TOWARDS COMPUTATIONAL FLIGHT DYNAMICS OF A PASSENGER JET AIRCRAFT

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Abstract

This paper investigates the efficient generation of an aerodynamic database for flight simulation of a regional jet aircraft. A hierarchy of aerodynamic models is used, from semi–empirical approaches up to computational fluid dynamics analyses. The prediction tools are first validated at both low and high speeds against wind tunnel measurements. To reduce the number and costs of computational fluid dynamics calculations, Kriging interpolation is exploited to generate the aerodynamic tables. Data fusion allows combining different aerodynamic sources into one single database that is more accurate than each single database. The longitudinal and lateral handling qualities are first investigated for the regional jet aircraft. Then, the impact of geometry changes on the aircraft dynamic characteristics is investigated. It is found that improved aircraft characteristics could be achieved for relatively small changes relative to the baseline geometry.

1 Introduction

The aircraft design process is very expensive and the largest part of the life–cycle cost is directly dependent on decisions taken during the conceptual design phase. Obtaining accurate and reliable information about aircraft stability and performance characteristics during the first steps of the design is then highly critical. The engineering tools for aircraft design are generally based on empirical handbook methods or linear fluid mechanics hypothesis [1]. These provide low–cost aerodynamic data predictions reliable for benign flow conditions, e.g. ruling out the most critical points of the flight envelope. The data points at the borders of the flight envelope do not consider the nonlinear flight dynamic behaviour of the aircraft. As discussed in Ref. [2], a solution may be found in using computational fluid dynamics (CFD) techniques in the conceptual design phase in order to predict the nonlinear effects. However the computation of the complete aerodynamic database over the whole flight envelope with CFD is very expensive and requires a long computation time. High–fidelity simulations are still expensive despite today high performance computing facilities are available Ref. [3]. In aircraft design where the geometry changes, the use of CFD is prohibitively expensive and unrealistic for computing the entire aerodynamic database. The computation of dynamic derivatives requires an unsteady time accurate CFD analysis, which needs a very long computational time [4, 5, 6]. Hence, acceleration techniques based on CFD allows retain the fidelity at a reduced cost. An efficient way to produce a good full aerodynamic database with a fewer computations is to use a Kriging–based surrogate model and fusion of two available databases as described in Ref. [7]. In the following work these methods are efficiently used to study the effect of some design parameters over aircraft stability and performance characteristics. For every considered configuration a full–order CFD aerodynamic model was computed with a few computations, maintaining the high–fidelity characteristics of CFD over the whole flight envelope. The handling qualities are then evaluated and the influence of the new configuration design parameters over the performances and stability are presented. The paper continues in Sec. 2 where the passenger aircraft model is presented. Section 3 discusses the generation of the aerodynamic tables, presenting the differences between the results obtained from different methods and the acceleration techniques that were adopted. Then the results of a trim analysis and the handling qualities, both longitudinal and lateral–directional, are presented for the model and for some modified configurations in Sec. 4. Finally, conclusions are given in Sec. 5.

2 Passenger jet aircraft model

The aircraft model used in this work is a conceptual design of a regional jet originally designed using traditional hand–book methods. The aircraft model belongs to the 100–120 passengers class. The existing similar models considered during the design process were the new Bombardier CS100, the Embraer E–190, the Boeing 737–600 and the Airbus A318–100. Table 1 presents the mission specifications and the main dimensions [1].

Table 1 Mission specifications and dimensions of the regional jet aircraft

Parameter	Value
Range	2,600 km
Cruise Mach	0.78
Cruise altitude	10,668–11,887 m
Number of engines	2
Number of passengers	110
Landing field length	1,450 m
Take off field length	1,550 m
Long. ref. length	3.6 m
Lat. ref. length	30 m
Wing area	105 m^2

For flight simulation, a model of the aerodynamic forces and moments is required throughout the entire flight envelope. Figure 1 presents the model in scale 1:23 used in the German–Dutch Wind Tunnels (DNW) at Reynolds number $4 \cdot 10^6$.

Fig. 1 Wind tunnel model of the regional jet aircraft in scale 1:23

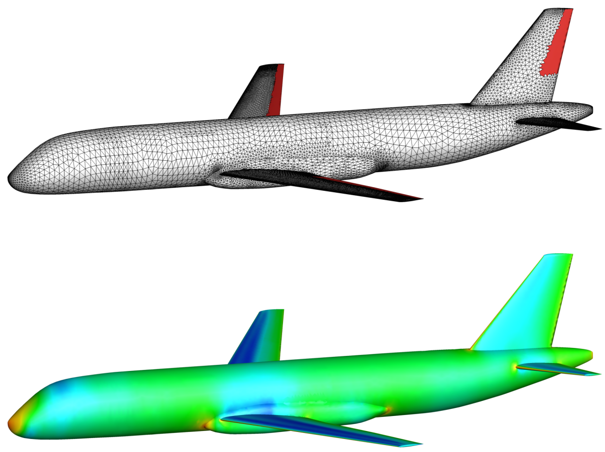


Fig. 2 Surface grid with the control surfaces in red and pressure coefficient distribution resulting from Euler solution at $M = 0.78$ and $\alpha = 3$ deg

The analysis presented in this work is obtained using the Computerised Environment for Aircraft Synthesis and Integrated Optimisation Methods (CEASIOM [2]) software. Inside CEASIOM, AcBuilder is a customized geometry construction system to define the aircraft configuration. It requires only ∼100 geometrical parameters because the design is still considered in the conceptual phase. With a simplified set of parameters, the CEASIOM model approximates the nose geometry and the tail. Once the geometry is

[1] The presented model that is stored in a CEASIOM–compatible format is open source and can be requested to Andrea Da Ronch A.Da-Ronch@soton.ac.uk.

[2] http://www.ceasiom.com/ [retrieved 14 July, 2014]

built, an automated grid generator is used to create within few seconds an initial mesh for CFD calculations. The Surface Modeller (SUMO [3]) was used. SUMO is a graphical tool for a rapid aircraft geometry creation coupled to high efficient unstructured surface and volume grid generators. It takes as input the AcBuilder basic parameterization and uses it to produce surface and volume grids for Euler CFD simulations. The surface unstructured grid with the control surfaces and the Euler CFD result about the pressure coefficient distribution for a Mach number (M) of 0.78 and an angle of attack (α) of 3 deg is shown in Fig. 2. This reference geometry is referred as baseline geometry in the remaining of the paper.

3 Generation of Aerodynamic Tables

In this work the stability characteristics are investigated. Aerodynamic tables are needed to study the aircraft static and dynamic properties. The following sections illustrate the models used for the aerodynamic predictions, their validation against wind tunnel measurements, and the approaches used to reduce the number of CFD calculations to a manageable computational cost.

3.1 Validation

The methods used for the aerodynamic predictions are an empirical method (Stability and Control Digital Data Compendium – Datcom [8]), a linear panel method based on Vortex Lattice Method (VLM) (Tornado [4]) and an unstructured CFD solver (Edge [5]).

The lift, drag and pitch moment coefficients (C_L, C_D, and C_m) with the angle of attack at Mach number of 0.5 are shown in Fig. 3. The good agreement with wind tunnel data found for DATCOM is not unexpected since it relies on a database of similar aircraft configurations to the one presented herein. Tornado provides the correct global trends but the quantitative differences are due to the limiting underlying assumptions (linear panel method) and the neglect of non–lifting surfaces that contribute significantly to the pitch moment. The flow solver Edge is used in Euler mode in this work. For this reason it does not consider the viscous term and so the resulting drag values appear smaller than the coefficients computed during the wind tunnel test. For high angles of attack Edge shows the most similar behaviour to the wind tunnel data. At the cruise Mach number of 0.78, similar considerations were found, with Edge showing a better correlation to experimental data. The results are not shown for brevity.

3.2 Aerodynamic Tables

The aerodynamic table is divided in static, control and dynamic derivatives. The static part of the table is based on a (α, M, β) three–dimensional domain. The α values were considered between -5 and 12 deg with a 1 deg step, M between 0.1 and 0.9 with 0.1 step and β values between -10 and 10 deg with a 1 deg step. The total number of static flight points is 3,402. The control derivatives part of the table considers the elevator, rudder and ailerons deflections separately. The elevator deflection was studied for values between -20 and 20 deg with 5 deg steps and the rudder and ailerons deflections for values between -15 and 15 deg with 5 deg steps. About the dynamic derivatives, the yaw, pitch and roll angular velocities are considered. They are taken from -80 to 80 deg/s with a step of 20 deg/s. Every considered control surface deflection and angular speed was studied singularly for any combination of α, M, so adding a total of 7,128 more entries to the table. The total size of the aerodynamic table was 10,530 points. The reference point considered for computing the moments and the angular velocities was the approximated centre of gravity position.

The CFD was not used to compute the dynamic derivatives because of the very high cost for computing an unsteady time accurate CFD solution. Datcom results were used for both the control and dynamic derivatives. Furthermore, for any geometry modification a new table needs

[3] http://www.larosterna.com/sumo.html [retrieved 14 July, 2014]

[4] http://www.redhammer.se/tornado/ [retrieved 14 July, 2014]

[5] http://www.foi.se/edge/ [retrieved 14 July, 2014]

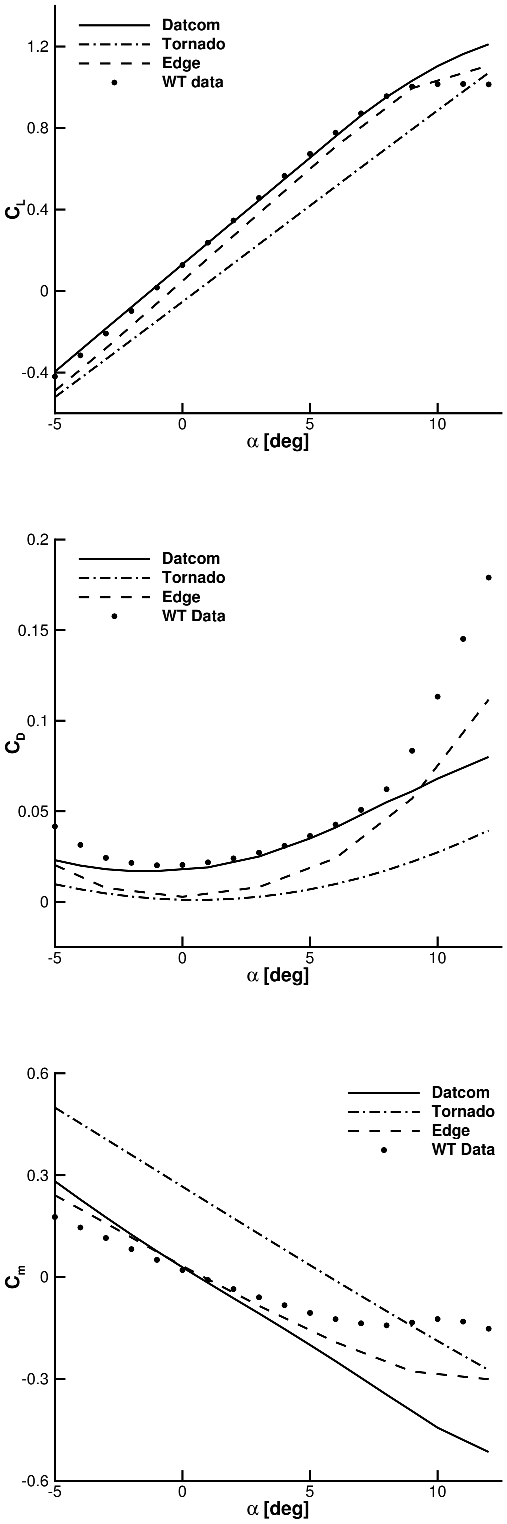


Fig. 3 Lift, drag and pitch moment coefficients at Mach number 0.5 and Reynolds number $2.2 \cdot 10^7$; the reference point is taken at the centre of gravity

to be generated, and so an efficient method to reduce the computational time is highly required. In order to fill in the aerodynamic table, the data were taken from the three aerodynamic models and experimental results. Figure 4 shows the flight states that were computed for each aerodynamic model. The semi–empirical method Datcom was used all over the domain to provide a quick overview of the aerodynamic data since it has good accuracy for traditional aircraft and very low computational cost. Tornado was used to compute the results for Mach number from 0.1 to 0.5, which is the appropriate range for the vortex lattice method. Tornado computational cost is relative low and it does not consider any compressibility correction. Edge was used for higher Mach numbers, from 0.5 to 0.9, in order to capture the nonlinear aerodynamic characteristics. For Mach numbers from 0.1 to 0.3 only 5 samples from Edge were computed on the edges of the domain to calibrate the low fidelity results. For all the combinations of these parameters, the results of different sideslip angle (β) were investigated for angles of 0, 5 and 10 deg apart from Datcom that does not provide a sideslip angle input option.

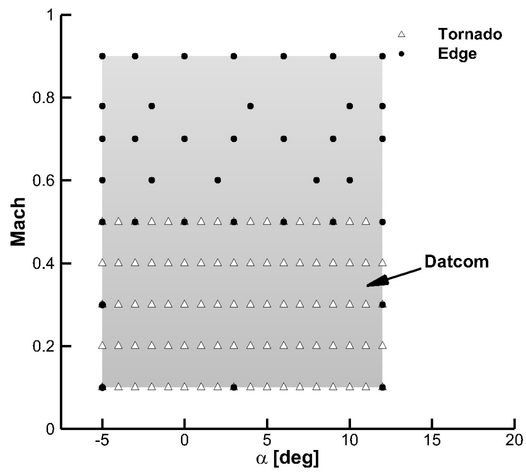


Fig. 4 Samples distribution over the $\alpha - M$ domain

Full tables were obtained for both Datcom and Tornado. About the table computed using CFD, Kriging interpolation and data fusion approaches were used to reduce the cost to a manageable requirement. A total of 97 non–viscous CFD calculations using Edge were performed in the (α, M, β) parameters space.

3.3 Kriging Interpolation

Kriging interpolation is an interpolation method for nonlinear and multi–dimensional deterministic functions. In Ref. [9, 10] the Kriging interpolation is efficiently used to reduce the computational cost for generating a full aerodynamic model. Once the Kriging model is created, it becomes a computationally cheap model for prediction of the function at untried locations. The available samples that were computed by Edge covered Mach numbers from 0.5 to 0.9, angles of attack from -5 to 12 deg and beta of 0, 5 and 10 deg. In Fig. 5 the pitching moment resulting surface in the (α, M) domain, obtained with the Kriging interpolation of the Edge data is compared with the experimental results from the wind tunnel testing. The linear trend shows a smaller slope for the wind tunnel results and for high Mach number the Edge pitch moment slope is much higher. This nonlinearity does not appear from the wind tunnel tests, for which the pitch moment slope is very similar for every Mach number. Only the pitch moment coefficient results are presented for brevity. The Kriging interpolating surface have the same trends with wind tunnel results for all the computed force and moment coefficients. The lift coefficient at low Mach numbers is very close to experimental results from every angle of attack. Close to the transonic field, for high Mach numbers, the values of lift coefficient are higher than the wind tunnel results. This also results in the differences between pitch moment coefficients on C_m Kriging surface and experimental results. About the drag coefficient predicted by Kriging model, it shows a good correlation with experiment results. The values are lower than wind tunnel because the solutions are achieved solving the Euler equations. In conclusion the Kriging model shows very efficient prediction capability and could considerably reduce the computational cost. In this study only the 5.45% of the total number of flight states of the full table were computed by CFD. This method extends a few calculations fidelity to the entire flight envelope at a reduced cost, enabling the use of CFD for aerodynamic predictions. Hence, the aerodynamic table accuracy is improved for a more accurate flight simulation. Furthermore Kriging interpolation allows studying different configurations with a good level of accuracy and without an excessively high computational cost as shown in the continuation of this study.

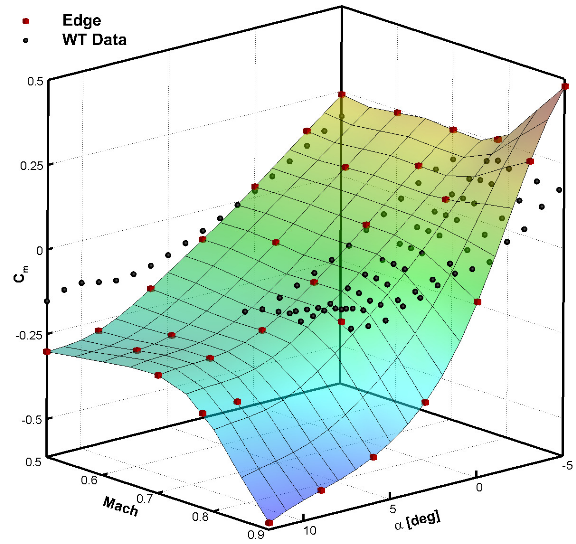


Fig. 5 Dependency of pitch moment coefficient on angle of attack and Mach number; the surface represents the Kriging interpolation of Edge samples (red cubes)

3.4 Data Fusion

The aerodynamic force and moment coefficients can be obtained from test or computed by using various methods predictions. Data fusion can combine different aerodynamic predictions into a more accurate database. Considering the available data coming from the empirical method Datcom (cheap and low–fidelity) and a CFD solver Edge (expensive and high–fidelity), it is possible to fuse them considering the new function with the same trend as the cheap samples but with quantitative values given by the expensive samples. Usually the cheap estimates are more densely distributed over the domain compared to the expensive ones. The method extensively employs the Kriging interpolation function, and it is based on the creation of an interpolated function whose domain is increased by one dimension with the values of the cheap computation at the expensive locations. The function is then evaluated over the entire domain as explained in Reference [7]. About this study Datcom was considered to be the low fidelity method, which was used to compute all the domain points. Expensive high fidelity samples were taken from Edge, and they were densely computed only in transonic field. Furthermore 5 samples were taken on the border at low speed (Mach 0.1) to avoid extrapolation problems. The data fusion results about the pitch moment are shown in Fig. 6. The

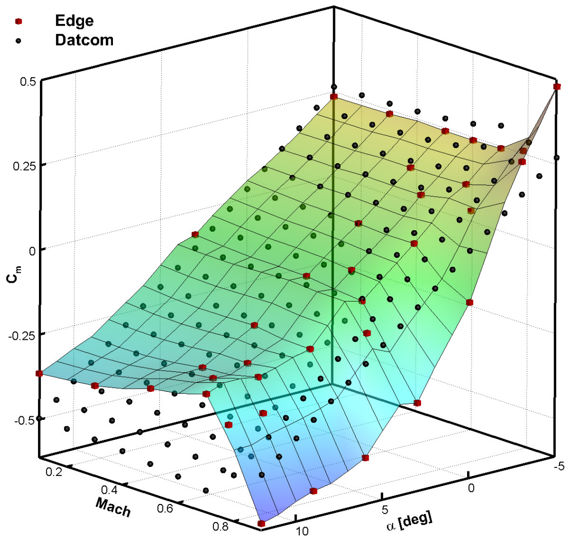


Fig. 6 Dependency of pitch moment coefficient on angle of attack and Mach number; the surface represents data fusion between Datcom and Edge

trend of data fusion model was influenced by the Datcom samples, but the values were corrected by the Edge samples. The data fusion model exhibits good capabilities at high Mach number and high angle of attack. Nonlinear aerodynamic effects can be still seen for the contributions of Edge samples. Data fusion, combined with Kriging interpolation, allows computing a full aerodynamic model with an overall low computational cost. The contribution of Datcom is not very evident because of the linear trend, but if a nonlinearity appeared in it, it would be transposed in the fused data, adding important information to the new model. During this study different fidelity aerodynamic methods, Kriging interpolations and data fusion models were used here to investigate their impacts on aircraft trim properties. The models that will be used in the following section are shown in Table 2. In the next section the trim and handling qualities resulting from the tables are compared. The proximity of the Kriging interpolation of the Edge samples database compared to the one using the wind tunnel data is assessed. During the conceptual design phase wind tunnel tests are usually too expensive to be integrated into the design cycle and so the T3 database can be a cheaper but well representative alternative.

Table 2 Generated full tables and reference numbers

Source of data	Table
DATCOM	T1
Tornado	T2
Edge with Kriging interpolation	T3
Data fusion of T3 and wind tunnel data	T4

4 Results

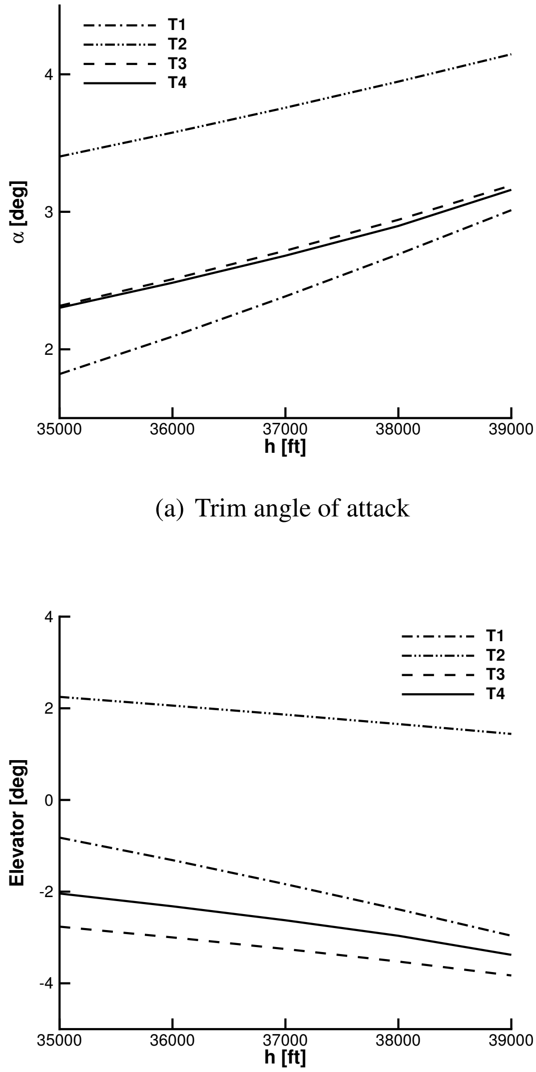
4.1 Baseline Geometry

The equations of motion, governing the static and dynamic behaviour of the aircraft, are composed by the aerodynamic forces and moments acting on the aircraft, geometrical and mass features, the command variables, notably throttle and elevator, rudder and aileron deflections and the state variables [11].

During the conceptual design phase, usually there is no accurate mass and inertia properties and so some approximated empirical methods are adopted. In this paper, weight and balance data were predicted by Howe's empirical method integrated in the CEASIOM Weight & Balance module. It is important to consider that the mass properties heavily influence the trim and stability results, and so these must be only considered as trend indications. Table 3 shows the main mass and inertia values of the baseline configuration. The resulting maximum take–off weight is similar to the values of the existing aircraft used as reference for this work.

Table 3 Baseline mass and inertia computed properties

Parameter	Value
MTOW	$4.97{\cdot}10^4$ kg
CG location	(16.13, 0, 0.0236) m
Ixx	$1.11{\cdot}10^6$ kg·m^2
Iyy	$1.90{\cdot}10^6$ kg·m^2
Izz	$2.87{\cdot}10^6$ kg·m^2
Ixz	$6.72{\cdot}10^4$ kg·m^2
Ixy, Iyz	0 kg·m^2



(a) Trim angle of attack

(b) Trim elevator deflection

Fig. 7 Trim conditions at different cruise altitudes; see Table 2 for tables definition

4.1.1 Trim and Stability

In order to longitudinally trim the aircraft in the whole flight envelope, e.g. for different values of angle of attack, the traditional way to obtain that is by a variation in pitching moment values by regulating the incidence angle of the horizontal tail plane. This may be achieved by use of the control surface or by rotating the whole horizontal tail.

The Mach number was fixed at 0.78 and the flight altitude was varied between 10,668 and 11,887 m, which is the step cruise height. Figure 7 shows the trim angles of attack and deflection of elevator, respectively, at different altitudes during the cruise mission phase. The aerodynamic model considering the wind tunnel experimental data (T4), which is expected to have the highest fidelity, is taken as reference solution for all methods. Tornado model (T2) is the only one with a positive elevator deflection for trimming the aircraft. Datcom table (T1) identifies a larger slope of the trim angle of attack increasing the altitude. The results obtained from the Edge database (T3) are very similar to the values computed with wind tunnel data (T4), obtaining an almost identical trimming angle of attack and a slightly smaller elevator deflection but with the same trend.

4.1.2 Longitudinal handling qualities

Aircraft handling qualities at Mach cruise of 0.78 and altitude of 11,887 m were evaluated using the resulting aerodynamic force and moment coefficients given by different aerodynamic models. Figures 8 and 9 show the phugoid and short period characteristics, respectively, according to International Civil Aviation Organization (ICAO) criteria. About the phugoid longitudinal dynamic mode, the models show similar results, with the lowest rating and the farthest being Tornado (with a smaller damping).

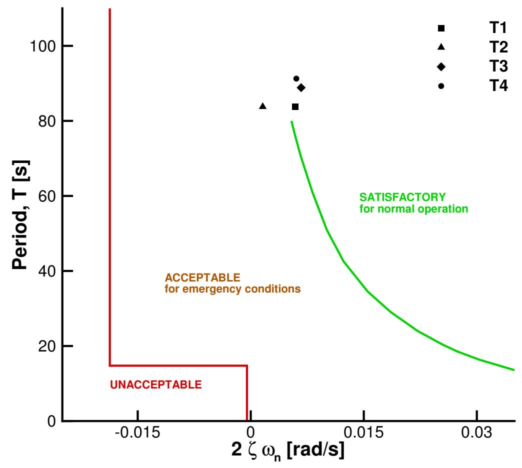


Fig. 8 Phugoid characteristics according to ICAO criteria at Mach number of 0.78 and altitude of 11,887 m; see Table 2 for definition

The short period mode for the 4 considered methods has almost the same period, but different times to half amplitude. The worst rating case is Tornado and the best is Datcom, with the other two in the middle. According to ICAO, both the phugoid and short period are acceptable for all the tables.

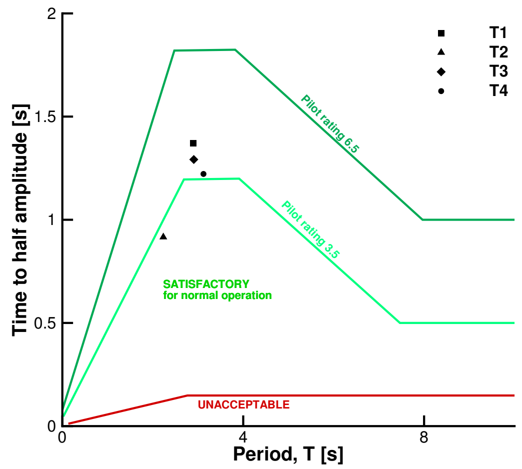


Fig. 9 Short period characteristics according to ICAO criteria at Mach number of 0.78 and altitude of 11,887 m; see Table 2 for definition

As for trim, linear panel method is suspected in transonic regime, unless corrections are made. However, corrections require experience and database of existing aircraft and are inadequate to support engineers to design innovative configurations.

4.1.3 Lateral–directional handling qualities

As previously done with the longitudinal handling qualities of aircraft, in this section the lateral–directional handling qualities are investigated. The flight conditions are Mach cruise of 0.78 and altitude of 11,887 m. Figures 10 and 11 show the dutch roll and spiral modes characteristics, respectively, according to the United States military standards MIL–F–8785C criteria at Phase B. The dutch roll mode shows different results for every considered table. The less damped mode is obtained using Edge database (T3) that may be caused by the neglected viscosity term in the fluid dynamic equations. The Tornado database (T2) is the only one to present an unstable nonconservative behaviour in damping. The natural frequency does not change consistently. According to MIL–F–8785C, the results are acceptable for all the tables.

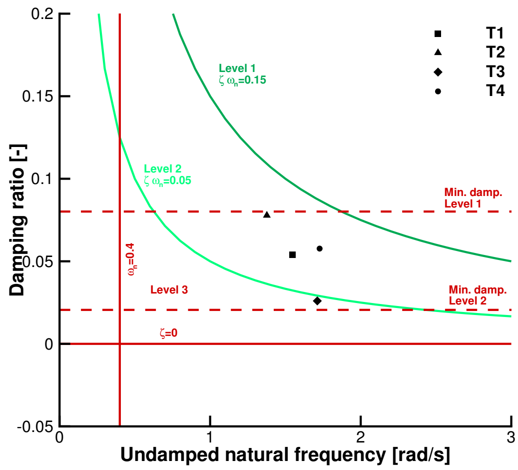


Fig. 10 Dutch roll characteristics according to MIL–F–8785C criteria at Phase B at Mach number of 0.78 and altitude of 11,887 m; see Table 2 for definition

For the spiral mode, Tornado (T2) is the only one to lead to an unstable mode. This means that for Tornado the static directional stability has a relatively higher level compared to lateral stability and dihedral effect [11].

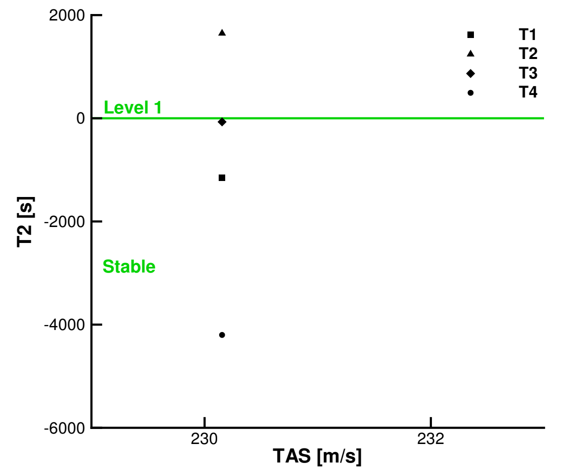


Fig. 11 Spiral characteristics according to MIL–F–8785C criteria at Phase B at Mach number of 0.78 and altitude of 11,887 m; see Table 2 for definition

The roll characteristics according to Cooper-Harper criterion are then showed in Fig. 12. According to Cooper–Harper criterion the rating of the roll mode characteristics are good (Cooper–Harper pilot assessment rating under 3.5). All the results are almost coincident apart from Tornado (T2).

The presented trim and handling qualities analysis show that the Kriging interpolation of the Edge computed samples (T3) are a good approximation of the table based on the wind tunnel test data (T4). The trend is very similar, and the off–set is always small. For some analysis, e.g. short period or phugoid mode, the resulting values are almost identical. For this reason the table obtained with Kriging interpolation of the CFD samples can be considered a good alternative to wind tunnel tests during the conceptual design phase.

4.2 New Wing Geometry

Having investigated the stability characteristics of the baseline geometry and the influence of aerodynamic models on the predicted static and dynamic behaviour, the next step is to explore

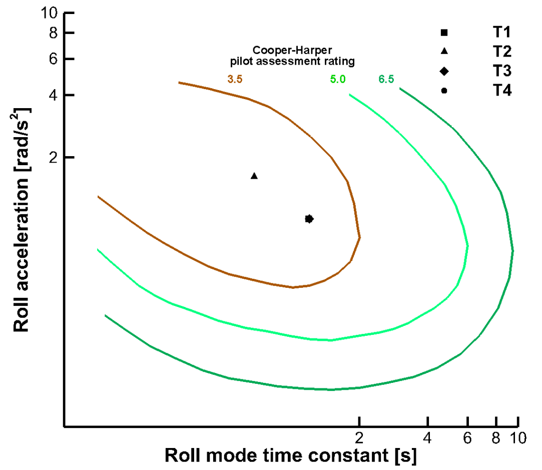


Fig. 12 Roll characteristics according to Cooper–Harper criterion at Mach number of 0.78 and altitude of 11,887 m; see Table 2 for definition

whether aircraft characteristics may be improved by a better geometry design. For every new configuration a new aerodynamic table needs to be generated With the tools and methods described above, the cost of this task is manageable even using CFD as source of the aerodynamic data. Using Kriging interpolation and data fusion was possible to compute a high–fidelity aerodynamic full–database with a few high–fidelity computation for every case. To study the geometry impact on aerodynamics and handling qualities, 8 configurations shown in Table 4 were considered starting from the baseline. The parameters in-

Table 4 Configurations with different leading edge sweep angle (Λ_{LE}) and aspect ratio (AR)

Configuration	Λ_{LE} $[deg]$	AR [–]
Baseline	27	9.4
Configuration 1	20	9.0
Configuration 2	20	9.4
Configuration 3	20	10.0
Configuration 4	27	9.0
Configuration 5	27	10.0
Configuration 6	33	9.0
Configuration 7	33	9.4
Configuration 8	33	10.0

clude leading edge sweep angle (Λ_{LE}) and aspect ratio (AR). For every configuration the mass and inertia properties were computed with Howe's method and a new aerodynamic table was computed. Since the differences between new configurations and baseline are not large, the same flow topology assumption was used here. Only 18 CFD samples at the border of the flight envelope were computed for every new configuration. Using data fusion between the baseline configuration table obtained with the Kriging interpolation of the Edge data (T3), and the new samples at the border, a full table was computed for every new considered configuration.

The aim of such modifications was to simulate a real design cycle, where different geometries are screened to find the best one. Figure 13 show the configuration geometry differences between baseline and Configuration 1 and Configuration 8 respectively.

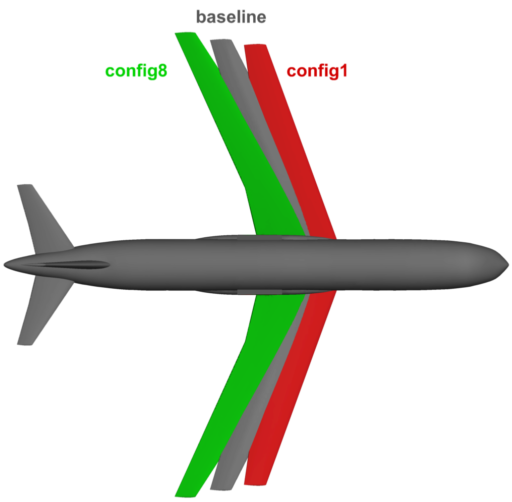


Fig. 13 Configurations 1 and 8 geometry compared with the baseline

4.2.1 *Aerodynamic characteristics*

The considered databases are now based on the Edge predictions for all the configurations. About the baseline the table is generated by using Kriging interpolation of the 97 computed samples (T3), while for the new configurations it is generated by data fusion between the baseline table (T3) and the 18 samples computed for each geometry. Since all the results are located between the values obtained for Configuration 1 and 8, in this section only the results of these two configurations are shown and compared with the baseline. Figure 14 shows the pitch moment coefficient trends comparison between baseline and new configurations. The lift coefficient, drag coefficient and pitch moment coefficient of new configurations are close to the baseline results. The most influencing parameter is the sweep angle, increasing it the pitching moment decreases at lower angle of attack and increases faster when close to the stall.

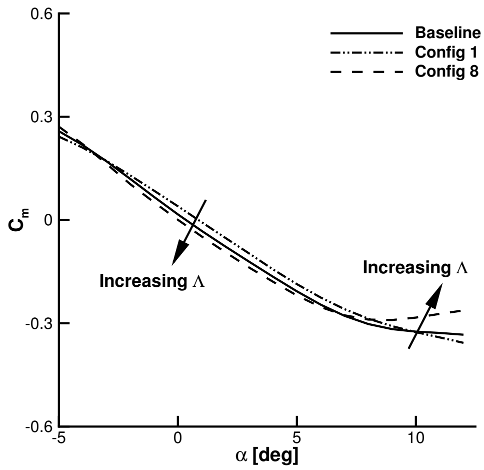
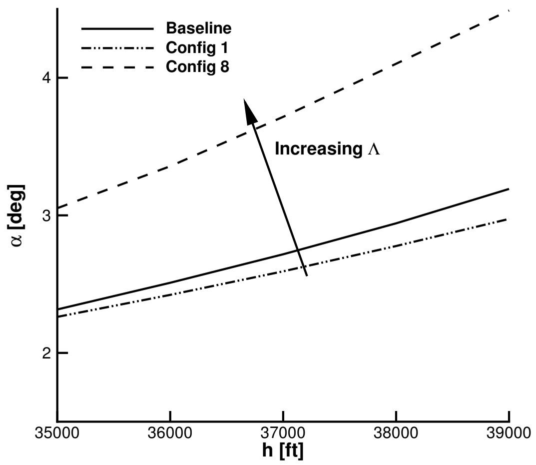


Fig. 14 Pitching moment coefficient comparison at Mach number of 0.78 and altitude of 11,887 m; see Table 4 for definition; arrows indicate increasing values of wing sweep angle

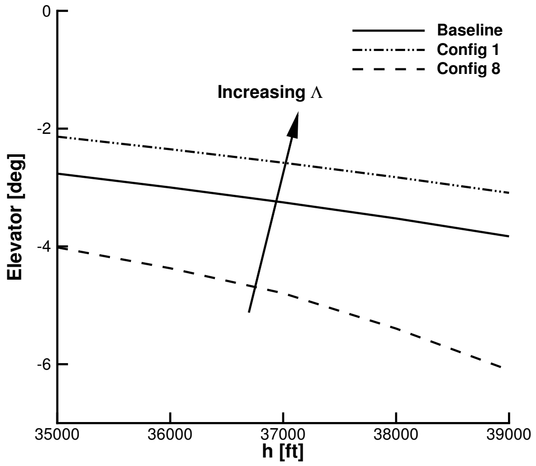
4.2.2 *Trim and Handling Qualities*

After computing a full–order aerodynamic model for all the configurations with the aerodynamic tables previously presented, it was possible to carry out an analysis on the impact of the modified design parameters over the handling qualities.

The trim angle of attack and elevator deflection results at step cruise stage for all the configurations and baseline are shown in Fig. 15. The most influencing parameter over the trim conditions is the sweep angle. Increasing it with respect to the baseline configuration, both the angle of attack and elevator deflection to trim the aircraft increase.



(a) Trim angle of attack



(b) Trim elevator deflection

Fig. 15 Trim conditions at different cruise altitudes; see Table 4 for definition; arrows indicate increasing values of wing sweep angle

For the 8 configurations presented in Table 4, the phugoid characteristics do not change considerably with respect to the baseline configuration. The period T is 90 ± 2 seconds and the damping ratio $2\zeta\omega_s$ is 0.045 ± 0.01 rad/s. The short period characteristics improve to some extent when increasing the sweep angle (Λ_{LE}). The trend of short period characteristics between baseline and 8 configurations are shown in Fig. 16. Increasing the sweep angle, the short period mode shows better characteristics increasing the time to half amplitude. At the same time the angle of attack and elevator deflection to trim the aircraft increase in module, causing an higher drag. So increasing the baseline sweep angle seems to lead to better handling qualities but decreases the aerodynamic efficiency.

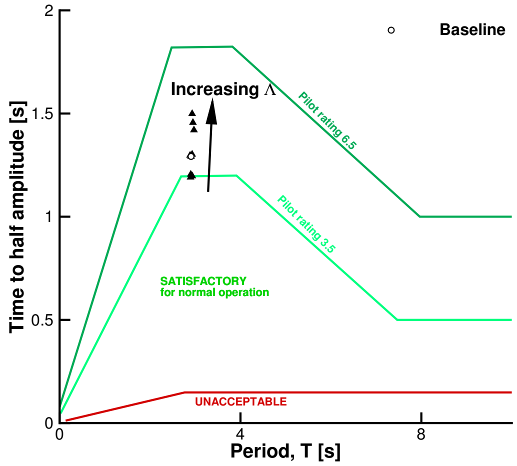


Fig. 16 Short period characteristics according to ICAO criteria at Mach number of 0.78 and altitude of 11,887 m; arrows indicate increasing values of wing sweep angle

4.3 New Horizontal Tail Geometry

Other four configurations were created modifying the horizontal tail. The difference is the horizontal tail area (S_{ht}) and position on the fuselage (x_{ht}). The horizontal tail of configuration 11 was moved forward by 3%, while configuration 12 was moved backward by the same value. The horizontal tail area of configuration 13 was increased by 10%, while configuration 14 decreased by the same value. Table 5 shows the position and area of horizontal tail for these four configurations compared to the baseline. The value of the horizontal tail position in table was divided by the length of fuselage (l_{fus}). Data fusion was also used to get the aerodynamic data and Edge Euler solver was used to compute additional data for these four configurations.

The phugoid characteristics do not change much by comparing with the baseline. The pe-

Table 5 Configuration with different horizontal tail

Configuration	x_{ht}/l_{fus} [–]	S_{ht} $[m^2]$
Baseline	0.8364	23.78
Configuration 11	0.8664	23.78
Configuration 12	0.8064	23.78
Configuration 13	0.8364	26.16
Configuration 14	0.8364	21.40

riod T is 89.5 ± 1.5 seconds and the damping ratio $2\zeta\omega_s$ is 0.049 ± 0.025 rad/s. The short period characteristics were improved by increasing the horizontal tail dimensional volume $x_{ht}S_{ht}$. The trend of short period characteristics between baseline and 8 configurations are shown in Fig. 17.

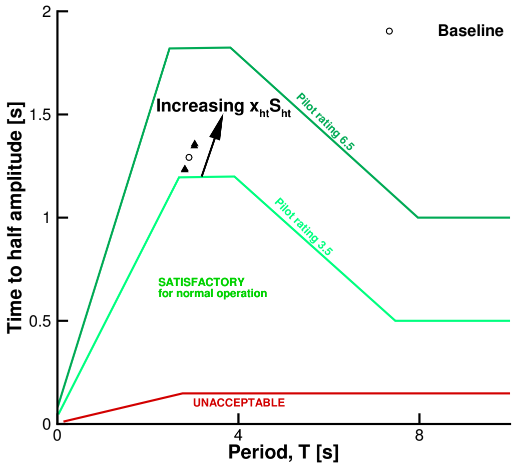


Fig. 17 Short period characteristics according to ICAO criteria at Mach number of 0.78 and altitude of 11,887 m; arrows indicate increasing values of horizontal tail volume

As for the wing sweep angle analysis, the same considerations may be done for the horizontal tail position. Increasing the horizontal tail volume, the phugoid mode increases the time to half amplitude but a longer fuselage or a bigger horizontal tail cause an higher drag. So increasing the baseline horizontal tail surface or position, better handling qualities were obtained but aerodynamic efficiency was reduced.

5 Conclusions

The performance and stability characteristics of a regional jet design are presented. The baseline configuration is studied with different aerodynamic models. Datcom results are very close to computational fluid dynamics (CFD) and wind tunnel experimental data, underlining the effectiveness of the empirical method Datcom for a traditional configuration. Some differences were found between the vortex lattice method Tornado because of linear assumptions. The CFD method Edge is the only one to capture the nonlinearity observed during the wind tunnel tests. The stall angles of attack predicted by Edge and measured in the wind tunnel are very similar but the CFD computation obtained a smaller effect from the nonlinear aerodynamics. The Kriging and data fusion methods are used to fill the aerodynamic tables with a reduced computational cost. The generated aerodynamic models are then compared and performance and stability characteristics computed. Among the computed models, Tornado is the only one to predict a positive elevator deflection to trim the aircraft during cruise and an unstable behaviour for the spiral mode. The impact of geometry changes on the aircraft dynamic characteristics is then investigated. The wing sweep angle is found to have a larger influence than the wing aspect ratio on the performance and stability characteristics. Increasing the wing sweep leads to a higher angle of attack and a less negative elevator deflection to trim the aircraft. Furthermore a more damped short period mode is obtained for higher sweep angle of the wing. The short period mode is influenced by the horizontal tail size and position. A higher tail volume coefficient causes a more damped short period.

The future work will include the application of the presented framework in an optimization environment to refine the aircraft geometry using higher fidelity aerodynamic tools than currently used in industrial practice and demonstrate that CFD techniques can be used in a routine manner for aircraft design.

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