \cdot \overline{BR} \cdot \cos\epsilon} \tag{2}$$

Thus, the position of the actuator is defined by the angle γ as:

$$\gamma = arccos\left(\frac{\overline{DR}^2 + \overline{BD}^2 - \overline{BR}^2}{2 \cdot \overline{DR} \cdot \overline{BD}}\right) \tag{3}$$

The stroke of the actuator is then computed as:

$$\Delta s = \overline{DR} - \overline{DR_0} \tag{4}$$

In order to verify that a given configuration can be installed on the aircraft, the possibility for the hydraulic cylinder to rotate freely within the hole in the rear spar of the vertical tail plane must be verified. Considering the geometrical scheme in Figure 5, the following quantities are defined:

$$i_1 = e \cdot \cos(\delta) + \Delta x_{min} + \Delta i \cdot p \tag{5}$$

$$i_2 = e \cdot \sin(\delta) \tag{6}$$

$$E = i_2 + i_1 \cdot \tan(\gamma - \Gamma) \tag{7}$$

Thus, if condition (8) is verified, then the body of the cylinder is partially inside the hole in the spar and the conditions (9) and (10) must be also verified to ensure it does not get in contact with the spar, nor it is limited in its movement:

$$i_1 < (L_{TOT} - L_0) \cdot \cos(\gamma - \Gamma) \tag{8}$$

$$E - 0.5 \cdot \frac{\phi}{\cos(\gamma - \Gamma)} > m + n \tag{9}$$

$$E + 0.5 \cdot \frac{\phi}{\cos(\gamma - \Gamma)} < m + n + s \tag{10}$$

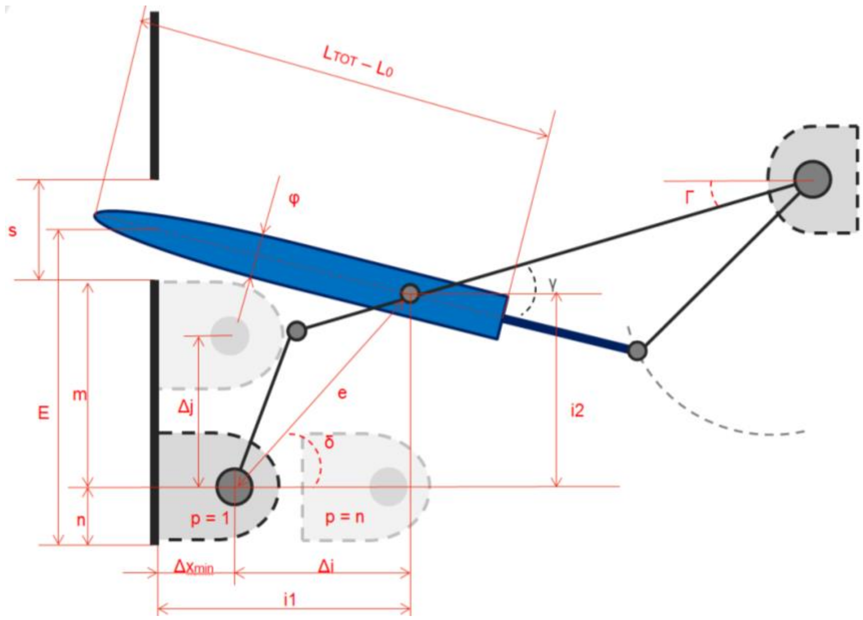

Figure 5. Verification of the kinematic constraints

E. Computation of the forces

The computation of the forces on the hinges has been done considering a 2D model made of two rods (corresponding to the reaction link and the kick link), each having two degrees of freedom, and three hinges (A, B and C), as shown in Figure 6.

Each hinge removes two degrees of freedom and the system is iso-static. Thus, only the equations for the equilibrium of the forces along X and Y directions, combined with the equation imposing a null resultant moment around the Z axis, are sufficient to solve the system.

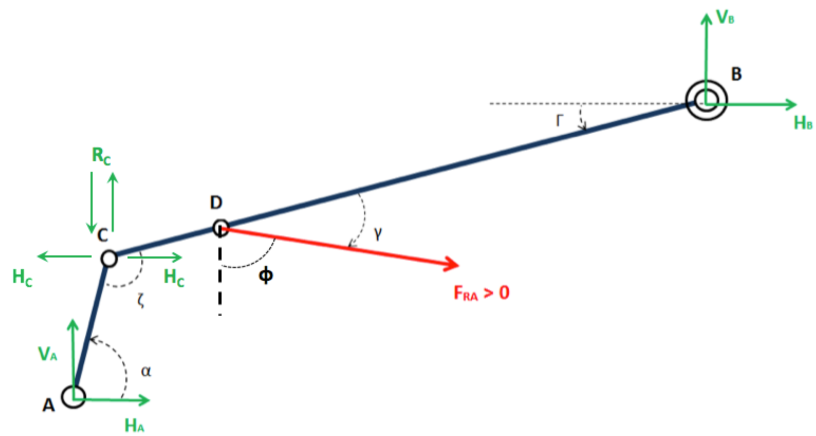

Figure 6. 2D scheme for the computation of the forces

The load applied by the actuator on the reaction link is considered as positive when the actuator *pulls* the rudder towards positive rudder deflection angles (nose-left demand).

In order to write the equations for the equilibrium, the system can be decomposed and each element considered alone. The resulting system of equations written with matrices is given by (11).

$$\begin{bmatrix} 1 & 0 & -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -1 & 0 & 0 \\ 0 & 0 & a \cdot \cos\alpha & -a \cdot \sin\alpha & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & -(b+c) \cdot \cos\Gamma & (b+c) \cdot \sin\Gamma \end{bmatrix} \cdot \begin{bmatrix} V_A \\ H_A \\ R_C \\ H_C \\ V_B \\ H_B \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ F_{RA} \cdot \cos\phi \\ -F_{RA} \cdot \sin\phi \\ -F_{RA} \cdot c \cdot \sin\phi \end{bmatrix} \tag{11}$$

Given M the matrix of the coefficients, **R** the vector of the reaction forces on the hinges and **F** the vector of the external applied loads, the reactions **R** are obtained through inversion of the matrix M:

$$\boldsymbol{R} = [M]^{-1} \cdot \boldsymbol{F} \tag{12}$$

F. Observations and optimization algorithm

The models for the study of the kinematics and the computation of the forces on the hinges have been used for a parametric analysis in order to better understand the behavior of the reaction/kick link actuator chosen as baseline.

By fixing all the geometrical parameters except the dimension of the reaction link and making the assumption of a constant load on the actuator (not realistic as the hinge moment varies with the rudder deflection angle, but conservative if the design stall load is used), it has been confirmed that the greater the ratio between the lengths of the reaction link and of the kick link, the smaller the percentage of the actuator load on the kick link (Figure 7). Moreover, the position of the hydraulic cylinder on the reaction link does not have a significant effect on the value of the force exerted by the kick link.

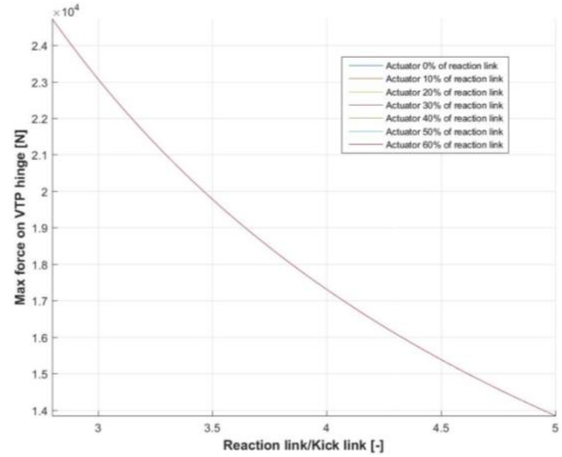

Figure 7. Effect on the forces on the VTP of an increase in the reaction link length

In addition, it has been observed that the maximum reaction force on the hinge of the vertical tail plane varies with the angle between the reaction and the kick links with a trend close to a second order function, with a minimum for 90° (Figure 8).

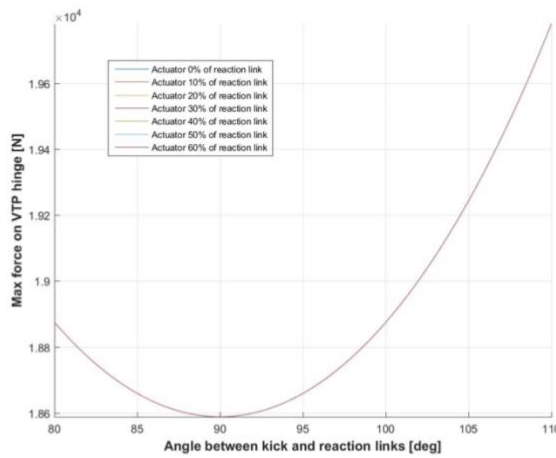

Figure 8. Effect on the forces on the VTP of an increase in the angle between the linkages

Thus, the values of the loads applied on the structure of the vertical tail plane can be reduced and optimized simply by changing the geometrical parameters discussed above. In order to do so with sufficient accuracy and to take into consideration the installation constraints, an algorithm to find the configuration of the system that minimizes the forces on the VTP rear spar has been developed in Matlab.

This algorithm uses the 2D kinematic model described in paragraphs D and F and, for each configuration, it verifies that the movement of the cylinder is not limited by the rear VTP spar for the entire rotation of the rudder.

On the basis of the results of the parametric study, it has been decided to optimize the geometry of the actuator by varying the following parameters:

- The VTP hinge position along X and Y from a reference point coinciding with the closest position to the rear VTP spar;
- The kick link length between 60mm and 120mm;
- The reaction link length, defined through the ratio with the kick link length between 2.8 and 8;
- The position of the actuator on the reaction link between 0% and 60% of the length of the reaction link from the internal hinge of the system.

The optimization, performed through nested "*for*" loops among $56 \cdot 10^5$ possible configurations, led to an improvement, in terms of reduction of the loads on the rear VTP spar, equal to 31% with respect to the baseline geometry (Figure 9).

Moreover, the maximum load obtained with the optimal configuration is withstandable by the current VTP rear spar and, thus, the study permitted to confirm the feasibility of the modification.

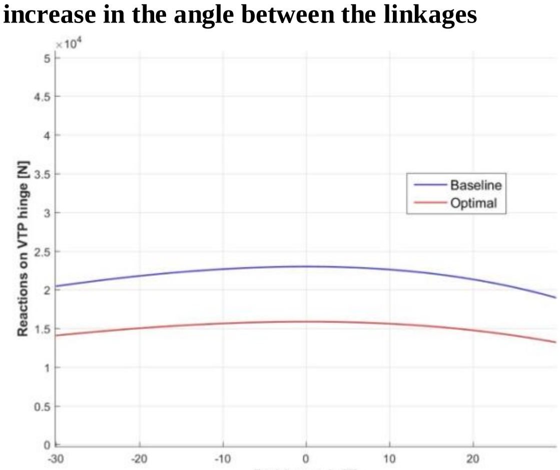

Figure 9. Comparison of the maximum loads on the VTP rear spar between baseline and optimized configurations

III. Design of a Direct Law

The introduction of electric flight controls implies the need to develop a control law to operate the surface. For a first approach to the problem, it has been decided to implement a Direct Law, whose purpose is to generate a rudder deflection as a direct function of the pilot's order.

The design of the control law has been preceeded by the development of a simulation model of the system on Simscape/Simulink in order to have a tool to perform an assessement of the response of the system when a Direct Law is implemented, rather than an analysis of the performances of the law itself (indeed, the flight physics of the aircraft is not simulated).

In order to have an accurate representation of the dynamics of the system, the possibilities offered by Simscape have been fully exploited and all the mechanical elements have been imported from CATIA with their real inertial characteristics. The different mechanical parts of the control chain have been connected with each other using different models of joints, representative of the real degrees of freedom between the connected parts.

Normal pin-to-pin actuators have been roughly modeled, as the design of the reaction/kick link had not been finalized yet.

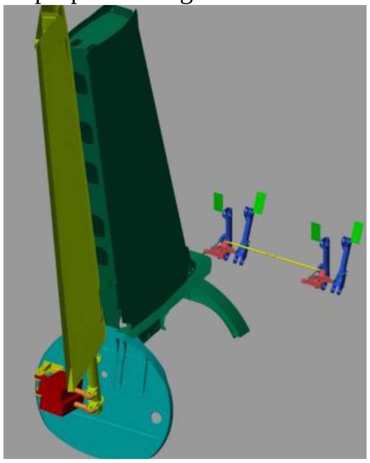

Figure 10. Simulation model on Simscape

G. Architecture of the Direct Law

The purpose of a Direct Law is to create an immediate link between the orders of the pilot and the control surface of the aircraft through an electrical signal.

Two levels can be identified:

- The Direct Law
- The control loop of each actuator

The Direct Law takes into account the position of the pedals and normalizes it with respect to their full mechanical deflection through gain N.

The normalized pilot's order is then multiplied by the maximum allowed rudder deflection angle, that is computed by the RTL module as a function of the Calibrated Air Speed, the engine torque and the flaps configuration.

Thus, an equivalent rudder order is produced and sent to the actuators' proportional control loop, whose role is to generate an electrical signal for the servo-valves and to control the rudder towards the desired position.

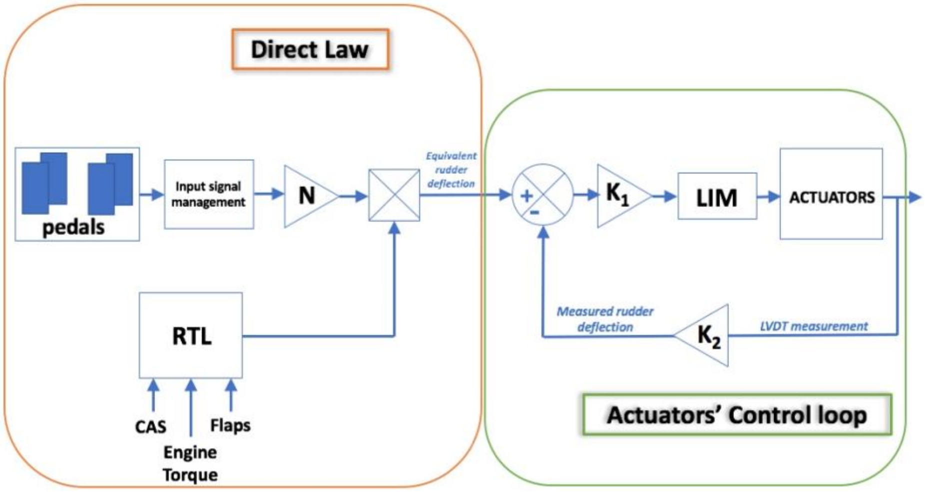

Figure 11. Architecture of the Direct Law

H. Input signal management

The information on the angular position of the pedal legs comes from three sensors placed on:

- Captain's pedals
- First Officier's pedals
- PFTU lever arm

These three electrical signals must be:

- Within an allowable range of values, whose extremes correspond to the full negative and full positive deflection angles of the pedal legs;
- Consistent between each other, meaning that discrepancies between the signals must be within a specified threshold.

The *In Line Monitoring* function performs the first of the verifications above: each signal is compared with the minimum and maximum mechanical deflection angles of the pedals and, if it is well contained in this range, an "*and"* port outputs a Boolean value indicating the validity of the electrical signal (Figure 12).

The *Monitoring* function, instead, takes as input the differences between couples of signals (DXY, where XY indicates the numbers of the compared signals): each of these differences is then compared to a given threshold and, whenever the threshold is trespassed for more than 100ms, a Boolean parameter (BXY) is set to 1 through a *Set-Reset* logic to indicate the anomaly.

If at least one anomaly is present in the information carried by the three signals, the "wrong" sensors are chosen among those causing the greatest deviation DXY.

The exclusion of a sensor is done whether the *In Line Monitoring* function or the *Monitoring* function detect an anomaly.

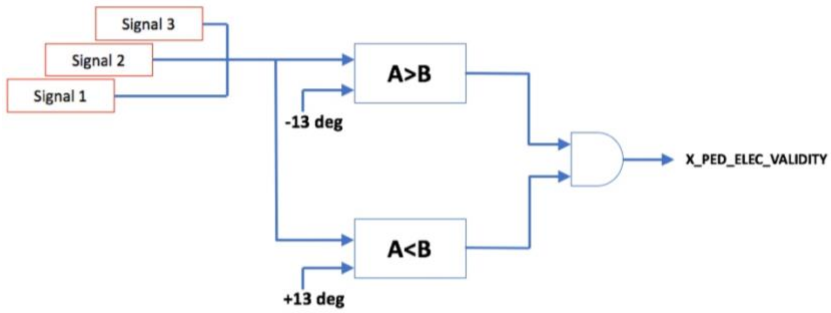

Figure 12. In Line Monitoring Function

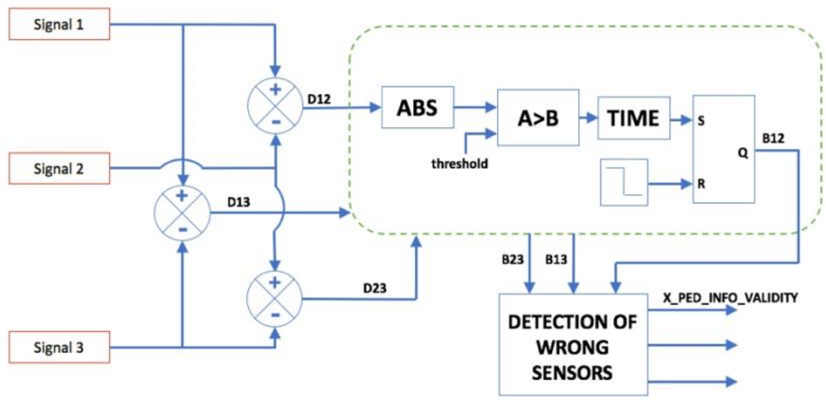

Figure 13. Monitoring Function

I. The RTL module

The function of the RTL module is to limit the rudder order according to the speed of the aircraft, the torque of the engine and the flaps configuration.

Significant deflections of the rudder at high speed, in fact, must be prevented in order to preserve the structural integrity of the empennage.

The limitations, whose values cannot be disclosed due to confidentiality reasons, on the rudder angle have been computed by the Handling Qualities deparment and linearly interpolated (Figure 14) for their implementation through Lookup tables in the Simulink model of the Direct Law.

J. The actuators' control loop

With reference to Figure 11 the equivalent rudder order, computed by the Direct law, is compared with the measured rudder deflection angle. The error is used to generate a proportional electrical current for the servo-valves of the actuators. The value of the current is limited in order to protect the servo-valves from over-heating.

The gain K_1 has to be a compromise between the need to have a sufficiently reactive response of the actuators, a sufficient accuracy in static conditions and the stability of the control loop. For a proportional control loop, the first two objectives are achieved by increasing the gain K_1, whereas the stability of the system requires the same gain to be lowered.

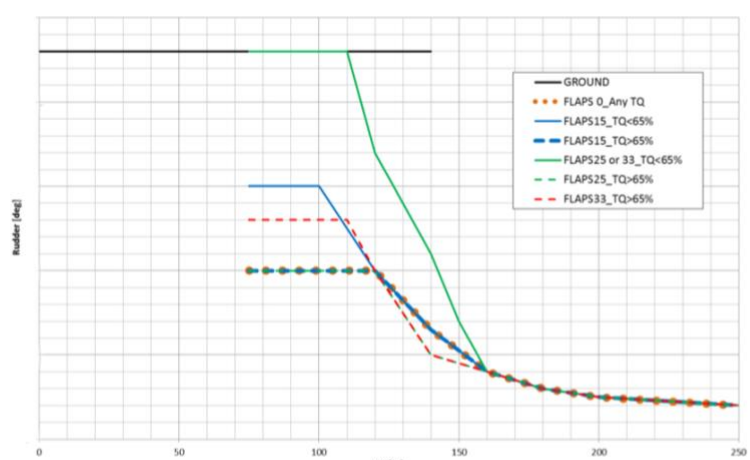

Figure 14. RTL values

The gain K_2 on the feedback branch performs a geometrical conversion of the linear position of the actuators'rods (measured by LVDT sensors) to the corresponding rudder deflection angle. The assumption of a linear relationship linking the actuators'stroke to the rudder deflection has been verified through a comparison between the real 3D kinematics and its linearized model (Figure 15).

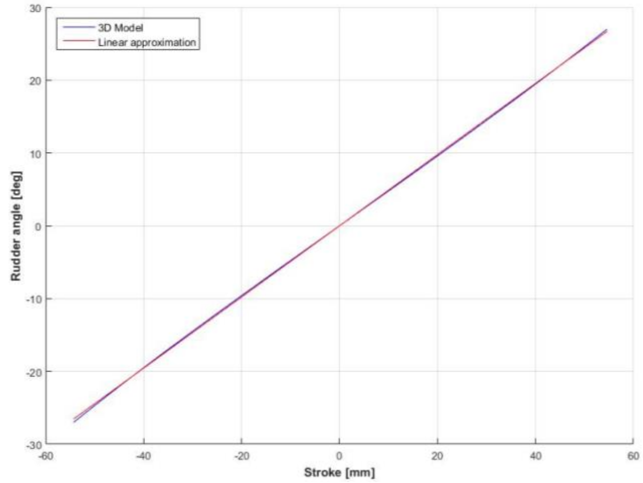

Figure 15. Comparison between the real actuator kinematics and its linearized model

K. Force- fight

The actuation of the rudder will be achieved using two actuators in *active mode* at the same time. Differences in their dynamic responses, or the non-perfect synchronization would lead to different forces on the control surface, causing an over-stress of the rudder and a dramatic reduction of the fatigue life of the actuators.

The difference between the differential pressures of the two hydraulic cylinders is called *force fight* and a controlled compensation needs to be included in the servo-loop:

$$FF = \Delta P_1 - \Delta P_2 \tag{13}$$

The idea behind the force fight control is to modify the feedback information of each actuator's servo-loop with a compensation signal in a way that, if the force exerted by one of the actuators is higher than the other one, the compensation signal will be added to the position information sensed by the LVDT sensors before its comparison with the order; this would allow to reduce the error between the order and the actual state of the actuator, leading to a reduction of the differential pressure in the chambers. On the other actuator, the compensation signal would be subtracted from the position information sensed by the LVDT sensors, so as to increase the error between the order and the actual state of the actuator and lead to an increase of the differential pressure in its chambers (Figure 16).

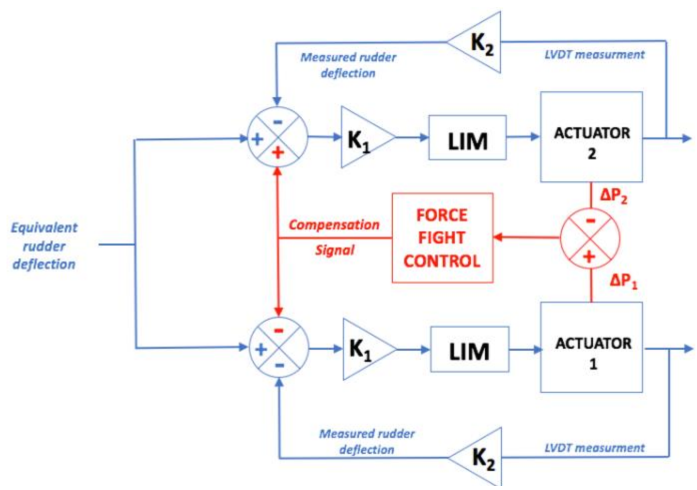

Figure 16. Force-fight control

The compensation signal Δs is generated through a proportional-integral logic, function of the force fight (Figure 17): the integral control is efficient at low frequencies, whereas the proportional term gives a fast response to reduce the delays between the two actuators.

In any case, the force-fight control authority is limited with a saturation of the generated signal to a few millimeters.

Figure 18 and Figure 19 show the effect of the introduction of the force-fight control between the two actuators' servo-loops: on the left, the control is disabled and a difference in the differential pressures of the two actuators is present; on the right, the same simulation with the control enabled shows that the difference previously observed is eliminated.

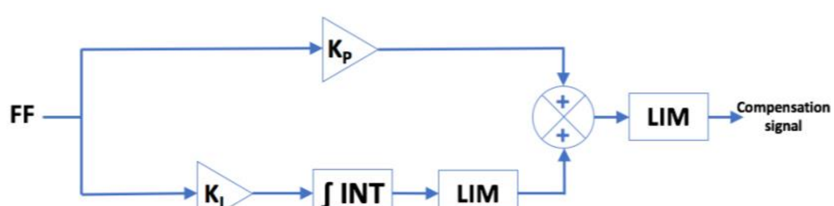

Figure 17. Force-fight control algorithm

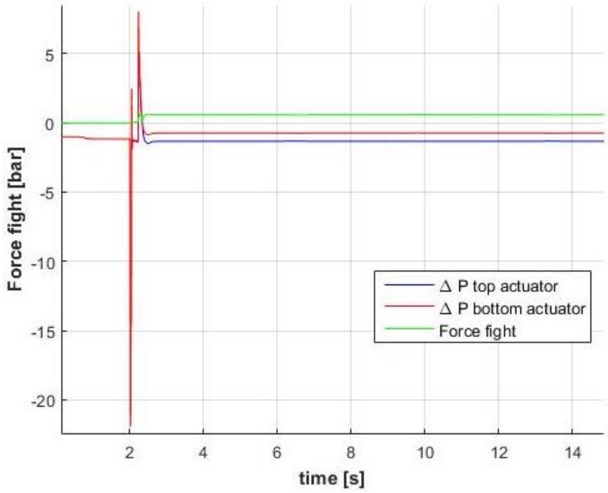

Figure 19. Force-fight control enabled

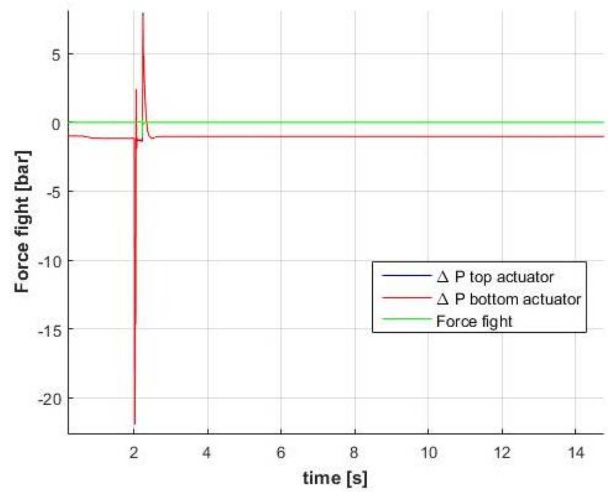

Figure 18. Force-fight control disabled

L. Results of the simulations

The Direct Law has been tested with the following types of inputs on the pedal legs:

- step input, to verify the accuracy in static conditions;
- square wave input, to highlight possible overshoots on the rudder position and to evaluate the capability to invert the sense of motion;
- sinusoidal input at 1.5Hz, to analyze the response of the control surface in terms of amplitude and phase.

The aerodynamic hinge moment, computed through simulation by the Loads Department as a function of the rudder deflection and of the sideslip angle, has been included in the simulation model.

All the simulations have been performed at:

- flight altitude $Z_P = 4000m$;
- $TAS = 100kt$;
- $Flaps = 25°$;
- Engine torque $T < 60\%$

The selected flight point allows the maximum RTL deflection angle.

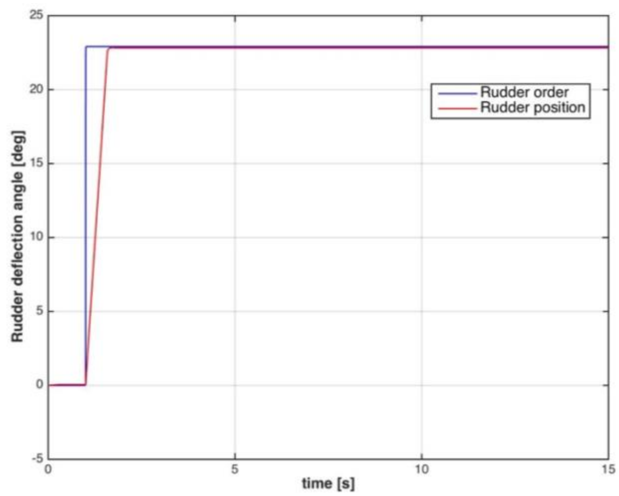

Figure 20. Response to a step input

1. Step Input

The step order highlighted a good and sufficiently reactive response of the system to the input (Figure 20), with a good actuation speed and a sufficient accuracy in static conditions (static error close to 0.08 degrees).

Also, the force-fight control loop efficiently removes the differences in the force exerted by the two actuators and synchronizes them towards the same objective.

The spikes on the differential pressure of the two hydraulic cylinders (Figure 21) are due to the sudden opening/closure of the servo-valves, whereas the increase of the differential pressure during the actuation of the surface is a direct consequence of the increase of the hinge moment with the rudder deflection angle.

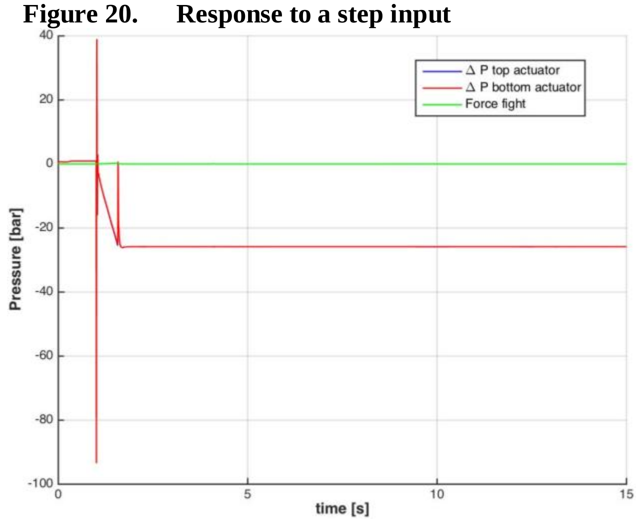

Figure 21. Differential pressure and force-fight

2. *Square wave input*

The response of the system is very similar to that after a step input: the control surface attains the required position with good accuracy and the inversion of the order is realized without any remarkable issue (Figure 22).

3. *Sinusoidal input at 1.5Hz*

The response of the system is basically in phase with the order and no amplification or attenuation of the input are present (Figure 23).

The differential pressures of the two actuators are kept at the same value by the force-fight control loop.

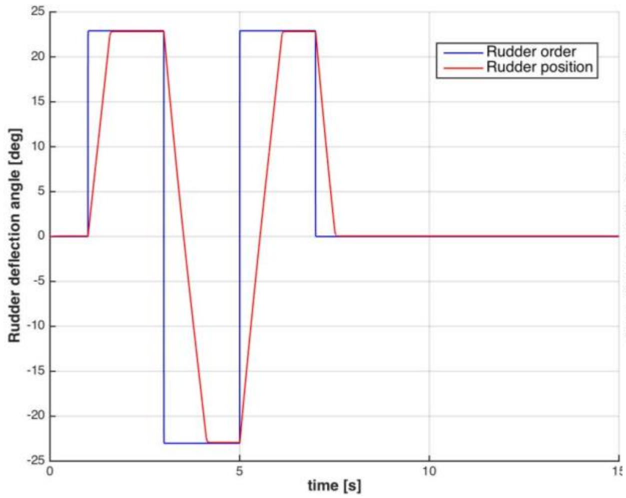

Figure 22. Response to a square wave input

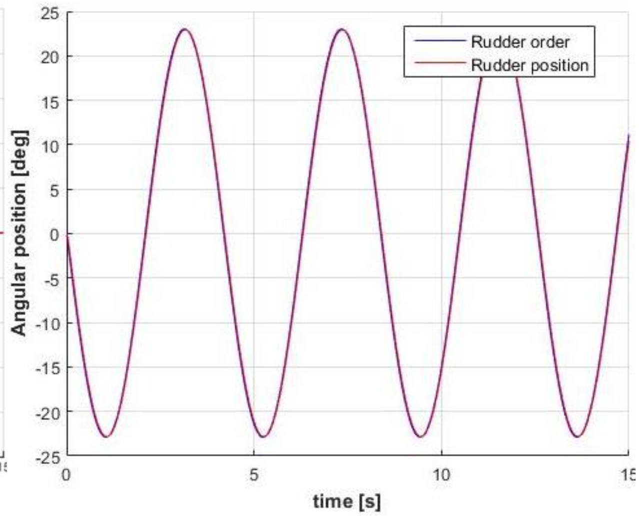

Figure 23. Response to a sinusoidal input

IV. Conclusions

The analysis and preliminary optimization of the reaction/kick link actuator allowed to understand that this type of actuator is suitable for the ATR 42 STOL as it contributes to a significant reduction of the loads on the vertical tail plane with respect to a normal pin-to-pin actuator, avoiding the need to review the structural design of the empennage. Moreover, it created a basis for future studies of the system and for a detailed sizing.

As regards the Direct law, a more thourough tuning of the gains will be performed in order to achieve the best performance. The simulation tool in Simscape will be used to verify the compliance of the response of the system with the requirements and with the EASA CS25.

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