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Creating Aero-Databases by Adaptive-Fidelity CFD Coupled with S&C Analysis to Predict Flying Qualities

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CEASIOM, the Computerized Environment for Aircraft Synthesis and Integrated Optimization Methods, is a framework tool that integrates discipline-specific tools for conceptual design. At this early stage of the design it is very useful to be able to predict the flying and handling qualities of this design. In order to do this, the aerodynamic database needs to be computed for the configuration being studied which then has to be coupled to the stability and control tools to carry out the analysis. This paper describes how the adaptive-fidelity CFD module of CEASIOM computes the aerodynamic dataset of an aircraft configuration, and how that dataset is analyzed by the SDSA module to determine the flying qualities of the aircraft. These predicted flying qualities are then compared with the flight-test data of the Ranger 2000 trainer aircraft in order to verify the goodness of the overall approach. The design, simulate and evaluate (DSE) exercise demonstrates how the software works as a design tool. The exercise begins with a design specification and uses conventional design methods to prescribe a baseline configuration. Then CEASIOM improves upon this baseline by analyzing its flying and handling qualities. This paper reports on the DSE case Transonic cruiser TCR from baseline design to Tier-I^+ design.

I. Introduction

Present trends in aircraft design towards augmented-stability and expanded flight envelopes call for an accurate description of the non-linear flight-dynamic behavior of the aircraft in order to properly design the Flight Control System (FCS). The first stages of the design process of a new aircraft are related to the sizing of the main components. The designer refers to some stability and control characteristics as a guidance of the design process. Up to now, the aerodynamic data considered in these early design steps were mostly based on tabulated data, issued from previous experience and/or semi-empirical approaches. Although satisfactory when determining some "high level" parameters (e.g. areas and planforms of lifting surfaces), such simplified approaches can lead to errors in the sizing process, especially when used in final conceptual design steps (e.g. sizing or allocation of control surfaces). These errors can be due to Reynolds number effects, configuration sensitivities, dynamic motion effects and related issues. Generally, these errors can only be detected when a significant increase in the fidelity of the aerodynamic data base is made available, for instance with wind tunnel data or even flight test data: the later (in the design process) the error is identified, the higher the cost of the "correction". Thus, the interest for an increase in the fidelity level of the aerodynamic data base is obvious, at all the steps of the design process: this is one of the main objectives of the SimSAC project (Simulating Aircraft Stability And Control Characteristics for Use in Conceptual Design). This FP6 European project gathers a total of 17 partners and is coordinated by Professor Arthur Rizzi from

KTH (www.simsacdesign.eu). Three main areas of activities are addressed: 1) Construction of a new tool, called CEASIOM, dedicated to the conceptual and preliminary design and analysis of fixed-wing aircrafts, 2) Assessment and improvement of existing CFD tools for predicting the stability and control dynamic derivatives, 3) Application of the CEASIOM software to two clean-sheet design studies; a near-sonic large transport aircraft (TCR) and an unconventional Z-wing general aviation configuration; in addition existing designs are studied further, such as a supersonic business jet and a regional aircraft.

There is much current interest in using CFD to compute the static and dynamic forces and moments acting on an aircraft as a complement to the usual practice of measuring them in a wind-tunnel. These forces and moments enter into the flight dynamics equations

$$
\begin{aligned}
&Transition: && m\dot{V} + \omega \times mV = F_{aero} + F_{prop} + F_{gravity} \\
&Rotation: && I\dot{\omega} + \omega \times I\omega = M_{aero} \\
&Kinematics: && \dot{\Theta} = L
\end{aligned}
$$

that determine the instantaneous motion of the aircraft. The system is de-coupled by a local linearization procedure where the forces and moments are expanded in a series expansion yielding the static and dynamic derivatives. The task then is to compute these derivatives.

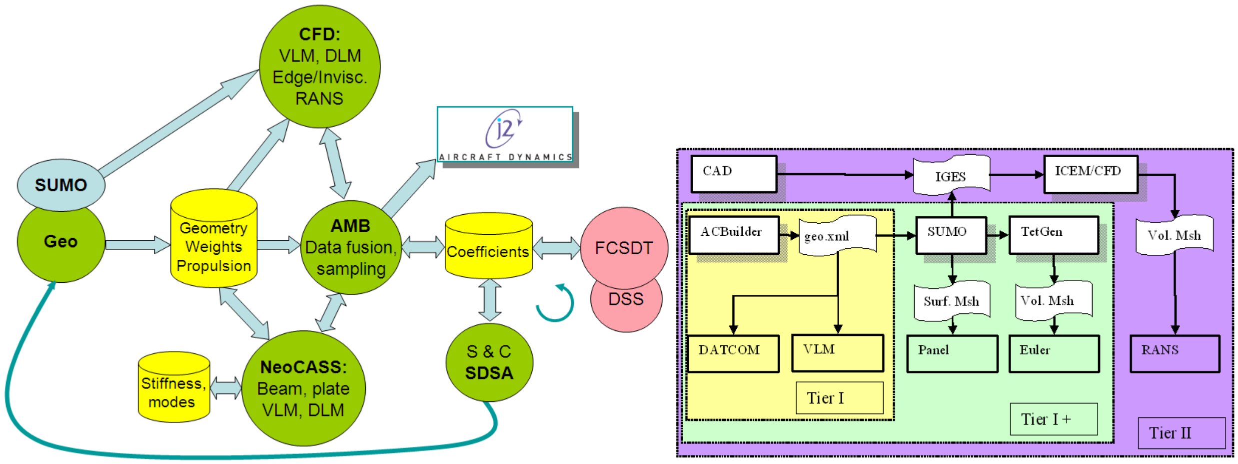
$$
\underbrace{C_m(t)}_{\text{time dependent pitching moment}} = \underbrace{C_{m_o} + C_{m_\alpha}\alpha + C_{m_{\delta_e}}\delta_e}_{\text{static}} + \underbrace{C_{m_q} q \frac{c}{2V}}_{\text{constant angular rate}} + \underbrace{C_{m_{\dot{\alpha}}}\dot{\alpha}\frac{c}{2V}}_{\text{dynamic}}
$$

In verifying the validity of this approach the usual exercise is to compute the static and dynamic coefficients or derivatives and compare these with the corresponding values measured in the wind tunnel. This is the objective of the DLR-F12 benchmark case. Such a comparison reveals the differences and similarities between the two values, but says little about the sensitivity of the stability & control characteristics to these differences. A further step must be taken to get some insight on the overall accuracy of the CFD predictions of aircraft behavior in flight. One way is to process the CFD-generated aero-data in either linear or non-linear stability & control analysis and extract flying or handling qualities that can be compared with flight-test data. This is the approach taken here in the study of the Ranger2000, a real flying aircraft. The tool we use to do this is CEASIOM, the *Computerized Environment for Aircraft Synthesis and Integrated Optimization Methods*, currently being developed within the frame of the SimSAC Project. CEASIOM uses adaptive-fidelity CFD to create the aerodynamic dataset of the aircraft and then uses the dataset to analyze flying qualities using its S&C analysis tool. The predicted flying qualities are compared to those observed in flight tests of the Ranger2000 jet trainer aircraft.

A major undertaking in SimSAC is the design, simulate and evaluate (DSE) exercise. The endeavor begins with a design specification and uses conventional design methods to prescribe a baseline configuration. Then CEASIOM improves upon this baseline by analyzing its flying and handling qualities. This paper reports on the DSE case Transonic cruiser TCR from baseline design to Tier-I design. The baseline is based on the design specification, which is a fairly non-complicated one with the exception for the design cruise speed of Mach 0.97. This design speed was chosen to stress the shortcomings the handbook methods have in the transonic speed envelope. The baseline, a T-tail design, was analyzed with CEASIOM tools for aerodynamics, mass properties, flight mechanics and aeroelastics. The aerodynamic analysis included handbook methods (DATCOM), potential calculations (TORNADO) and Euler calculations (EDGE). The flight dynamical analysis showed that there is a problem with trim. Too large deflections are needed to trim the TCR aircraft in the design point. The stability margin is very large. This is a typical problem in the transonic envelope. In addition the aeroelastic analysis showed that the T-tail fluttered, even in low speed. The first step in the Tier-I design was to try to cure the trim-problem by moving the wing forward in order to increase the distance between the center of gravity and the horizontal tail. This improved the trim characteristics a bit, but more was needed. A new approach with a canard configuration was suggested. For this the stability margin was decreased drastically, but the canard deflection for trim was still substantial. The tail flutter problem was solved. This configuration is judged to be better than the T-tail configuration and is being built as a model and tested in the wind tunnel to verify the entire design functionality. CEASIOM delivers the configuration as an IGES file that can be used to construct the windtunnel model. This evolution shows how CEASIOM is becoming a useful tool for aircraft design.

II. CEASIOM Software

CEASIOM is a framework tool that integrates discipline-specific tools like: CAD & mesh generation, CFD, stability & control analysis etc., all for the purpose of aircraft conceptual design.[1] Figure 1(a) presents an overview of the CEASIOM software, showing aspects of its functionality, process and dataflow.



(a) (b)

Figure 1. CEASIOM Software - a) Core modules Geo-sumo, AMB-CFD, NeoCASS and S&C in the CEASIOM software; - b) Geo-sumo software chain: from Geo to CFD grids.

Significant features developed and integrated in CEASIOM as modules are:

1. Geometry module Geo-sumo
   A customized geometry construction system coupled to surface and volume grid generators; Port to CAD via IGES

2. Aerodynamic module AMB-CFD
   A replacement of and complement to current handbook aerodynamic methods with new adaptable-fidelity modules referred to as tier I (a.), tier I + (b.), and tier II (c.):

   a. Steady and unsteady TORNADO vortex-lattice code (VLM) for low-speed aerodynamics and aero-elasticity

   b. Inviscid Edge CFD code for high-speed aerodynamics and aero-elasticity

   c. RANS (Reynolds Averaged Navier-Stokes) flow simulator for high-fidelity analysis of extreme flight conditions

3. Stability and Control module S&C
   A simulation and dynamic stability and control analyzer and flying-quality assessor. Six Degrees of Freedom test flight simulation, performance prediction, including human pilot model, Stability Augmentation System (SAS), and a LQR based flight control system (FCS) package are among the major functionalities of this module.

4. Aeroelastic module NeoCASS
   Quasi-analytical structural analysis methods that support aero-elastic problem formulation and solution

5. Flight Control System design module FCSDT
   A designer toolkit for flight control-law formulation, simulation and technical decision support, permitting flight control system design philosophy and architecture to be coupled in early in the conceptual design phase

6. Decision Support System module DSS
   An explicit DSS functionality, including issues such as fault tolerance and failure tree analysis.

The focus of the present paper is on modules 2 & 3, and the following paragraphs describe how they are used.

A. Adaptive fidelity geometry modeling for aerodynamics

The task is to build a tabular model for the aerodynamic forces and moments on the airframe by simulation. The geometry should be represented in a way to be parameterized by a small number, say O(100), parameters with intuitive interpretation. The computational models considered here range from handbook methods (USAF Digital DATCOM[12]), through linear singularity methods (Vortex Lattice Method,[13] Panel Methods such as dwfSolve[16]) to full non-linear Euler and RANS compressible flow CFD packages ([8]), see 1(b). The lower fidelity tier I models are acceptable for low angles of attack and low speed, whereas the tier I+ Euler model extends the predictable region of the envelope by capturing compressibility effects, and the tier II RANS models include also viscous effects. The tools for managing the geometry modeling will be described below with comments on the workflow, in particular on the degree of automation achievable while preserving the engineer's accountability for the quality of the data compiled. A challenge is to approach automatic volume mesh generation for tier I+, with geometries including control surface deflections.

1. Geo-`sumo` software chain

The relevant part of the CEASIOM package is shown in 1(b). The `geo.xml` file defines the geometry with sufficient details for the Tier I computations. The lifting surfaces are assembled from quadrilateral planforms, twist, dihedral, etc., and airfoil definitions. Body, booms, cockpits, etc., are described by only a few key parameters; for the VLM the slender body approximation provides a rough estimate of the body influence on the downwash on lifting surfaces. The lifting surfaces are modeled as lamina, and control surface deflections can be effected by actually changing the geometry or by just manipulating surface normals in the numerical flow tangency conditions.

The `geo.xml` file is edited by the ACBuilder GUI which gives visual feed-back of not only external geometry as needed for aerodynamics but also data necessary for weights and balance estimates. In addition to `geo.xml`, VLM requires a few "solver" parameters, such as lattice densities, wake relaxation scheme, etc.,. These parameters can easily be set by the engineer and have default values based on past experience.

Panel methods and Euler simulations require much higher fidelity geometry. The aircraft must be represented by a closed surface, smooth enough to support a surface grid with proper refinements at critical places like leading and trailing wing edges, wing tips, etc. But also the surfaces on the fuselage, canopy, fairings, etc., must be well-rounded not to create spurious pressure peaks or troughs. The `sumo` package[15,16] builds the aircraft surface from a set of closed spline surfaces and provides a proper GUI for designing the shapes from cross sections and control points. `sumo` calculates the intersections and can perform local smoothing and closure of features such as open wing tips, as necessary, to make a single closed surface. It can proceed to generate a triangular surface mesh with density controlled by radii of curvature, etc., from a small set of user parameters.

The `geo.xml - sumo` interface provides most of the data necessary, but user interaction is required when the xml geometry is inadequate. Typically, components such as vertical and horizontal tails and the rear fuselage may not intersect properly; `sumo` will then attempt repair with default parameter settings and issue error messages; the response called for is to change the geometry using ACBuilder. Control surface deflections can be done by actual geometry deformation before mesh generation, or by manipulation of surface normals. The surface deformation currently fills the gaps that are created; details of multi-element high-lift systems are not supported. The step from surface mesh to volume mesh is taken by the TetGen[17] package, which needs only a few user parameters to fill the volume between exterior of aircraft and the far-field sphere by a tetrahedral mesh. The quality of the surface mesh is crucial. Inadequate surface meshes are often caused by surface irregularities, and call for geometry repair by the engineer.

The Tier II geometry models require high-quality surfaces with all relevant details. Such high-quality geometry models can be created by `sumo` and sent as IGES[5] files to fully-fledged mesh generator systems such as Ansys ICEM CFD.[21] For existing aircraft, data, including a CAD model, may be available for validation experiments and modification exercises. The approximation of a given CAD geometry by the `geo.xml` format is not a well defined task. It is currently done "manually" by the engineer, by extracting cross sections etc.

as native sumo input, or, with even more radical shape approximation, by adapting the O(100) parameters of `geo.xml` to "best fit" the CAD surface data.

B. Adaptive-Fidelity CFD

1. *Aerodynamic tables for S&C*

A prerequisite for realistic prediction of the S&C behavior and sizing of the FCS is the availability of complete and accurate aerodata (i.e. the S&C database). The aerodata is represented by an multidimensional array of dimensionless coefficients of aerodynamic forces and moments, stored as a function of the state vector and control-surface deflections. The aerodynamic table in AMB has the following format.[11]

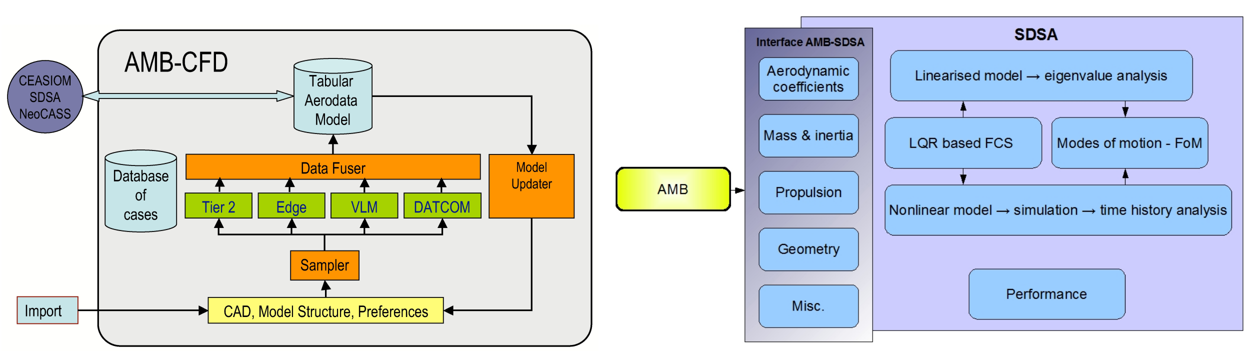
α	M	β	q	p	r	δ_e	δ_r	δ_a	CL	CD	Cm	CY	Croll	Cn
x	x	x	-	-	-	-	-	-	x	x	x	x	x	x
x	x	-	x	-	-	-	-	-	x	x	x	x	x	x
x	x	-	-	x	-	-	-	-	x	x	x	x	x	x
x	x	-	-	-	x	-	-	-	x	x	x	x	x	x
x	x	-	-	-	-	x	-	-	x	x	x	x	x	x
x	x	-	-	-	-	-	x	-	x	x	x	x	x	x
x	x	-	-	-	-	-	-	x	x	x	x	x	x	x

Table 1. Format of the aerodynamic table

where α is the angle of attack, M is the Mach number and β the side slip angle. q, p and r are the three rotations in pitch, roll and yaw. The three control surfaces that can be deflected are the elevator (δ_e), the rudder (δ_r) and the aileron (δ_a). The table is linearised and is build up from 7 three-dimensional tables with α, M and a third parameter (β, q, p, r, δ_e, δ_r or δ_a).

Traditionally, wind-tunnel measurements are used to fill look-up tables of forces and moments over the flight envelope but wind-tunnel models become available only late in the design cycle. To date, most engineering tools for aircraft design rely on handbook methods or linear fluid mechanics assumptions. The latter methods provide low cost reliable aerodata as long as the aircraft remains well within the limits of the flight envelope. However, current trends in aircraft design towards augmented-stability and expanded flight envelopes require an accurate description of the non-linear flight-dynamic behavior of the aircraft. The obvious option is to use Computational Fluid Dynamics (CFD) early in the design cycle. It has the predictive capability to generate data but the computational cost is problematic, particularly if done by brute force: a calculation for every entry in the table. The total entries can number in the tens of thousands. Fortunately methods are available that can reduce the computational cost.

There are essentially three issues, see Fig 2(a).



(a) (b)

Figure 2. AMB-CFD and S&C Modules: a) Architecture of the Aerodynamic Dataset Generator AMB-CFD; b) SDSA structure and functionality.

Firstly, a spectrum of computational tools are available, from RANS to potential flow models and semi-empirical methods. Each of the tools has a range of validity which can be exploited to keep the computational cost down. For the preliminary design of the aircraft and its FCS and as long as the flight attitude remains well within the limits of the flight envelope in the range of low-speed aerodynamics, tier I computational methods can provide the aerodata. For a refined design of the FCS or for flight attitudes close to the border of the flight envelope, the linear or inviscid methods used in the tier I tools fail to predict the proper aerodynamic behavior and tier II RANS methods will be used. In addition, data fusion[11] can be used for data from different sources, with low fidelity/low-cost data indicating trends and a small number of high fidelity/high-cost simulations correcting the values.

Secondly, mesh-free interpolation methods can significantly reduce the number of data points which actually need to be computed to fill the table. Some studies[3,6,11] of using kriging for the generation of aerodynamic data have been published.

Thirdly, the identification of parameter regions where the aerodynamics is nonlinear, and hence where tier II fidelity is needed, is a *sampling* problem. Therefore CEASIOM's Aerodynamic module develops along with these three elements.

A range of computational tools are available in CEASIOM. TORNADO,[7] a vortex-lattice method for conceptual aircraft design and education has been integrated into CEASIOM as the main tier I tool. TORNADO allows a user to define most types of contemporary aircraft designs with multiple wings, both cranked and twisted with multiple control surfaces located at the trailing edge. Each wing is permitted to have unique definitions of both camber and chord. The TORNADO solver computes forces, moments, and the associated aerodynamic coefficients. The aerodynamic derivatives can be calculated with respect to: angle of attack, angle of sideslip, roll-pitch-yaw rotations, and control surface deflections.

More elaborate than vortex-lattice methods is the inviscid version of the Edge CFD code[8] that has been selected to determine the aerodata for transonic flight. A first exercise with the Horizon 1100 aircraft aimed at checking the complete simulation procedure from `geo.xml` to automatic meshing and CFD solution. The Edge solver gave a fully converged result in 800 MultiGrid four-level cycles on a modern laptop in 15 minutes, and the steps described above took less than one and a half hour, with minimal user intervention.

The tier II CFD tools are currently loosely coupled to CEASIOM because users are mainly interested in coupling their own RANS CFD tools. However, standard interfaces and file formats are defined in CEASIOM to which different RANS solvers have been coupled with MATLAB and Python scripts to perform sequences of runs and collect results.

C. S&C Analysis of Aerodata

Once the aerodynamic coefficients have been obtained along with the mass and inertia properties, the S&C aerodata database is in hand. The S&C analysis can begin with the SDSA (Simulation and Dynamic Stability Analyzer) which provides the following functionalities:

1. Stability analysis:
    a. Eigenvalue analysis of linearized model
    b. Time history identification (nonlinear model)
2. Six Degree of Freedom flight simulation:
    a. Test flights, including trim response
    b. Turbulence
3. Flight Control System:
    a. Human pilot model
    b. Stability Augmentation System
    c. FCS based on Linear Quadratic Regulator (LQR) theory
4. Performance prediction
5. Miscellaneous (data review, results review, cross plots, etc.)

Figure 2(b) illustrates the structure and functionality of this module. SDSA uses the same Six DoF mathematical nonlinear model[9] of the aircraft motion for all functions. For the eigenvalue analysis, the model is linearized numerically around the equilibrium (trim) point. Eigenvalues and eigenvectors analysis allow automatic recognition of the typical modes of motion and their parameters. The flight simulation module can be used to perform test flights and record flight parameters in real-time. The recorded data can be used for identification of the typical modes of motions and their parameters (period, damping coefficient, phase shift). The stability analysis results are presented as ”figures of merits” based on JAR/FAR, ICAO, and MIL regulations. The SDSA embedded flight control system allows a “pilot in the loop”, and SAS and FCS based on a LQR approach. The LQR-FCS module allows computing and saving control matrices for simulations over the whole envelope. In this way, SDSA includes the FCS for stability characteristics nd in flight simulation for the ”closed loop” case. The performance option is designed to compute basic performance parameters: flight envelope (V_{min} and V_{max} versus altitude of flight), selected manoeuvres (e.g. regular turn), range and endurance characteristics. For all mentioned functionalities the starting point is the computation of the trimmed state with sufficient initial conditions. The test flight settings include initial state, disturbances, and single / double step controls. SDSA is a stand-alone application integrated into CEASIOM. As a module of CEASIOM, it receives all the necessary data (aerodynamics, mass, inertia, available thrust), when available, without special prompting.

The necessary data can be delivered to SDSA as an XML file or as a set of plain text files. The second option is useful e.g. for experimental data. The data set contains aerodynamic coefficients or/and stability derivatives tables, mass and inertia data, propulsion data, control derivatives and reference dimensions. The control and propulsion data can be completed and edited using special options of SDSA. SDSA accepts aerodynamic data as tables of stability derivatives as function of angle of attack and Mach number. SDSA also accepts as a multidimensional array of force and moment coefficients versus six state parameters (angle of attack, Mach number, sideslip angle and rotational velocity components). A similar array is defined for control derivatives and stability derivatives versus selected accelerations (i.e. alpha dot derivatives). All aerodynamic data (derivatives) can be reviewed and are checked by comparison with typical values.

1. Flight Dynamic Modes of Motion: Eigenvalue analysis of linearized model

The SDSA analysis reveals several dynamic modes, including phugoid and Dutch roll that indicate the handling quality characteristics.

Phugoid This mode is characterized by very slow oscillations in pitch angle and velocity, and a nearly constant angle of attack. To excite this mode, begin with the airplane trimmed in level flight. Pull back slightly on the stick and maintain, or increase elevator trim. This pitches the airplane up into a climb. As the airplane climbs, it loses speed and lift, causing it to gradually pitch downward and enter a dive. During the dive, the airplane gains speed and lift, bringing it back into a climb.

Short Period This mode is characterized by rapid oscillations in angle of attack about a nearly constant flight path. This mode is probably best excited by rapidly deflecting the elevator, and usually it is fast and well damped.

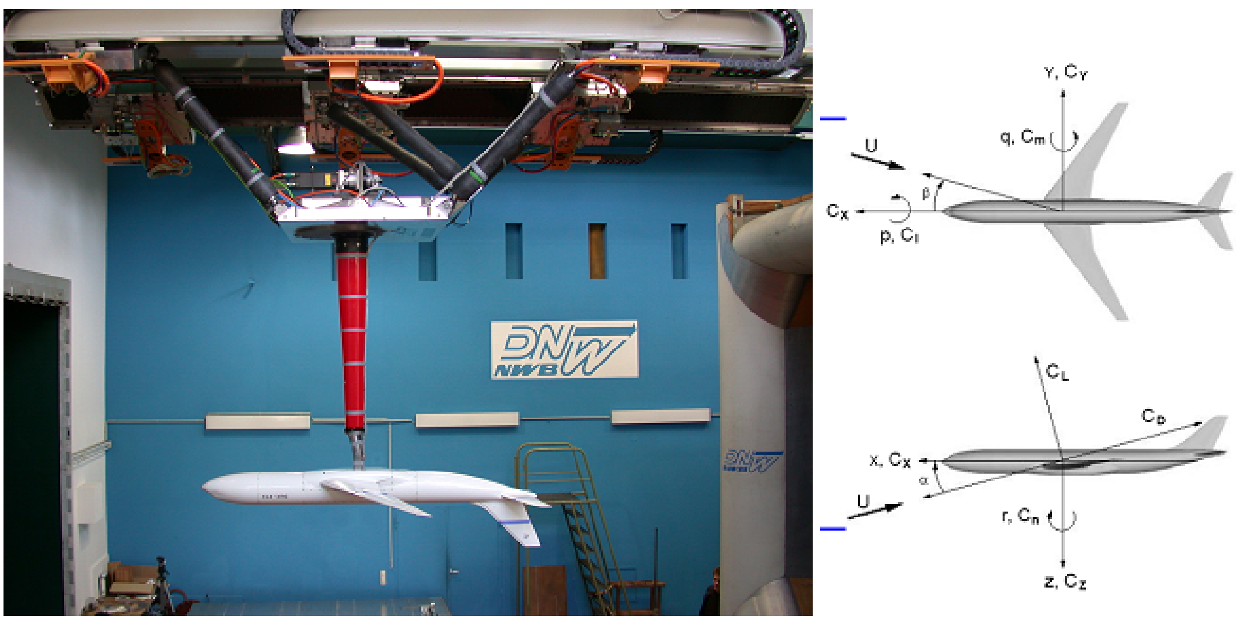
Dutch Roll This mode is moderately fast side-to-side swaying of the aircraft. It involves oscillations in bank, yaw, and sideslip angles. In a flight-state display, a Dutch roll will be indicated by the velocity vector circle oscillating from side to side.

Spiral Mode This mode is very slow and may be stable or unstable. This mode can be observed by starting the aircraft in straight and level flight and then applying aileron or rudder to bank the airplane slightly. With aileron and rudder set to neutral, the aircraft will either return to level flight in a *stable spiral mode*, or experience increasing bank angle accompanied by a dive, *spiral divergence*. The damping time to half amplitude is usually given to asses the spiral.

Adverse Yaw This motion is a handling characteristic that may be experienced when rolling the airplane with aileron. To execute a left turn, the pilot will apply left stick, dropping the right and raising the left aileron. The right wing generates more lift than the left wing, causing the airplane to roll to the left. While carrying extra lift, the right wing is also likely to produce more drag than the left wing. This causes the airplane to yaw to the right, opposite to the intended left turn.

III. DLR-F12 Benchmark

The DLR-F12 model used is a typical geometry of a generic transport aircraft and was constructed specifically for dynamic tests. Such a model must meet different design criteria than conventional wind tunnel models. The mass of a dynamic wind-tunnel model as well as its moments of inertia must be as low as possible to achieve a favorable ratio between the aerodynamic forces of interest and the additional acting forces from mass. On the other hand, the elastic deformation has to be as small as possible. Furthermore, the first Eigenfrequency of the model should be one order of magnitude above the excitation frequency, at least 15 Hz, to avoid the excitation of the model's higher harmonics. The best material to meet all these requirements proves to be carbon fibre reinforced plastic (CFRP). Using CFRP-Sandwich structure as is used in building full-size gliders, the DLR-F12 model has a weight of 12 kg. The model was manufactured by the DLR plastics workshop in Braunschweig. In order to evaluate the influence of individual components of the tested airplane configurations, such as winglets, vertical or horizontal stabilizers, nacelles, on the dynamic derivatives the models are designed in a modular way so that every component of interest can be added to the model. The DLR-F12 model does not only allow the measurement of unsteady forces and moments but also unsteady pressure distributions using pressure taps at specific chordwise stations on the wing and horizontal and vertical stabilizers. In the SimSAC project, static and dynamic force measurements and steady and unsteady pressure distribution measurements in three sections distributed on the wing, the horizontal and the vertical tailplanes, have been performed on the DLR-F12 configuration in the 3 m Low Speed Wind Tunnel of the foundation German-Dutch Wind Tunnels (DNW-NWB) in Braunschweig, Germany. This low speed facility works at atmospheric pressure. For the experimental determination of the dynamic wind tunnel data a new combined motion test capability was developed by DNW and DLR as an improved successor to the previous test set-ups, using a unique six degree-of-freedom test rig called 'Model Positioning Mechanism' (MPM) see Fig 3.



(a) (b)

Figure 3. Windtunnel measurements of F12. a) DLR-F12 model on the MPM, b) Axis-system for force coefficients

A. Comparison of Aerodynamic Coefficients

1. *Steady Coefficients*

The evolutions of the computed aerodynamic coefficients is compared with the experimental data on Fig 4(evolution versus angle of attack, aerodynamic axis system) and Fig 5 (evolution versus sideslip, model axis system). The lift coefficient is well predicted by CFD tools with a lift overestimation by Euler methods for the highest angles of attack. A shift in the pitching moment of about 0.03 exists between experimental and computational data and is likely to come from the model support effect (ventral sting), not taken into account in the computations. As far as the VLM tools are concerned, the discrepancy of the results is large, probably coming from differences in the geometries and/or meshes.

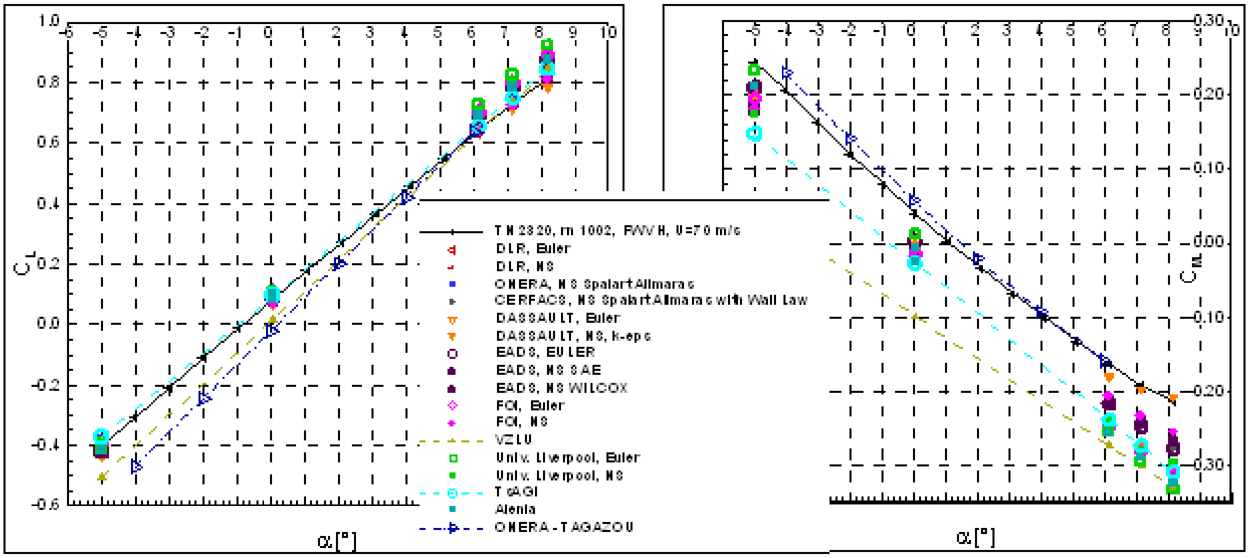


Figure 4. Evolution of lift and pitching moment coefficients with angle of attack

The lateral coefficients (Fig 5) are rather well predicted with all the methods employed. When comparing Euler and Navier-Stokes results, it can be seen that the viscous effects are moderate for this configuration. It has also been checked that calculated pressure coefficient distributions in the three sections are in an excellent agreement with the experimental data.

2. Pitch Motion

QUASI-STEADY PITCH The steady dynamic derivatives are plotted on Fig 6(a) for lift and pitching moment coefficients. The experimental data exhibit a insignificant dependency on the angle of attack. The plots include results obtained with linear inviscid tools as well as Euler and Navier-Stokes solvers. The experimental data include the contribution for derivatives. The discrepancy for the static derivatives establishes in the region of 15/20% of the absolute values of the q derivatives, which is rather small if one considers the model large differences. The viscous effects are slightly higher for the pitching moment derivative (10% of the absolute value) than for the lift (5%).

UNSTEADY PITCH The unsteady dynamic derivatives obtained with unsteady solvers as well as frequency-domain tools are plotted on Fig 6(b). These results include the contribution and thus, are directly comparable to the experimental data. As far as the lift derivative is concerned, the agreement with the experimental data is slightly less good than for the quasi-steady data. On the other hand, the agreement is better for the pitching moment. The (resp.) contribution computed with CFD tools is negative and in the region of 5/10% (resp. 25%) of the (resp.) value. So, it can be important to take these components into account in the aircraft aerodynamic model because they can lead to significant errors in longitudinal flight dynamics criteria (e.g. short period incidence oscillation).

3. Roll Motion

The dynamic derivatives with respect to a rotary motion around the $X axis$ are needed to assess the classical lateral flight dynamic criteria, like the spiral mode or the time to reach 30° bank angle. For the F12 configuration, the quasi-steady and dynamic derivatives are the most important ones compared to the other lateral derivatives. A comparison of computed and experimental data is given in Fig 7(a). All the numerical results are obtained with quasi-steady approaches except for FOI data, which are obtained with a fully

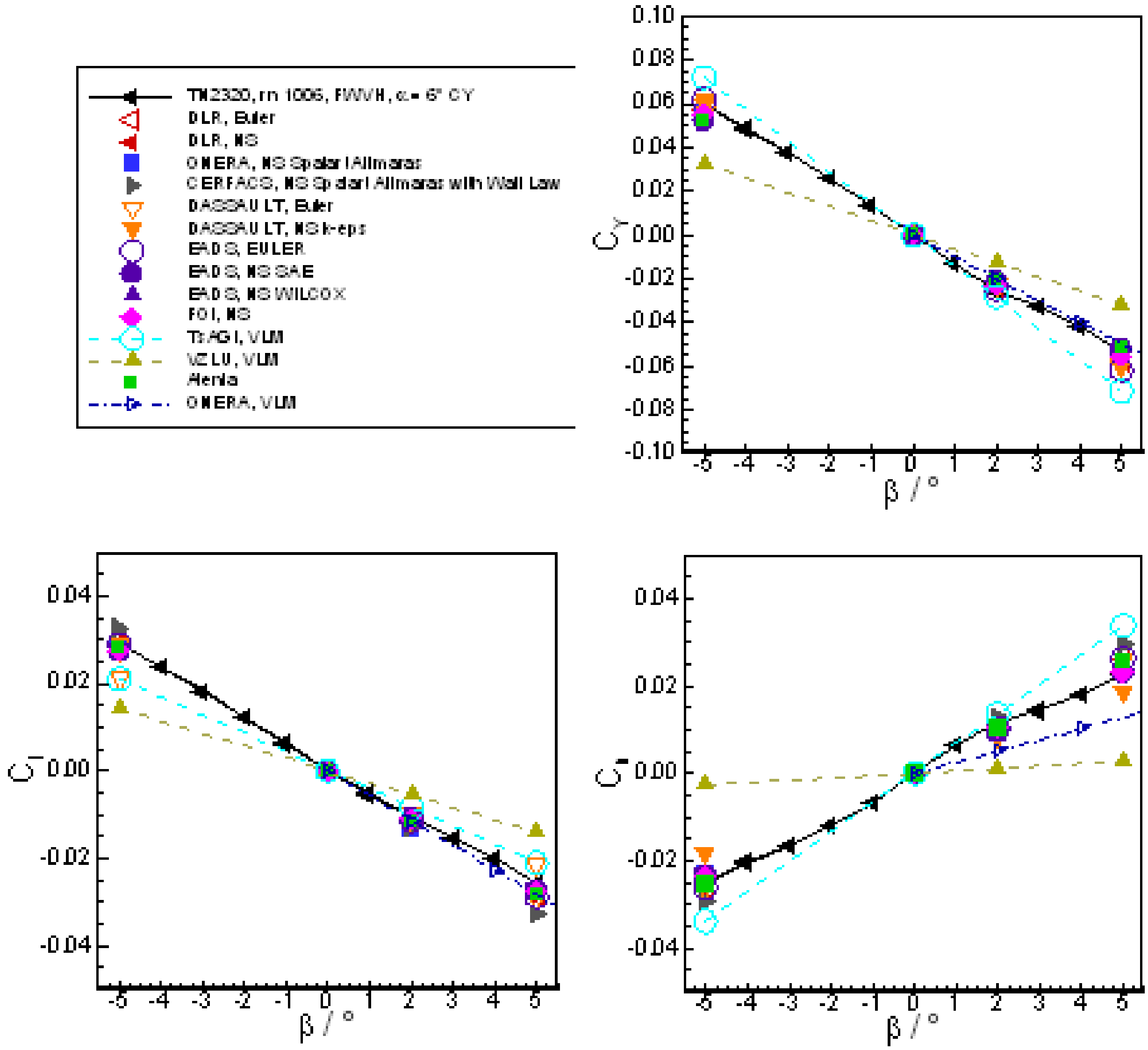
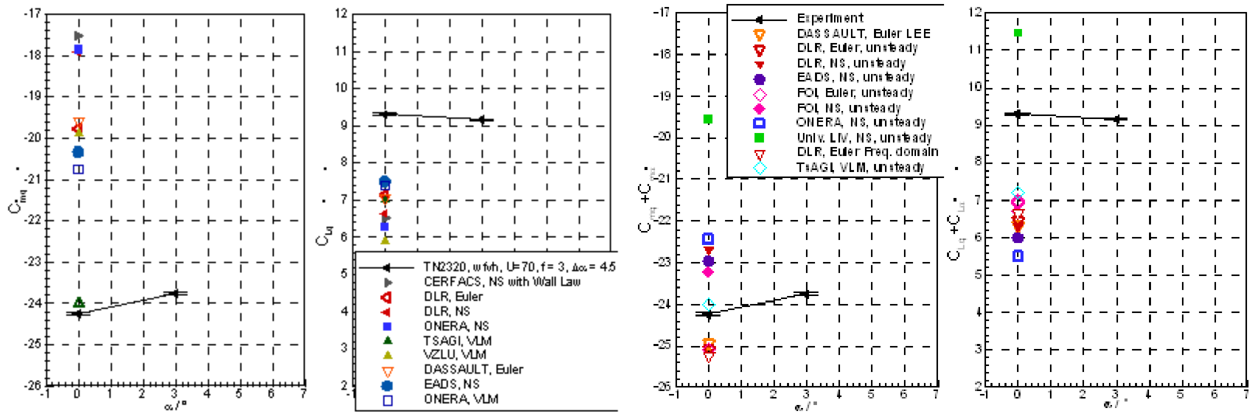


Figure 5. Evolution of the side force, rolling and yawing moment coefficients with sideslip

unsteady computation. A very good prediction of the is obtained with all the codes, including the VLM tools. The discrepancy on the derivative reaches about 100% of the absolute value, which is small with, one VLM tool not predicting the right sign: the prediction is not as good as for the roll moment derivative, however the impact of on the flight dynamic criteria is smaller. It's worth noticing that another VLM tool predicts very well the derivatives. The viscous effects are very small on these coefficients.

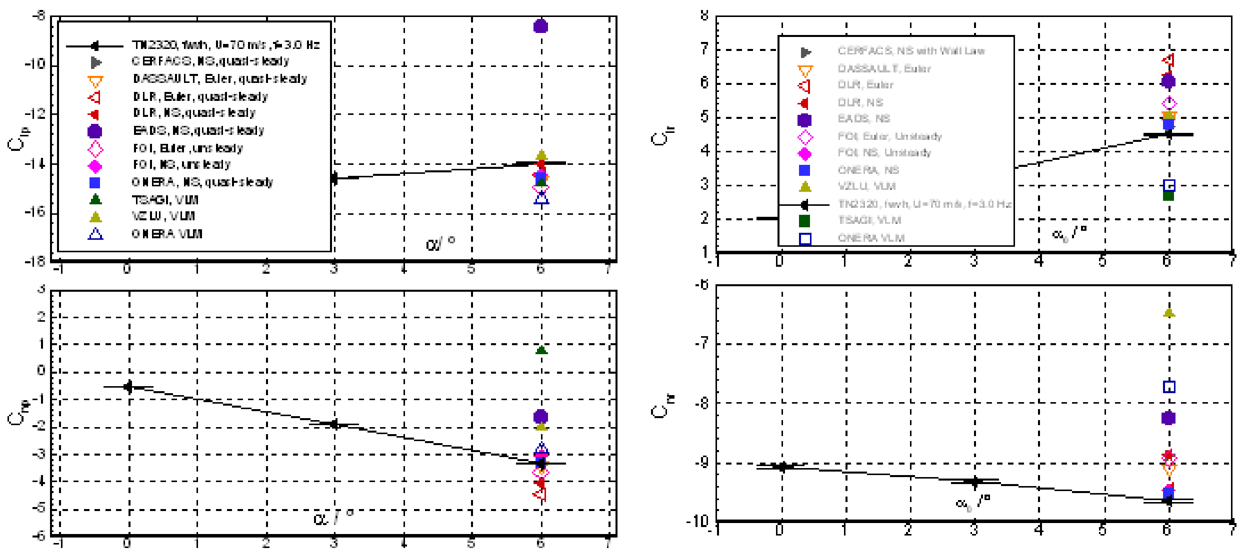
4. Yaw Motion

The derivatives with respect to yaw motions can affect some lateral flight dynamic criteria, like the spiral mode. Figure 7(b) presents the comparison of experimental data (,) with numerical results. The prediction of the roll and yaw moment derivatives is accurate for CFD tools. The viscous effects are not significant, as well as the contribution of derivatives with respect to , only taken into account in the FOI results. The results obtained with VLM tools are less accurate, and quite large differences are observed among the results



(a) (b)

Figure 6. Pitch Motion q **- a) Steady Dynamic Derivatives obtained with Quasi-Steady Tools,** $Ampl. = 4.52°$, $f = 3Hz$, $\alpha = 0°$, $V = 70m/s$;
- b) Unsteady Dynamic Derivatives obtained with Unsteady and Frequency Domain Tools, $Ampl. = 4.52°$, $f = 3Hz$, $\alpha = 0°$, $V = 70m/s$.



(a) (b)

Figure 7. Dynamic Derivatives - a) Unsteady roll motion p, $Ampl. = 4.86°$, $f = 3Hz$, $= 6$, $V = 70m/s$;
- b) Unsteady yaw motion r, $Ampl. = 4.32°$, $f = 3Hz$, $= 6°$, $V = 70m/s$.

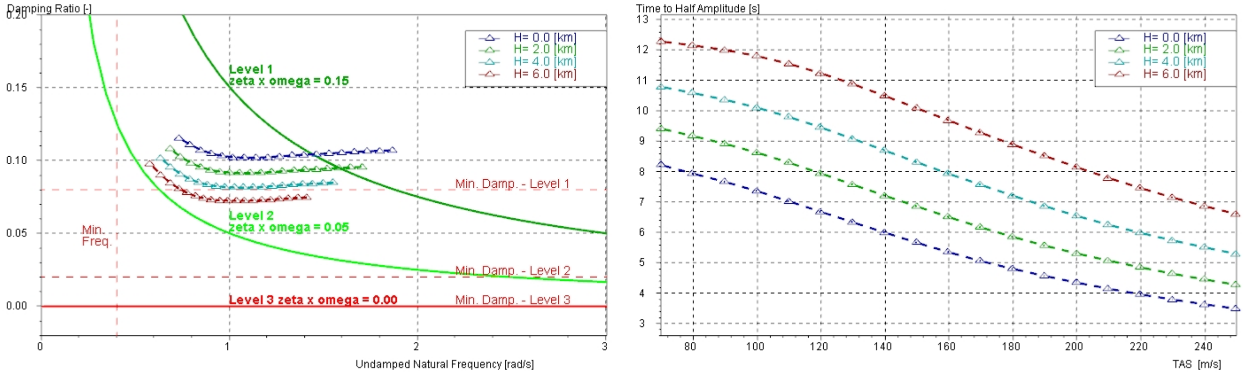
of the three tools.

B. Stability analysis

Tomasz, please write some text to go alone with your figures for Dutch Roll...

replace text below...

Figure 8 presents the results for the Dutch Roll mode - undamped natural frequency and damping ratio. Both values have very close values for all data sets. It is interesting, that the results are so close, despite significant differences between values of key stability derivatives for Dutch Roll - $\partial Cl/\partial\beta$ and $\partial Cn/\partial\beta$. Also lateral damping derivatives are different for all data sets. Generally lateral stability depends strongly on these values, however sometimes other values (i.e. other characteristics, mass and inertia) cause, that stability analysis is not sensitive on these derivatives. Figure **??** presents Dutch Roll characteristics against a background of MIL[20] criteria characteristics for aerodynamic data from HISSS[19] and EDGE.[8]



(a) (b)

Figure 8. Dutch Roll Characteristics vs true airspeed given by SDSA for measured data: a)MIL figure of merit to classify the Dutch Roll characteristics (damping ratio) b)Time-to-half amplitude for Dutch Roll mode vs. true airspeed.

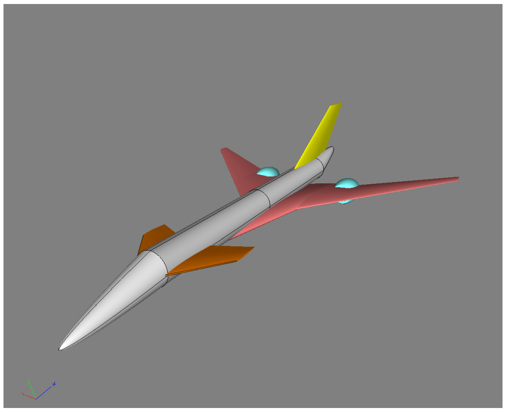
IV. TCR Design Study

A major undertaking in SimSAC is the design, simulate and evaluate (DSE) exercise. The endeavor begins with a design specification and uses conventional design methods to prescribe a baseline configuration. Then CEASIOM improves upon this baseline by analyzing its flying and handling qualities. This paper reports on the DSE case Transonic cruiser TCR from baseline design to Tier-I design. The baseline is based on the design specification, which is a fairly non-complicated one with the exception for the design cruise speed of Mach 0.97. This design speed was chosen to stress the shortcomings the handbook methods have in the transonic speed envelope. The baseline, a T-tail design, was analyzed with CEASIOM tools for aerodynamics, mass properties, flight mechanics and aeroelastics. The aerodynamic analysis included handbook methods (DATCOM), potential calculations (TORNADO) and Euler calculations (EDGE). The flight dynamical analysis showed that there is a problem with trim. Too large deflections are needed to trim the TCR aircraft in the design point. The stability margin is very large. This is a typical problem in the transonic envelope. In addition the aeroelastic analysis showed that the T-tail fluttered, even in low speed. The first step in the Tier-I design was to try to cure the trim problem by moving the wing forward in order to increase the distance between the centre of gravity and the horizontal tail. This improved the trim characteristics a bit, but more was needed. A new approach with a canard configuration was suggested. For this the stability margin was decreased drastically, but the canard deflection for trim was still substantial. The tail flutter problem was solved. This configuration is judged to be better than the T-tail configuration and is being built as a model and tested in the wind tunnel to verify the entire design functionality. CEASIOM delivers the configuration as an IGES file that can be used to construct the windtunnel model. This evolution shows how CEASIOM is becoming a useful tool for aircraft design.

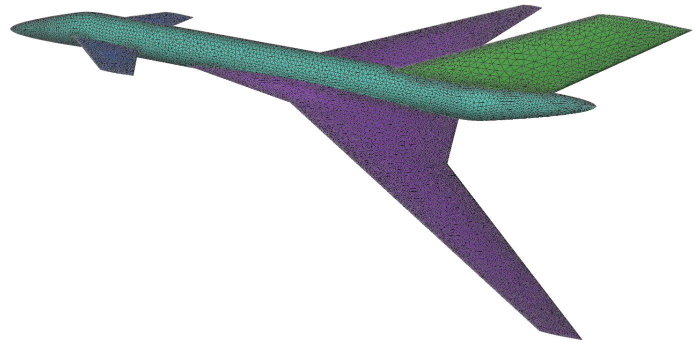
A. Re-design to Canard Config

The poor trim characteristics of the baseline configuration together with the predicted flutter of the T-tail call for a re-design of the TransCruiser. An alternative all-moving canard configuration was proposed, and SAAB requested to further investigate it by varying the longitudinal position of the canard wing, the longitudinal position of the main wing and the canard area, while keeping the main wing shape.

Canard configurations have several advantages, such as the possibility of designing a stall-proof aircraft. If the design is correct, the canard should stall before the main wing does. As a result, the canard stops generating lift and induces a nose-down pitching moment which reduces the angle of attack, causing a lift recovery in the canard. However, these configurations have many drawbacks too, such as being more unstable than conventional ones, since the aerodynamic center is located closer to the center of gravity of the aircraft. Figure 9(a) presents the canard configuration designed in CEASIOM. Figure 9(b) presents the sumo surface mesh for Euler computations on the TCR-C15 configuration designed in CEASIOM.



(a)



(b)

Figure 9. TransCruiser canard configuration a) designed in CEASIOM, and b) sumo surface mesh for Euler

B. SDSA Predictions of Expected Trimability

The aerodatabase for the TCR has been computed with Tornado and Euler for low speed and with Euler for high speed.

1. Comparison of Aerodynamic Coefficients

Figure 10 presents and compares some Tornado and Euler results for longitudinal coefficients...

Low Speed Trim As it has already been mentioned, the trim characteristics of the canard configuration improve with respect to the original TCR. The canard deflection is much smaller, and the angle of attack required remains similar. Thus, the canard configuration is more adequate for the goal that is to be achieved. Some tests will be run on the wind tunnel model by TsAGI, in order to be compared to the ones obtained with SDSA.

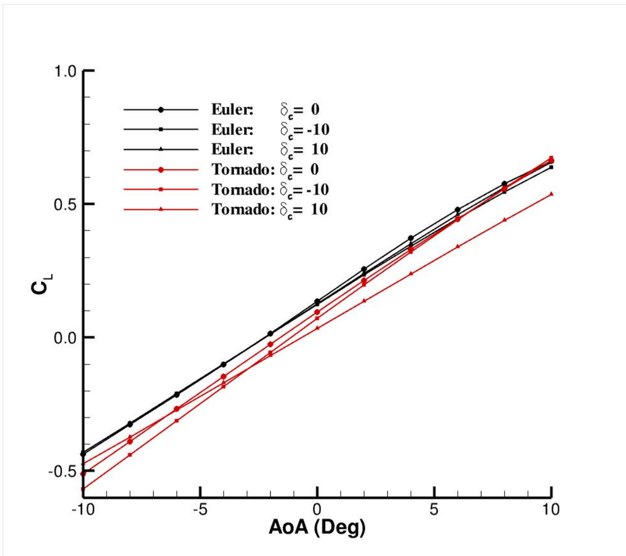
Transonic Speed Trim The aerodata for the TCR-C15 in transonic speed has been computed using the Tier 1^+ tool Edge (Euler solver). Edge requires as an input a volume mesh of the aircraft plus some boundary conditions. Both of them are generated via sumo, but the geo.xml file is needed as an initial input. Once the volume mesh and the boundary conditions are available, Edge can be launched. The user must provide the program with an axis and point of rotation when calculating cases with control surface deflections. The aerodata obtained with Edge could not be used for trim analysis, because its accuracy was considered dubious. The results suggested that the canard deflection had almost no influence at all in the lift coefficient, which is evidently wrong. One possible cause which was investigated when this paper was written is that the cases with control surfaces deflections are not correctly inputted. At the moment, one single mesh of the aircraft, with no canard deflection, is used for all Edge computations. The deflection is achieved by a transpiration boundary condition, which has not been sufficiently tested yet (particularly when it comes to all moving surfaces). An alternative way of computing results that is currently being used is creating a different mesh for each canard deflection. This slows down the calculation process, but ensures more accurate results. Figure 12 presents the trim conditions at transonic speed.

See Fig 13 for aft shift in aero center with increasing transonic speed.

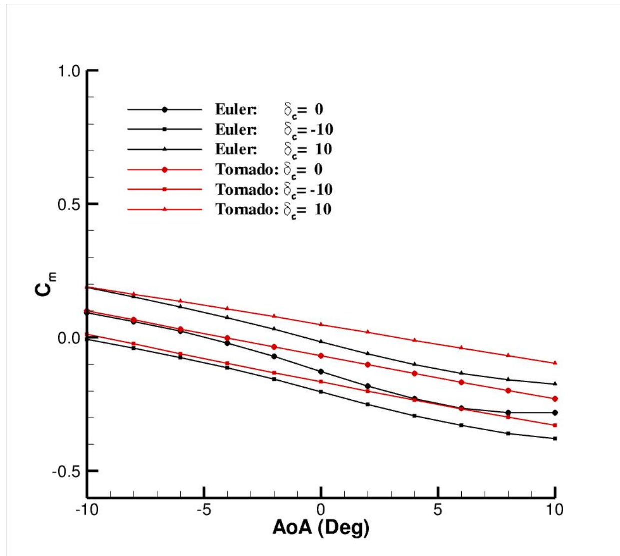
hopefully tomasz will produce similar trim figs for transonic range

V. Ranger2000 Aircraft

The Ranger 2000 aircraft, Fig 14, is a mid-wing, tandem seat military training aircraft with a turbofan engine. The wing and fuselage are manufactured of composite material and the empennage is a metal T-tail



(a)



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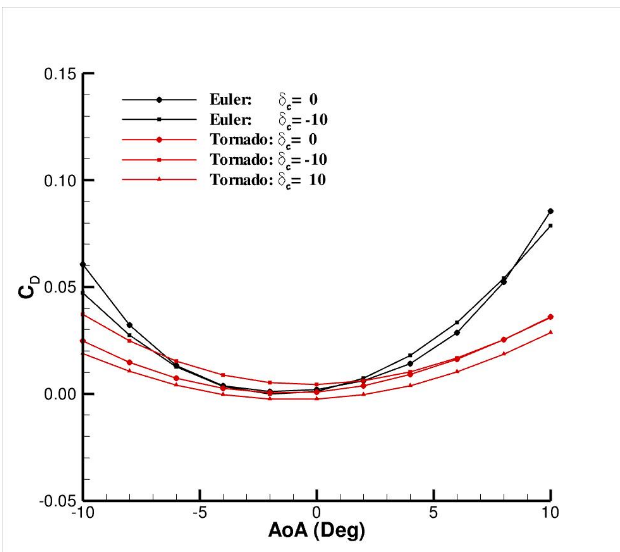

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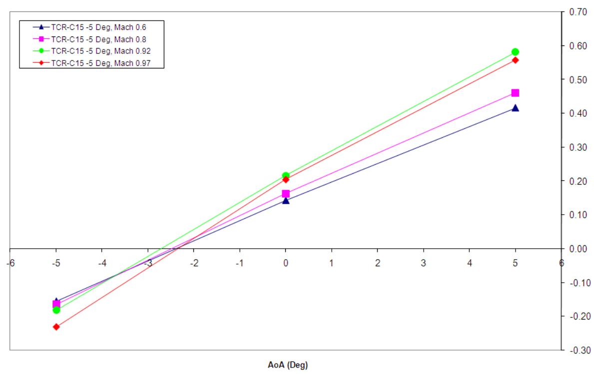

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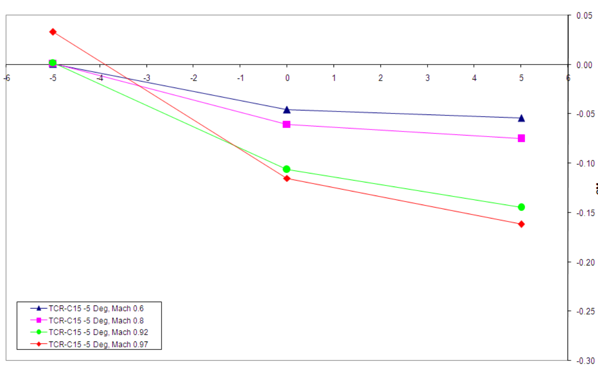

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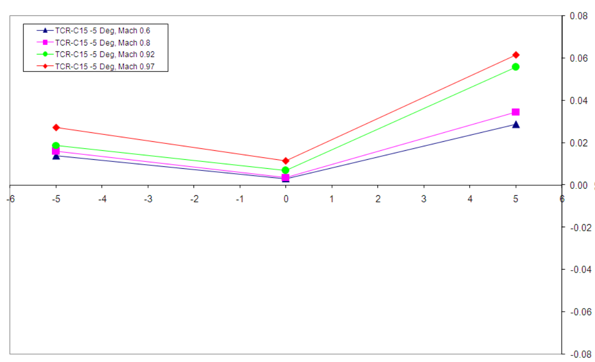
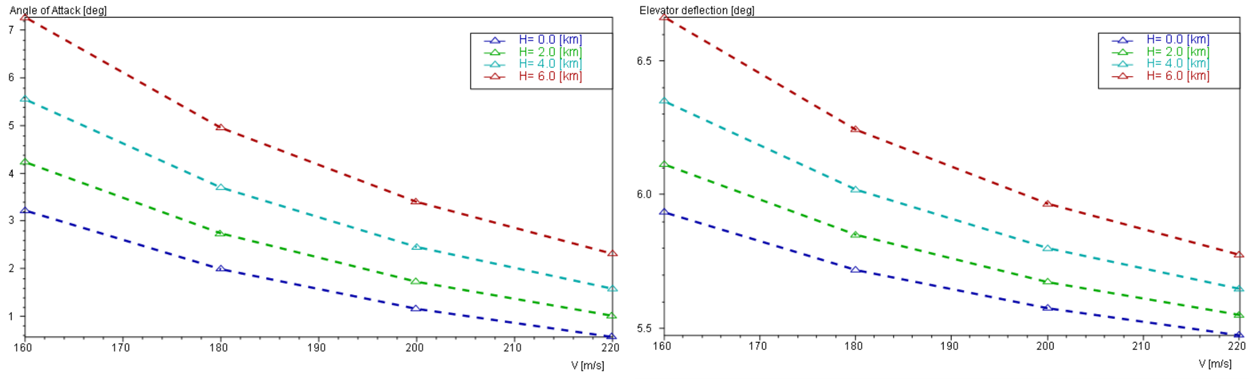


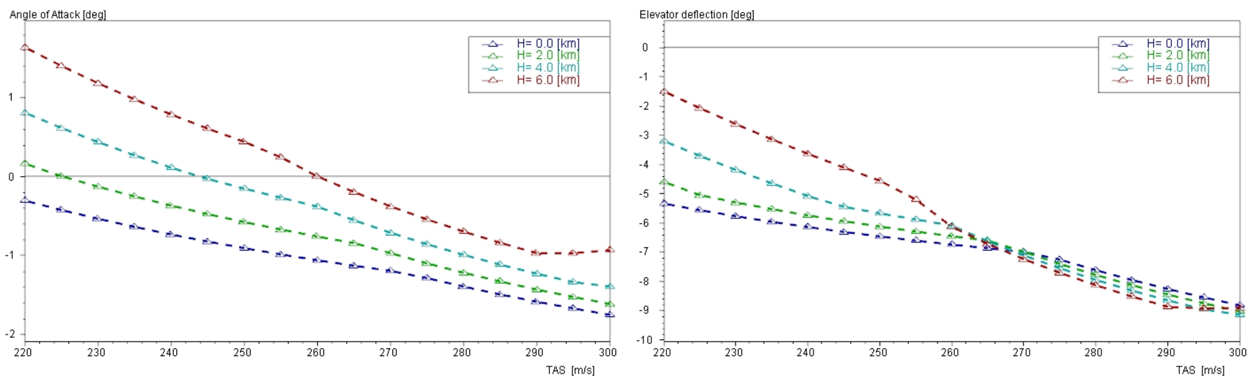
(f)

Figure 10. TCR computed aerodynamic coefficients versus α for various canard deflection angles δ_c and: I) low speed $M\infty = 0.5$ for a) lift, b) pitch moment, c) drag; II) transonic cruise with canard deflection $\delta = 0$ for d) lift, e) pitch moment, f) drag.



(a) (b)

Figure 11. Trim conditions at low speed for TCR-C15 : a)angle of attack, and b)canard deflection for various airspeeds and altitudes.



(a) (b)

Figure 12. Trim conditions at transonic speed for TCR-C15 : a)angle of attack, and b)canard deflection for various airspeeds and altitudes.

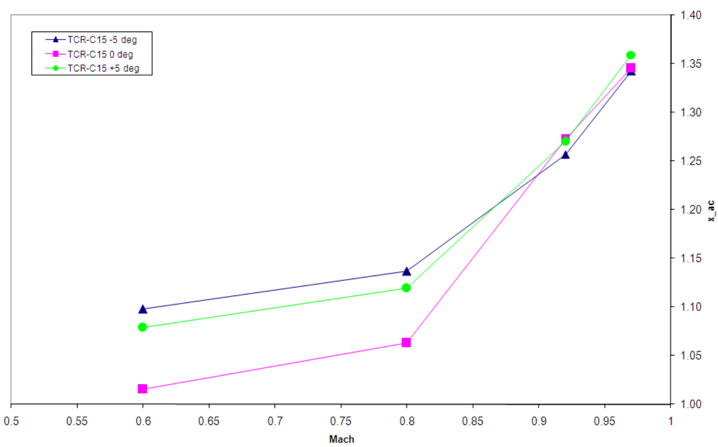


Figure 13. Aero center shifts aft with increasing Mach number

design. The control surfaces are manually operated elevator and rudder, hydraulically assisted ailerons, a belly mounted speed-brake, and electrically operated split flaps.

Figure 14. Ranger 2000 Military Training Aircraft

The results presented in the previous chapter allowed assessment of SDSA as Stability & Control tool. However, the question is how strongly the stability depends on aerodynamic data. Even big differences in aerodynamic data may fail to cause significant differences in S&C results.[10] The paper presents results of stability analysis for five different aero data sets.

1. The first and reference aero data set, is obtained from wind tunnel[18] investigations. The results were presented in the previous chapter.
2. The high order panel method HISSS[19] provides the second aero data set.
3. The vortex lattice method TORNADO is the third dataset. TORNADO[13] is embedded in the CEASIOM environment and was tested in comparison with the high order panel method HISSS.
4. The DATCOM, embeded in the CEASIOM, is the source of the fourth aero data set.
5. A fifth dataset is a combined Euler and DATCOM set. The dynamic derivatives were calculated using DATCOM, while the rest of the coefficients were calculated by EDGE.[8] The Euler calculations were done on the sumo geometry.

A. Comparison of Aerodynamic Coefficients

An analysis of the aerodynamic coefficients was done to be able to explain some of the differences of the stability and control results between the different models. In addition to the aerotables quoted above, some Euler and Navier-Stokes calculations were done by the NSMB solver[14] for comparison.

Some comments about the coefficients:

- DATCOM doesn't estimate accurately the lift curve slope and the pitching motion curve slope, which explains the inaccuracy in predicting the longitudinal eigenmodes (see Stability Analysis section).
- TORNADO and HISSS results differ for some coefficients, this is due to:
  - TORNADO does not yet take into account the fuselage
  - HISSS predicts better transsonic effects
  - HISSS uses the real CAD geometry, TORNADO only a simplified XML geometry
  - A viscosity correction is not yet included in TORNADO

  These differences explain why HISSS is better in predicting the eigenmodes.
- The coefficients calculated with EDGE show a significant improvement in comparison with panel methods or handbook methods, and thus also eigenmodes (see Stability Analysis section).
- With the simplified geometry one gets reasonably good results (EDGE) in comparison with CAD geometry results (NSMB, HISSS). Hence, geometry difference has only a minor effect.

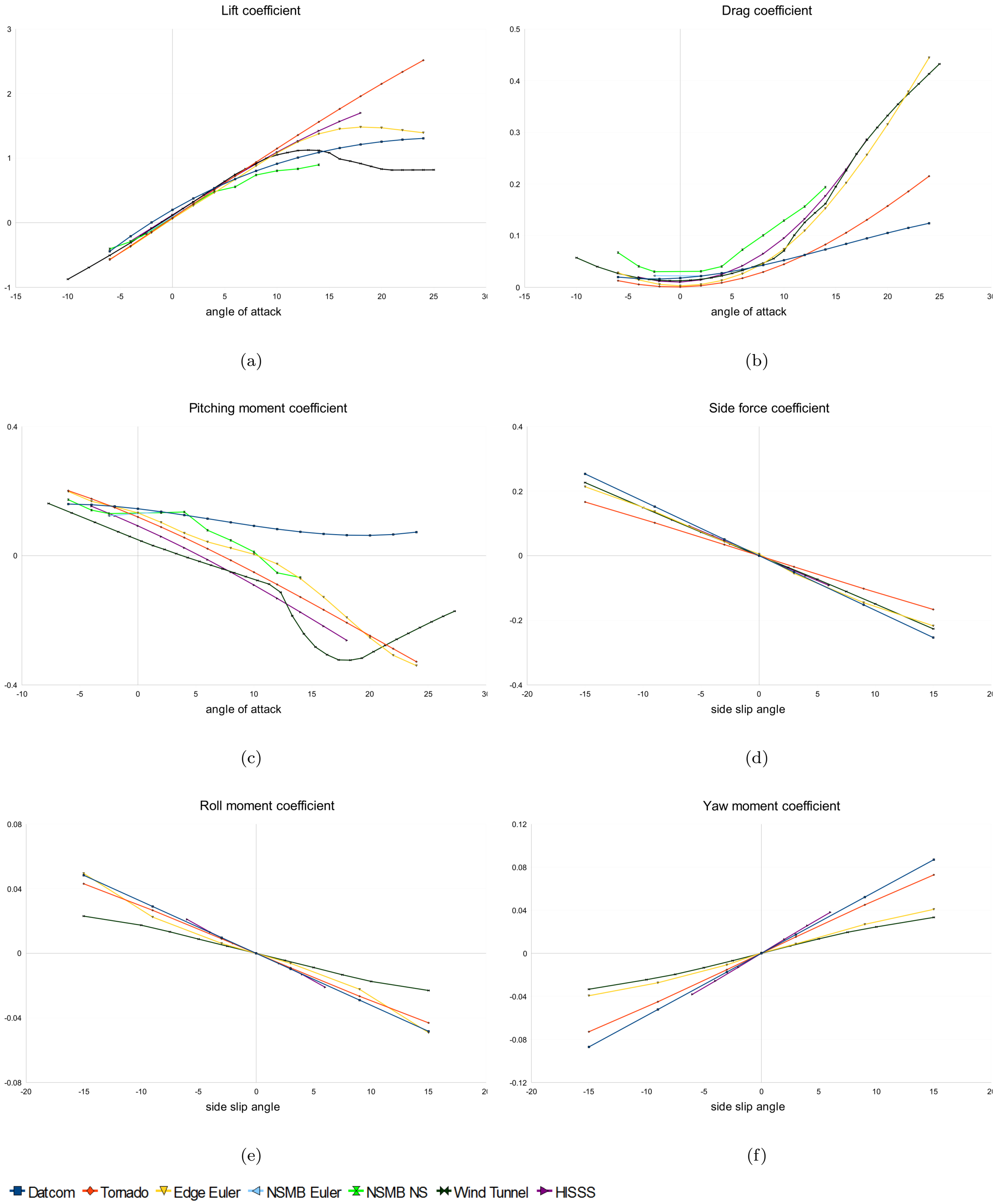
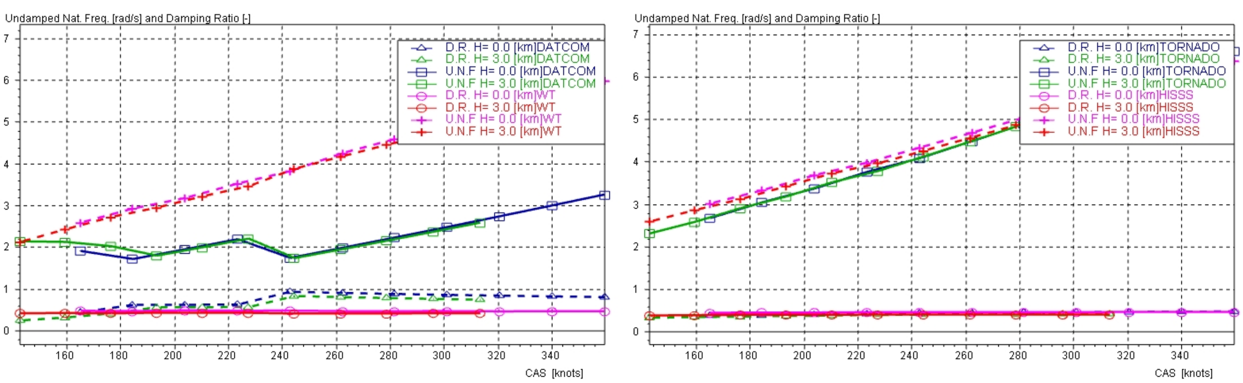


Figure 15. Aerodynamic coefficients for Mach = 0.5

- One can separate the different methods in two groups:
  - TORNADO and DATCOM, whose results are not so good
  - HISSS, Euler and NS, whose results are much better
- Higher Mach numbers rules out linear methods.
- The eigenvalues are calculated for the linearized model, which is linearized around the trim. The Ranger 2000 is trimmed at an angle of attack between -1 and 3, depending on the altitude and the speed. Thus, one only needs to consider the coefficients between these values. Hence the larger differences between the datasets at higher alpha will not enter into the stability analysis in the next section.
- The Engine intake is closed in the NSMB calculations, which explains part of the higher drag for the NS results.
- The largest differences at low angles of attack are
  - for the lift coefficient: DATCOM is the only method which does not calculate accurate the lift curve slope.
  - for the drag coefficient: Both TORNADO and EDGE calculations do not take into account the viscosity and have a zero-lift drag of 0.
  - for the pitching moment coefficient: All the methods are slightly offset, but most method predict good the slope.
  - for the Mach 0.75 calculations: At Mach 0.75, transonic effects play a large role. TORNADO is using the Prandtl-Glauert correction to estimate the compressibility effects, which is not accurate when shocks are encountered.

B. Stability analysis

Full stability and maneuvers analysis give many results. The selected graphs allow to compare and asses the results. Figure 16 presents Short period frequency vs. calibrated airspeed obtained for five data sets: WT - Wind Tunnel, HISSS - high order panel method, TORNADO - embedded VLM, DATCOM and Edge. The differences between results for all aero data sets except DATCOM are very small.

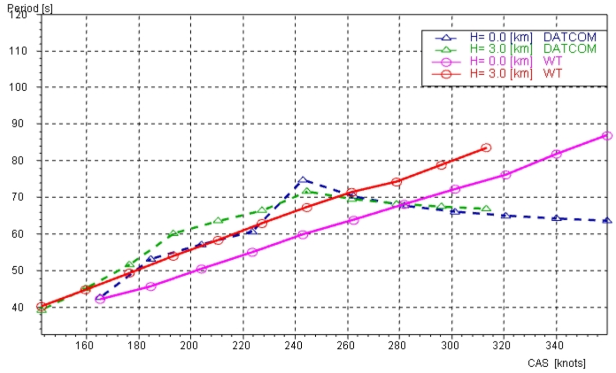


(a) (b)

Figure 16. Short Period frequency vs calibrated airspeed - results of SDSA for different aero data sets.

Figure 17 presents the phugoid period. In this case results are not so good and values obtained with DATCOM aero data set differs significantly. The difference between values of lift curve slope and drag prediction is the cause, because lift is the generator of phugoid vibration and drag is the damper.

Figure 18 presents the results for the Dutch Roll mode - undamped natural frequency and damping ratio. Both values have very close values for all data sets. It is interesting, that the results are so close, despite significant differences between values of key stability derivatives for Dutch Roll - $\partial Cl/\partial \beta$ and $\partial Cn/\partial \beta$.



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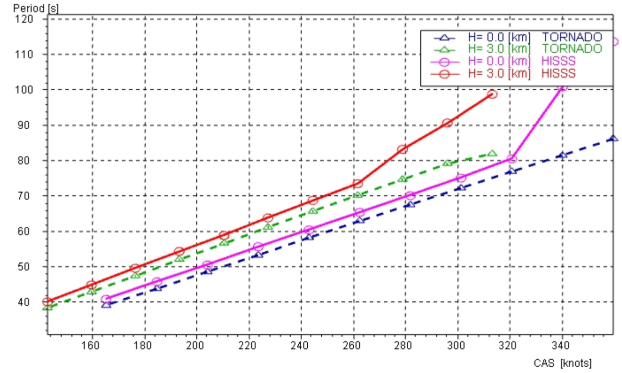
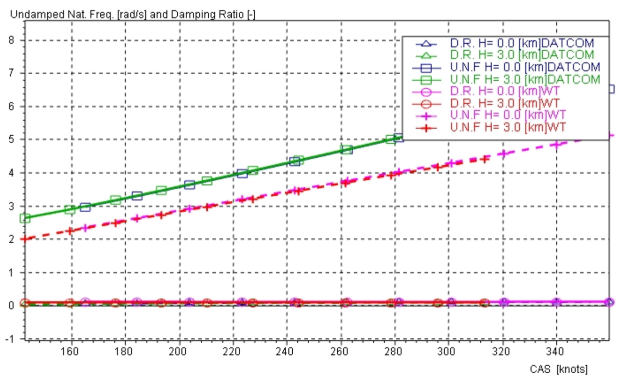


(b)

Figure 17. Phugoid period vs calibrated airspeed - results of SDSA for different aero data sets.

Also lateral damping derivatives are different for all data sets. Generally lateral stability depends strongly on these values, however sometimes other values (i.e. other characteristics, mass and inertia) cause, that stability analysis is not sensitive on these derivatives.



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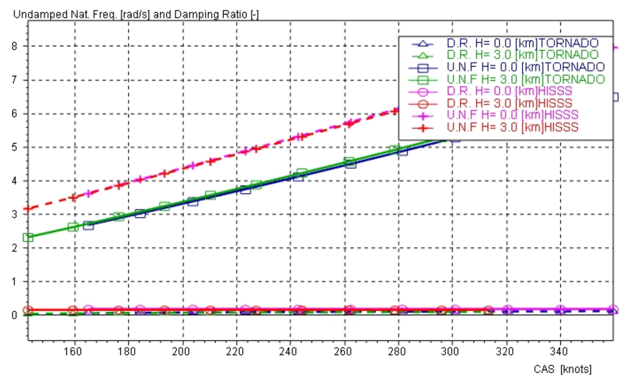

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Figure 18. Dutch Roll frequency vs calibrated airspeed - results of SDSA for different aero data sets.

VI. Concluding Remarks and Future Work

This paper presents the status of the S&C module of CEASIOM in design at the two-year mark in the three-year SimSAC Project. The current state of work allows to make the S&C analysis of the aero dataset generated using the full range of the adaptive-fidelity CFD tools appropriate for both low-speed and high-speed flight. The obtained results allow to asses computational methods of aerodynamics from stability analysis point of view. Generally the best results for all modes of motion gives aerodynamic data from TORNADO.[13] It can seem strange, that the simplest flow model gives the best results, but this feature of VLM is known (*Margason*[23]) - method is well conformable with experiment, because neglects effects of thickness and viscosity concurrently. Viscosity effect compensates the thickness of lift surface, in most cases. All these things cause, that VLM, despite it's simplicity, is very attractive tool to prepare aerodynamic data for stability analysis.

The next work will focus on complex testing of existing and new designed aircraft. The S&C module is potentially ready to compute stability characteristics for any configuration, unconventional as well. However it requires many test to be sure, that possible strange dynamic characteristics of unconventional aircraft (e.g. unsymmetrical GAV) are result of configuration but not result of computational method.

VII. Acknowledgments

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References

[1] von Kaenel R., Rizzi A., Oppelstrup J., Goetzendorf-Grabowski T., Ghoreyshi M., Cavagna L., and Bérard A. *CEASIOM: Simulating Stability & Control with CFD/CSM in Aircraft Conceptual Design*, Paper 061, 26th Int'l Congress of the Aeronautical Sciences, Anchorage, Alaska, Sept 2008.

[2] Bérard A., Rizzi A. and Isikveren A.T. *CADac: a New Geometry Construction Tool for Aerospace Vehicle Pre-Design and Conceptual Design*, AIAA, 26th Applied Aerodynamics Conference Honolulu, Hawaii, USA, August 18-21, 2008.

[3] Tang, C.Y., Gee, K. and Lawrence, S. *Generation of Aerodynamic Data using a Design of Experiment and Data Fusion Approach*, 43rd AIAA Aerospace Sciences meeting, (Reno, NV), 2005, AIAA-2005-1137.

[4] Ghoreyshi, M., Badcock, K.J. and Woodgate, M. *Integration of Multi-Fidelity Methods for Generating an Aerodynamic Model for Flight Simulation*, 46th Aerospace Sciences meeting, (Reno, NV), 2008, AIAA-2008-197.

[5] *IGES (ANS US PRO/IPO-100-1996) Initial Graphics Exchange Specification IGES 5.3*, http://www.uspro.org/documents/IGES5-3_forDownload.pdf

[6] Laurenceau, J. and Sagaut, P. *Building Efficient Response Surfaces of Aerodynamic Functions with Kriging and Cokriging*, AIAA Journal, Vol. 46, No. 2, pp. 498–507, 2008.

[7] Bérard A., Rizzi A. and Isikveren A.T. *Development and implementation of aerodynamic analysis methods for aircraft conceptual design*, in CASI AERO 2007, (Toronto, Canada), April 24-26, 2007.

[8] Eliasson P. *A Navier-Stokes Solver for Unstructured Grids.*, FOI/FFA report FOI-R-0298-SE, FOI, Stockholm, Sweden, 2001.

[9] Goetzendorf-Grabowski T. *Modelling of the aircraft motion - theory and application, in Optimalsteuerungsprobleme von Hyperschall-Flugzeugsystemen*, Workshop des Sonderforschungsbereichs 255, Greifswald-München 1997.

[10] Goetzendorf-Grabowski T. *Influence of Stability Derivatives on a Quality of Simulation (supersonic flow)*, Journal of Theoretical and Applied Mechanics, No. 4, Vol 32, pp. 773-791, Warsaw 1994.

[11] Ghoreyshi, M., Badcock, K.J. and Woodgate, M. *Integration of Multi-Fidelity Methods for Generating an Aerodynamic Model for Flight Simulation*, 46th Aerospace Sciences meeting, (Reno, NV), 2008, AIAA-2008-197.

[12] Hoak, D. E., et al., *The USAF Stability and Control DATCOM*, Air Force Wright Aeronautical Laboratories, TR-83-3048, Oct. 1960 (Revised 1978).

[13] Melin T., *Using Internet Interactions in Developing Vortex Lattice Software for Conceptual Design*, Licentiate Thesis Report 2003, Department of Aeronautics, Royal Institute of Technology, Stockholm.

[14] http://www.cfse.ch/cfse/site/tools-NSMB.php

[15] D. Eller. SimSAC Delivery report 2.3-5. Mesh generation using sumo and tetgen. Royal Institute of Technology, Stockholm.

[16] http://fdl8.flyg.kth.se/dwf/dwfs.html

[17] Si,H., and Gaertner,K. *Meshing Piecewise Linear Complexes by Constrained Delaunay Tetrahedralizations*. In Proc. 14th International Meshing Roundtable, pages 147-163, September 2005, http://tetgen.berlios.de/

[18] DASA-TN-R-R-002-M-0011 - RANGER 2000 FR06/RP01 aerodynamic dataset release 1.1, 1994

[19] Fornasier L., HISSS - A Higher Order Subsonic/Supersonic Singularity Method for Calculation Linearized Potential Flow. AIAA Paper 84-1646, 1984

[20] MIL-F-8785C - Military Specification - FLYING QUALITIES OF PILOTED AIRPLANES

[21] http://www.ansys.com/products/icemcfd-mesh-gen.asp

[22] http://web.mit.edu/drela/Public/web/xfoil/

[23] Bertin J.J., Smith M.L.: Aerodynamics for Engineers, Prentice-Hall International, Inc. London 1989