# AEGATS'18
# REDUCTION OF VERTICAL TAIL USING DIFFERENTIAL THRUST: INFLUENCE ON FLIGHT CONTROL AND CERTIFICATION

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**KEYWORDS:** distributed electric propulsion, differential thrust, certification, vertical tail design, flight control and stability.

**ABSTRACT:**

The flight control characteristics and certification compliance of a Distributed Electric Propulsion (DEP) aircraft using differential thrust is studied through exploration of flight envelops. Identification of critical flight phases specific to the use of propulsion systems as actuators for flight control is performed. In particular the influence of engine failures on the flight envelop and means of mitigation are given. It is concluded that an aircraft using differential thrust has a most advantageous flight envelop at the point of neutral directional static stability allowing a reduction of 45% of the vertical tail surface area. Additionally, the directional control could be entirely provided by differential thrust, eliminating the need for a rudder. Study of this type of aircraft showed specific failure modes that differ from the actual certification prescriptions. New more relevant definitions and parameters are proposed as basis to demonstrate compliance with high level certification objectives.

## 1. INTRODUCTION

Distributed Electric Propulsion is seen as a way to increase the efficiency of an aircraft through drag reduction offered by aero-propulsive synergy such as blowing [1] or boundary layer ingestion [2], efficiency increase offered by hybrid or all electric aircraft configurations [3] as well as increase of flight control authority and handling qualities [2]. Within this last subject, recent papers studied the possibility to use differential thrust to increase the directional control authority [4] [5]. Whether or not to use differential thrust on an aircraft depends on the possible benefits it could bring. Most of the benefits come with the reduction of vertical tail surface area, thus a gain in mass and surface drag. These benefits depend highly on the configuration of the propulsion, the flight conditions and the safety associated with such a system. This study aims at bringing more knowledge about the characteristics of a directional control with differential thrust, in normal and failure modes, its impact on the design of the aircraft and on the safety demonstration. The focus is held on the influence of the surface area of the vertical tail to assess its possible reduction. The design point of the vertical tail is usually constrained by certification requirements. However, in the case of distributed electric propulsion these requirements might not restrict anymore the design point of the vertical tail. In this case, one or many new design points must be defined in the specific case of differential thrust control.

In parallel, certification of an aircraft with novel propulsion integration and usage raises several questions. Certification specifications prescribe requirements based on traditional aircraft, and therefore are not well-adapted to DEP aircraft. Research in this direction is an active field with the emergence of numerous distributed propulsion architecture [1] [4] [5] [6]. A common problematic encountered in these researches is the adoption of the current means of demonstrating certification compliance which are not well suited to the specific configuration. In addition, the high number of different configurations and the predominance of system design in distributed systems [1] [6] [7], force the regulation to be less prescriptive on the design to cope with the lag on innovation. This change of paradigm would necessitate the establishment of flexible means of demonstrating compliance to certification requirements to support innovation while keeping high safety as a priority as recently introduced in CS-23 amendment 5.

The strategy retained to study the characteristics of differential thrust control is the exploration of flight envelop. The first part of this study briefly describes how the flight envelop are obtained. Then, based on previous results, critical flight phases and relevant parameters are chosen to explore their influence on the flight envelop. In a second part, based on the knowledge obtained on the use of differential thrust, means to demonstrate compliance with safety regulation of an aircraft using differential thrust are discussed.

## 2. FLIGHT ENVELOP USING DIFFERENTIAL THRUST

Determining the flight envelop in aircraft design is a crucial step that conditions the operational use of the aircraft. The aircraft designer must determine the possible flight domain of an aircraft both in normal conditions and in most likely failure modes. Any configuration that does not meet an aircraft designer's requirements on the flight domain should be withdrawn from the solution space.

The flight envelop can be determined by computing equilibrium points through a trimming algorithm that directly solves the non-linear 6 DOF equation of flight. This method, although requiring some time for calculation, has the advantage of not simplifying the equation prior to find an equilibrium point. The method, presented by Goman in [9], allows comparing aircraft on the basis of their attainable equilibrium points. Once adapted to distributed propulsion as presented by Nguyen Van and al. in [4] it permits a fast assessment of one control actuation system over another at different flight condition and subsequently allows identifying design points for unconventional control actuation system. For the sack of brevity, only the important features of the framework will be presented in the next subsection and the interested reader is referred to [4] for full details.

### 2.1. THRUST MODELING

On distributed electric propulsion, where each engine can be controlled independently as shown in Figure 1 the thrust model is expressed as:

$$T_{x,i} = \frac{P_L}{N} V^{-1} \eta_m \eta_p \delta_{x,i} \qquad (1)$$

Where $P_L$ is the total electric power available from the power line, *N* is the total number of engine, $\eta_m$ and $\eta_p$ are respectively the engine and propeller efficiency (both considered constant) and $\delta_{x,i}$ the throttle level of the $i^{th}$ engine. Hence, the power is equally divided between each engine.

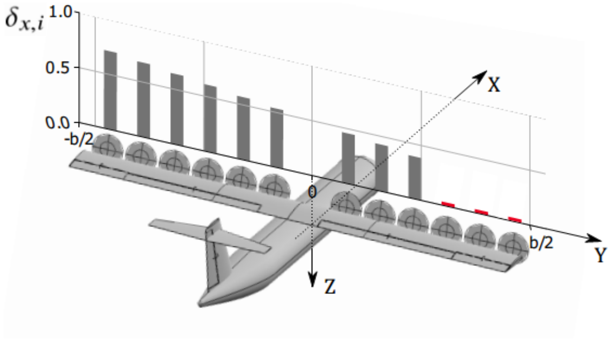


*Figure 1 : Illustration of an ATR72 with distributed propulsion, differential thrust and engine failures.*

The total moment around the yaw axis generated with differential thrust depends on the lateral location of each engine, $y_i$:

$$M_z = \sum_{i=1}^{N} -T_{x,i} y_i \qquad (2)$$

Using Eq. (1) the moment becomes

$$M_z = \frac{P_L}{N} V^{-1} \eta_m \eta_p \sum_{i=1}^{N} -\delta_{x,i} y_i \qquad (3)$$

In comparison, the moment created by the rudder can be expressed as:

$$M_{z,\delta_r} = \frac{1}{2} \rho S V^2 l \, c_n(\beta, \delta_r) \qquad (4)$$

With $\frac{1}{2}\rho V^2$ the dynamic pressure, $S$ the reference surface area, $l$ the reference length and $c_n(\beta, \delta_r)$, the yaw moment coefficient, depending on the side slip $\beta$ and the rudder deflection $\delta_r$. One can see the main difference being that the moment created by propulsion is inversely proportional to the velocity while the one produced by the vertical tail and rudder is quadratic with the velocity. In consequence, with differential thrust, reduced controllability is expected at high velocity. Inversely, high controllability can be expected at low velocity where the vertical tail is ineffective. Based on these formulations, one can expect a reduction of the vertical tail surface area thanks to the increase control authority at low velocity. From this aspect comes the question of a new sizing point for the vertical tail.

### 2.2. VERTICAL TAIL PERFORMANCE PREDICTION

An important feature present in the framework to evaluate flight envelop is the possibility to quickly modify the vertical tail and update the stability coefficient accordingly. This is made possible by implementing the VeDSC method [8]. This method predicts the vertical tail efficiency as a function of its geometry and aircraft components. It assumes that the contribution of the fuselage, wing and vertical tail on the lateral stability coefficients

$\{C_Y, C_l, C_n\} \equiv C_{Lat}$ can be decoupled as in Eq (5) :

$$C_{Lat_\beta} = C_{Lat,F_\beta} + C_{Lat,W_\beta} + C_{Lat,v_\beta} \quad (5)$$

Where subscripts *F*, *W* and *v* refer respectively to fuselage, wing and vertical tail and $C_{lat,\cdot\beta} = \frac{\partial C_{lat}}{\partial \beta}$. The contribution of the vertical tail, $C_{Lat,v}$, is then corrected for the interaction with the fuselage, wing and horizontal tail. The reader is referred to [4] and [9] for the complete formulation of these parameters.

### 2.3. TRIMMING ALGORITHM

When the engines are seen as actuators, a high number of additional degrees of freedom are added to the system. This means that the system of equations describing flight dynamic becomes underdetermined. To cope with this problem the equilibrium is found using an optimisation algorithm that can be briefly resumed as:

$$\min_{[\vec{x},\vec{u}]} P$$

Such that:

$$\dot{\vec{x}} = 0$$
$$\delta_{x,1}, \dots, \delta_{x,n} = 0$$

Where P is the power needed to maintain the flight position, $\vec{x}$ and $\vec{u}$ are respectively the state variables (velocities, rotation rates and Euler angles) and the control inputs. The constraints are zero acceleration for equilibriums or constant acceleration for pseudo-equilibriums such as steady turns. Engine failures are imposed by constraining throttle level $\delta_{x,1}$ to $\delta_{x,n}$ to zero.
Formulating the problem in this way, avoids selecting a particular allocation strategy and the optimizer is allowed to explore a larger solution space.
The flight envelop can then be computed with various flight conditions, configurations or engine failures.

### 2.4. FLIGHT ENVELOP

As examples, flights envelops with engine failure of a twin engine ATR72 and its counter-part equipped with distributed propulsion as shown in Figure 2: Twin engine ATR72 with one engine failure and Figure 3. These envelops are computed in take-off conditions with a climb angle of 3% which is conservative for both of these configurations.
For each equilibrium map, a point indicates equilibrium. If this equilibrium is on the edge of the stability map a line shows the limiting parameter. It is either the 5° limitation in roll, stall or rudder saturation. For distributed propulsion, engine saturation is indicated with different markers. A rectangular marker signifies that one engine is saturated, up-triangle two engines, down triangle three engines, left triangle four engines and finally right triangle five engines. Additionally, the complete zone after ||β|| ≥ 15° is faded, signifying that any equilibrium is valid under the condition that the VT did not yet experienced stall.

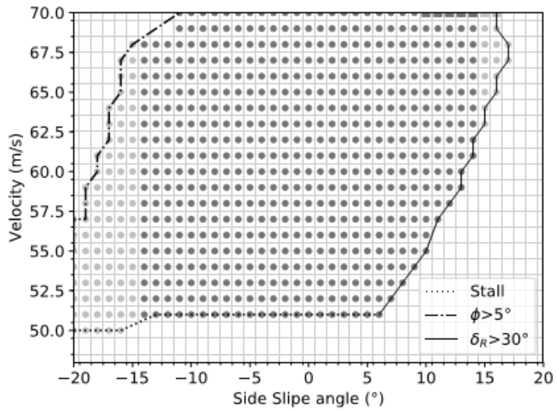


*Figure 2: Twin engine ATR72 with one engine failure*

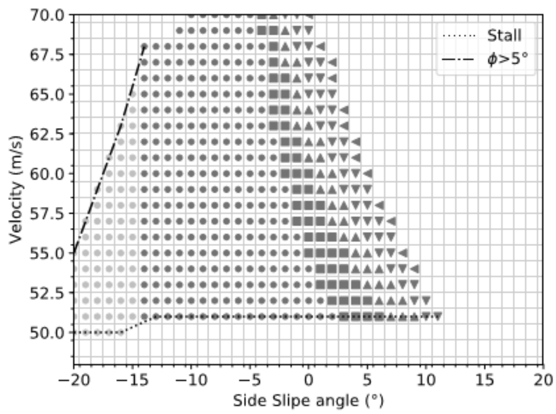


*Figure 3: DEP ATR72 using differential thrust only and three engine failures as shown in Fig. 1.*

### 2.5. CHARACTERISTICS OF DIFFERENTIAL THRUST IN THE DIRECTIONAL CONTROL

The previous flight envelop shows the characteristics of differential thrust in directional control. In case of engine failure the flight envelop is larger at low velocity and narrows at larger velocities such that the aircraft can hardly maintain β=0° at 69m/s. The explanation is that the mean power level needed to maintain the aircraft climbing at this speed is close from engine saturation. This means fewer margins for differential thrust while maintaining the speed and/or the climb angle. From this observation, critical flight phases for the use of differential thrust can be deduced. Flight conditions limiting the margin for yaw moment generation are simply flight phases requiring low or high power. These are threefold:

I. Take off
II. Best climb
III. Final landing.

These phases will serve as basis for the evaluation of the influence of the vertical tail on the flight envelop.

reference stall velocity or 1.3Vsr (CS25.147a) [10]. This manoeuver being more difficult for a differential thrust control, it is conserved.

At the best climb condition, the aircraft is expected to have reached a safe altitude with all engines operational. The certification requires that there must be enough excess lateral control to allow a limited amount of manoeuvring and to correct for gusts (CS25.147f) [10]. Both of these situations are dynamic since entering a manoeuver would automatically degrade the climb angle regardless of the configuration. In consequence, this flight phase cannot be studied with the present tool and will be addressed in future studies.

| | Speed | Climb angle | Weight | Side slip | Bank angle |
|---|---|---|---|---|---|
| Take-Off | V2 = 58m/s | 2.7% | 22.8T | - | $\varphi \leq 5°$ |
| Take-Off | 1.3Vsr = 68m/s | 2.7% | 22.8T | - | $\varphi \leq 5°$ |
| Landing | 49m/s | - | 15T | 15° | $\varphi \leq 5°$ |

*Table 1 : Flight parameters at the studied flight conditions*

## 3. INFLUENCE OF THE CONFIGURATION

As the interest is to study the influence of design parameters, such as the size of the vertical tail, the evaluation of the complete flight envelop is not necessary. The edges of the flight envelop are sufficient to evaluate a configuration. For each configuration, the upper and/or lower bound(s) of the flight envelop is determined and plotted on a graph for different flight phase and failure mode.

### 3.1. DEFINITION OF FLIGHT CONDITIONS

As opposed to the traditional methodology, this study does not only consider the conditions specified in certification rules. Due to the unconventional characteristics of distributed propulsion, traditional means of demonstrating that an aircraft ensures safety might be unrelevant. The methodology adopted is hence to explore the flight envelop to deduce critical flight phases and failure modes specific to distributed propulsion.

For the take-off, we restrict ourselves to cases where the aircraft is airborne and won't study the acceleration for the simple reason that a trimming tool is not adequate for this criterion. However, the aircraft is expected to be able to take-off and climb with lateral winds even with failed engines. The certification imposes that the aircraft should be able to yaw into a failed engine at 1.3 times the

At landing the aircraft must be able to perform a de-crab manoeuver during final approach while maintaining a negative slope to be able to land even with engine failures. Usually, it is the maximum landing weight that is considered for this phase. However, at equilibrium the thrust force must equal the drag and projection of the weight by the climb angle:

$$T = D + mg \sin \gamma \qquad (6)$$

With a negative climb angle $\gamma$, increasing the mass lowers the thrust needed to maintain the flight velocity. In consequence, lower thrust margin is available for directional control. For this reason, a low mass of 15T is selected corresponding to 1.5T higher than empty weight.

The selected flight conditions are resumed in Table 1.

### 3.2. PERFORMANCE OF DIFFERENTIAL THRUST

The directional controllability at take-off in normal and failure modes is evaluated by finding the maximum positive and negative side slip achievable. Figure 4 shows the results as a function of the relative size of the vertical tail and the number of inoperative engines. The flight envelop is delimited by the upper and lower curves.

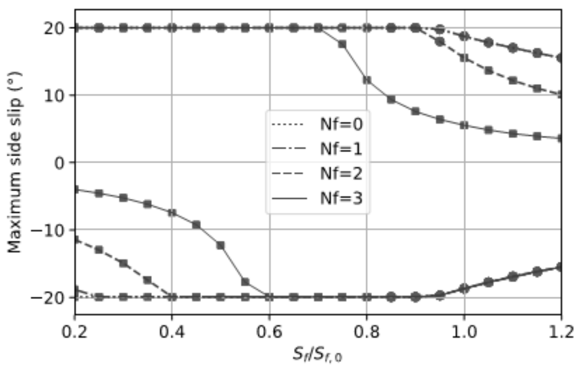


*Figure 4: Maximum positive and negative $\beta$ at V2 in take-off conditions. Nf refers to number of failed engine. Rectangles show saturation of engines and circles show limit of bank angle.*

The exploration space to find the maximum side slip is limited to $\pm 20°$ to avoid flight regimes where the vertical tail may experience stall. This is why the curves are constant at $\pm 20°$. One can observe that in these flight conditions the loss of one engine is almost insignificant as the parameter limiting the flight envelop is the maximum bank angle. With two or three engine loss the flight envelop is bonded by the maximum yaw moment created by the remaining engines. However it can be compensated for by bringing the relative size of the vertical tail close to 0.65, corresponding to a neutral directional static stability. The curves are showing a symmetric pattern such that the largest flight envelop with engine failures can be achieved at the point of neutral stability.

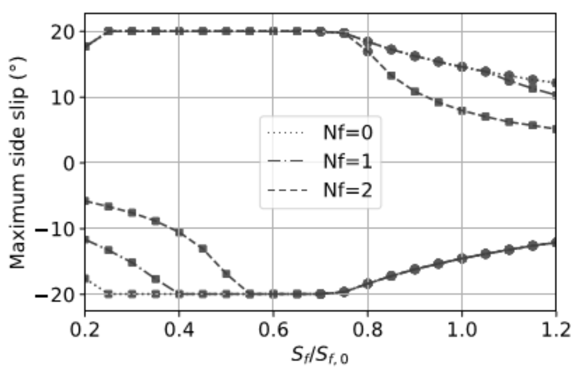


*Figure 5: Maximum positive and negative $\beta$ at 1.3Vsr in take-off conditions. Nf refers to number of inoperative engines. Rectangles show saturation of engines and circles show limit of bank angle*

Figure 5 shows the aircraft in take-off conditions at higher velocity where the control with differential thrust is less efficient. The case with three inoperative engines is not shown as it is not possible to maintain zero side slip. This means that the necessary thrust cannot be re-allocated such as to be symmetric. In this configuration, the use of a rudder becomes necessary to control the aircraft. This case could define a critical loss of thrust on this aircraft. Furthermore, the traditional mean of balancing an asymmetric thrust is through the use of the rudder. The efficiency of the rudder depending on the velocity, there is minimum velocity at which the asymmetric thrust cannot be balance. When using differential thrust however, the thrust can be re-allocated to remain symmetric up to a maximum velocity or climb angle.

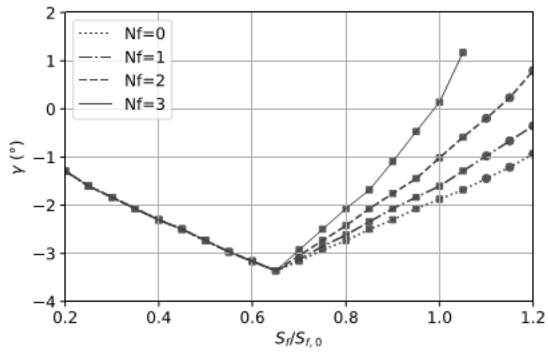


*Figure 6 : Maximum descent angle in landing conditions as a function of vertical tail relative surface area and number of engine failure.*

Figure 6 shows the maximum descent angle achievable while performing a $\beta = +15°$ de-crabe manoeuver. Except for large size of vertical tail, the maximum descent slope is bounded by the engines, meaning that to increase the descent slope the total thrust has to be lowered, rendering it impossible to generate enough yaw moment to de-crab. There exist configurations where the slope is positive showing that the aircraft cannot land while performing de-crab. These are limited to high directional stability or instability. One must also notice that the manoeuver is performed at a positive side slip. Due to the instability, at relative sizes of vertical tail lower than 0.65, negative side slip becomes more challenging. Hence the full flight envelop is expected to be symmetric around $S_f = 0.65 S_{f_0}$.

From this graph, is appears that at $S_f = S_{f_0}$ and three engines inoperative, the aircraft cannot land while maintaining a decrabe. However, this graph does not give information on the influence of the velocity in this flight phase.

This information is given in Figure 7, showing the complete flight envelop with three engines inoperative in landing conditions. According to this graph, to be able to land, the aircraft has to maintain a speed between 42m/s and 48m/s, below the indicated landing speed of 49m/s for this weight. In this case the aircraft has to go out of the flight envelop defined by the manufacturer to land. This confirms the idea of a critical loss of thrust for this particular configuration.

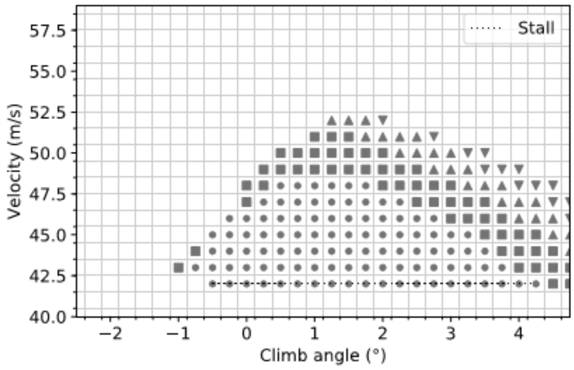


*Figure 7: Flight envelop in landing condition with three inoperative engines and $S_f/S_{f_0}$ = 1*

## 4. DISCUSSION AND CONSEQUENCES

This study contains limitations such that the absence of a propeller-wing interaction model, propeller forces and non-linear effects such as stall. From the point of view of flight dynamics propeller wing interaction should produce induced rolling moment due to local change of lift on the wing. However, this impact should be low and/or easily countered by the aileron especially if these ones are embedded in propeller slipstream. The use of low fidelity methods is justified by the interest in spanning different configurations in a limited amount of time and rapidly put in light critical flight phases or limiting design parameters for a non-traditional propulsion system.
Nevertheless this study shows the sensibility of the directional static stability on the flight envelop when using differential propulsion in normal and failure conditions. The consequences of the exploration is that due to the lower efficiency of the propulsion system at high velocity and the sensibility to engine failure, it seems that the vertical tail needs to be designed to obtain a neutral aircraft to maintain the largest flight envelop at all time. It is has also been shown that differential thrust can handle alone the directional control of the aircraft up to a critical loss of thrust, leaving the possibility to remove the traditionally used rudder.
Further explorations in dynamic flight stability need to be conducted to be able to conclude on the optimal or limiting design point for both the vertical tail and the distributed propulsion.

## 5. CERTIFICATION

As demonstrated above, through a DEP-configuration, aircraft directional control and stability could be ensured through the propulsion system. Therefore, this system combines two functions: to provide the required propulsive thrust, and to provide the required differential thrust for control and stability. From a regulatory point of view, it can be considered as a novelty relative to the design practices on which the current applicable certification specifications are based, which have to comply with established safety objectives.
Indeed, those requirements are mostly established and built upon considering conventional aeroplanes architecture, with two to four turbine engines (even if there is no mentioned upper limitation in the number of engines installed) and directional control and stability through aerodynamic surfaces, thus possibly not adapted to DEP-configurations. Rudder is for example explicitly mentioned in static directional and lateral stability requirements.

This study refers to EASA CS 25 Amendment 20 and its subpart-B dealing with the FLIGHT [10] requirements with the objective to derive, based on the above results, some guidance regarding certification of DEP aircraft irrespective of any given architecture.

### 5.1. PERFORMANCE AND CONTROLLABILITY IN CONSIDERATION TO ENGINE FAILURE

For determination of performances data, and controllability and manoeuvrability characteristics, the EASA CS25 considers the One-Engine-Inoperative (OEI) situation, resulting from a critical engine failure condition, with the associated effects of loss of thrust and thrust imbalance. For some cases, the failure of second critical engine while in an OEI situation is also considered for aircraft with four or more engines. The above results show that loss of engine situations may adversely affect in various ways performances or handling qualities in different phases of flight. As closely linked to the aircraft propulsion configuration, its systems architecture and redundancy, and its thrust control system, the current OEI situation as based on the critical engine definition is highly questionable for DEP-Aircraft. It is considered here that reference in certification requirements to critical losses of thrust is more appropriate for DEP-aircraft than the critical engine failure.
Such failure condition can be defined, from a regulatory point of view, as the loss of thrust which would most adversely affect the performances or handling qualities of an aircraft. It should be determined by the manufacturer, as strongly related to design choices for propulsive architecture and directional control. Furthermore, the dual function of the propulsion system strengthens the longitudinal/lateral coupling, for example highlight in descent in the above results, leading to possible uncommon new critical loss of thrust situations.
Flight phases where maximum continuous power is necessary would constitute a critical situation as directional control would become impossible. This is illustrated in Fig.6 where the loss of three

engines does not allow directional control with differential thrust due to the fact that the remaining engines are providing maximum thrust. The identification of a critical loss of thrust or critical flight situation could be done by evaluating the power margin available for differential thrust and directional control while maintaining current climb angle and velocity.

### 5.2. ALL ENGINES FAILURE AND TOTAL LOSS OF ENERGY

The loss of all engines, either due to vicinity causes or following shortage of the main source of energy on board becomes more critical when the directional control relies on the propulsion system.
As such, no contradiction with the current certification could be identified. Demonstration of controllability in these conditions must be conducted and should results in strong connexion with system integration and safety analysis. Therefore, more demanding requirements on system design appear reasonable. An example can be the demonstration of an emergency control system, requiring immediate availability of an alternate control system allowing continued safe flight and landing. Additionally, new or more stringent safety concerns specific to DEP architecture could be edited. These are linked to identification of loss of thrust and related reaction times, robust thrust allocation and management of redundancy.

### 5.3. MINIMUM CONTROL SPEED

The minimum control speed, Vmc, must be determined in the most critical mode of powerplant failure with respect to controllability (CS 25.149 (a))[10]. Vmc is defined as the speed at which, when the critical engine is made inoperative, it is possible to maintain control of the aeroplane and to be able to maintain straight flight with a bank angle of not more than 5°.
This criterion is closely linked to the traditional aircraft architecture and means of directional control as discussed and illustrated previously in section 2.1 and 2.4. Recalling the development of section 2.1, the results of section 2.4 and 3.2 and the questioning about the one engine inoperative situation, the relevancy of this criterion if existing, for demonstration of control of DEP is questionable.
For DEP aircraft, the critical loss of thrust depends on the system architecture and cannot be resumed to the loss of one or two engines as currently prescribed by the certification requirements. Instead of one or two engine inoperative, the critical loss of thrust as previously defined in section 5.1 seems more adapted.
In addition, results from Figure 4 to Figure 7 put in light the sensitivity of DEP to high velocity during critical loss of thrust, while no special concerns are visible at lower velocity. As opposed to a minimum control speed, the demonstration of a maximum control speed not lower than a certain margin to stall seems to be a relevant certification requirement for DEP.

## 6. CONCLUSION

The characteristics of directional flight control with differential thrust have been studied in parallel with the new paradigm that this type of aircraft brings in certification activity.
The influence of engine failures, the size of the vertical tail and critical flight phases have been put in light through the exploration of flight envelop. The use of differential thrust to control the aircraft becomes critical in flight phases requiring high or low power. The criticality of engine failure can be assessed by the consecutive diminution of flight envelop. It has also been shown that regardless of engine failure the point offering the largest flight envelop is located at the neutral directional static stability, calling for a reduction of nearly 45% of the size of the vertical tail. Additionally, the study showed the potential for a directional control made exclusively by differential thrust, allowing removal of the traditional rudder.
A new point of view on demonstrating certification compliance brought by the use of differential thrust has been explored. Considering usage of the critical loss of thrust approach in certification requirements, instead of critical engine(s) loss, and considering a non-technically prescriptive regulation (e.g. rudder, number of engines), relevancy of top-level safety objectives related to performance, controllability and manoeuvrability, have been evaluated for DEP-aircraft. In answer to the strong coupling between longitudinal and lateral control caused by differential thrust, a notion of power margin to maintain control of the aircraft in any flight situation and to evaluate critical loss of thrust has been introduced. The minimum control speed has been questioned as a relevant parameter for DEP aircraft and a maximum control velocity is proposed as a new parameter to evaluate the safety of directional control with differential thrust.
The transfer of flight control functions to the propulsion system requires an increase of reliability in the system design in order to prevent any catastrophic failure. Overall, it can be concluded that the underlying safety objectives of CS-25 FLIGHT requirements and flight conditions considered in compliance demonstration are fully applicable to the use of differential thrust with distributed architecture. Nevertheless it would result in stronger design requirements on system design.

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