# CONTROL ALLOCATION FOR A DISTRIBUTED ELECTRIC PROPULSION AIRCRAFT USING DIFFERENTIAL THRUST

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## Abstract

The CleanSky2 D08 Distributed Electric Propulsion – Scaled Flight Demonstrator DEP–SFD can be controlled by means of differential thrust in addition to or instead of the classical control surfaces. The overall control architecture, the longitudinal and lateral allocation strategies will first be introduced. The closed-loop Handling Qualities (HQ) will then be evaluated by time responses as well as pole charts at different speeds in nominal and failure cases. These numerical results have been validated by flight tests taking place between May and July 2024.

Keywords: keywords list (not more than 5)

## 1. Context and Objectives

Distributed Electric Propulsion DEP has been identified within WP1.6.1 as a key technology enabling to achieve CleanSky2's top level objective of 20% of fuel burn reduction. [1, 2, 3].
Within WP1.3, the concept of Scaled Flight Testing has been validated as a complementary test mean with respect to windtunnel tests and real size flight tests. The Scaled Flight Demonstrator D03 SFD allowed to reproduce in flight the same dynamic behaviour as the corresponding twinjet real size transport aircraft [4, 5]. It has therefore been decided to derisk this key technology mainly in terms of dynamics and handling qualities during flight tests with a scaled flight demonstrator. The D08 DEP-SFD has been derived from the D03SFD by installing 6 electrically driven propeller engines at lowest development cost by reusing as much as possible the original D03 components [6].
It has been tested in the DNW LLF windtunnel facilities in Marknesse, The Netherlands, on January 2023, $11^{th}$ and $12^{nd}$ during about 300 test runs [7]. The overall development and the lessons learnt from the project will be presented in another paper submitted to ICAS 2024 [8].

## 2. Main results

The aerodynamic data confirmed the predicted slip-stream effect which allows to control the aircraft's roll and yaw by differential thrust in addition to or instead of the classical control devices aileron and rudder. The flight mechanics model has been based on this aerodynamic data base. The inertia data have also been adapted whilst the simulation environment, the Guidance, Navigation and Control GNC system as well as the Ground Remote Pilot Station GRPS developed by CIRA during the D03 project have been reused as much as possible. In Fig. 1 is depicted the overall control architecture proposed by ONERA. It has been added as additional flight modes into CIRA's GNC. There are 4 modes :

1. classical control using aileron and rudder
2. control using rudder and differential thrust (no-aileron)
3. control using aileron and differential thrust (no-rudder)
4. control using just differential thrust (full electric)

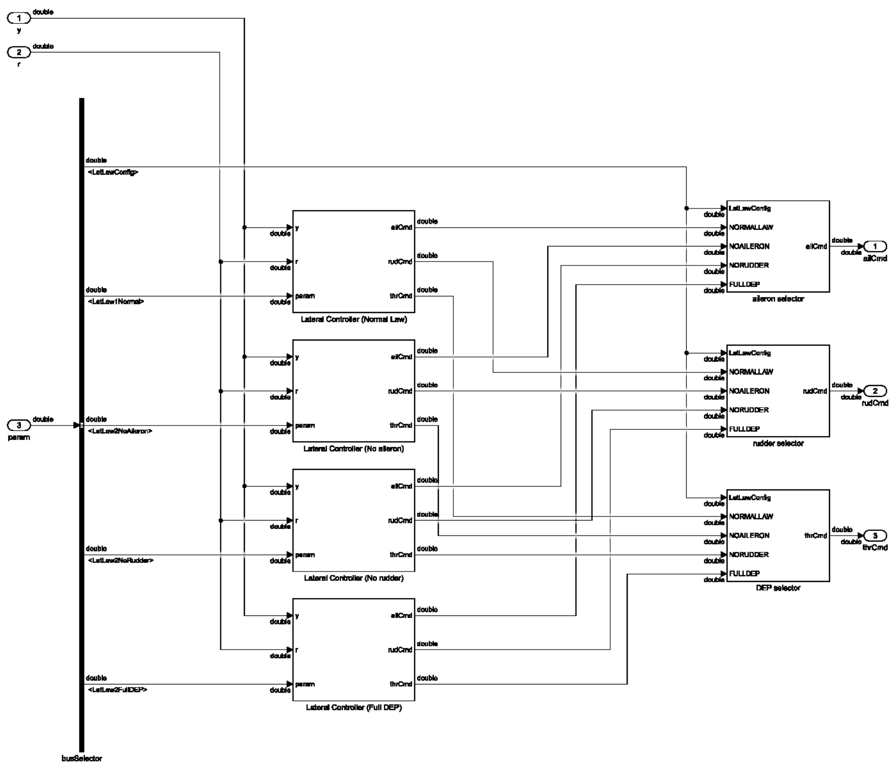


Figure 1 – Overall control architecture

You have the possibility to switch between these modes during flight in order to speed up the flight tests.
The following measurements are used : the sideslip angle $\beta$, roll rate $p$, yaw rate $r$ and bank angle as well as the integral of the sideslip angle error $\beta - \beta_c$ and the integral of the bank angle error $\phi$ˇ$\phi_c$ in order to ensure the tracking of the sideslip angle and bank angle reference signals $\beta_c$ and $\phi_c$. Usually, the sideslip angle reference $\beta_c$ is zero in order to minimize the drag (except during landing with cross-wind). The bank angle reference $\phi_c$ depends on the flight phase. It is zero for a straight flight without lateral wind. The ailerons are modelled by a first order transfer function with a time constant $\tau_1$ between the signal $d_{1c}$ computed by the allocation matrix $K_{alloc,lat}$ and the aileron deflection $d_1$, the rudder by a first order transfer function with a time constant $\tau_2$ between the signal $d_{2c}$ computed by $K_{alloc,lat}$ and the rudder deflection $d_2$, and each of the 6 engines by a first order transfer function with a time constant $\tau_{mot}$. In contrast to the longitudinal case, each engine $i$ receives its own control signal $d_{thr,i}$ computed by $K_{alloc,lat}$. The static allocation matrix $K_{alloc,lat}$ is for the moment being a pseudo-inverse applied to the virtual signals $(dl_v, dn_v)$ calculated by the controller matrix $K_{lat}$ from the measurement values. $\delta_{thr}$ is allocated to the 6 engines in the following way :

1. $\delta_{thr}$ is divided by 6 in order to determine $|\delta_{thr,i}|$ for each engine in the nominal case. Otherwise, it is divided by the number of operating engines.

2. For engines on the right wing, $\delta_{thr,i}$ is applied, for engines on the left wing $-\delta_{thr,i}$.

$K_{lat}$ is first determined using the Robust Modal Control Toolbox RMCT [9] supposing that the DEP-SFD is controlled by a virtual roll command $dl_v$ and by a virtual yaw command $dn_v$ based on the state space representations

$$\dot{x} = Ax + Bu \quad (1)$$
$$y = Cx + Du \quad (2)$$

obtained by the trim and the linearization of some flight conditions in fonction of the airspeed $V$ and the altitude $h$. The poles are placed in order to satisfy a certain time response with respect to the

sideslip and bank angle. The sideslip angle is decoupled from the bank angle by a constraint on the eigenvector associated to the sideslip angle, and vice versa. See [10, 11] for more details.
The virtual command signals $dl_v$ and especially $dn_v$ are then distributed to the real control actuators which are the ailerons $d_1$, the rudder $d_2$ and a certain number of the engines $d_{thr,i}$ by determining the pseudo-inverse $K_{alloc,lat}$.

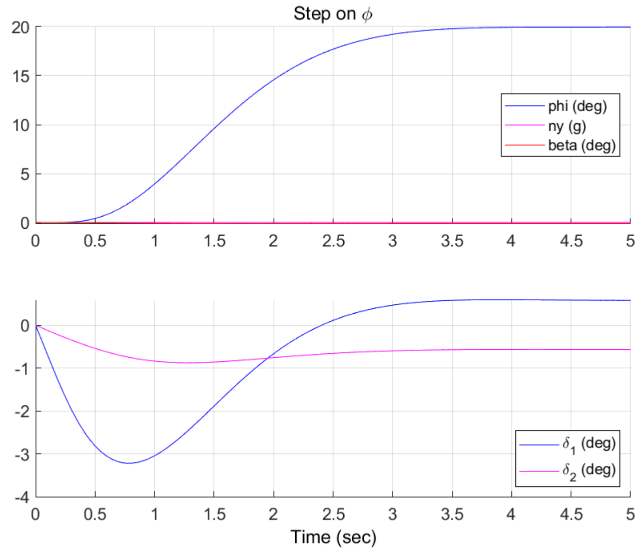


Figure 2 – The classical lateral flight control mode using aileron and rudder

On the top of Fig.2 and 3 are for example depicted the resulting time responses in bank angle $\phi$, sideslip angle $\beta$ and lateral acceleration $n_y$ of the D08 with respect to a step in the desired bank angle $\phi_c = +20^o$ to the right in a coordinated turn with $\beta_c = 0^o$. On the bottom of Fig. 2 are shown the corresponding classical aileron deflection $\delta_1$ and classical rudder $\delta_2$ in degrees for flight mode 1 (classical mode), while on the bottom of Fig. 3 is shown the corresponding total commanded thrust setting $\delta_{thr} \in [0,\, 1]$ for flight mode 4 (full electric).

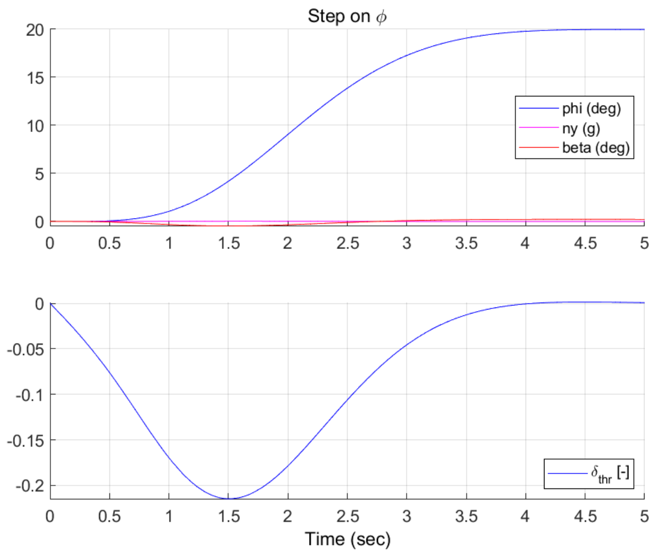


Figure 3 – The full electric flight control mode (no-aileron/no-rudder)

The reader can observe that the resulting time response in $\phi$ is almost the same in the classical mode and the full electric mode, while $\beta$ and $n_y$ are just slightly different. The necessary aileron deflection $\delta_1$ (on the right wing) is negative as expected in order to roll to the right. In order to ensure the coordinated turn, the rudder is also deflected to the right (negatively). The thrust for each right engine is reduced by $1/6|\delta_{thr}|$ in order to reduce the lift on the right wing, while the thrust for each left engine is increased by $-1/6|\delta_{thr}|$ in order to increase the lift on the left wing. The reduction of the thrust on the right wing and its increase on the left wing also created a yaw moment to the right in order to keep the coordinated turn.

In the final paper, the context and the D08 development will be developed more precisely. All lateral results will be presented in detail for the 4 different flight modes including the engine failure case. The classical longitudinal control system architecture with its controller $K_{lon}$ and its intuitive allocation matrix $K_{alloc,lon}$ will also be presented. During the presentation at ICAS, the validation of this concept during flight tests in April and May 2024 will also be shown.

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## 4. Copyright Statement



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