Virtual Aircraft Design of TransCruiser – Computing Break Points in Pitch Moment Curve

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The SimSAC project has developed the design software CEASIOM, a framework tool that integrates discipline-specific tools like CAD & grid generation, CFD, stability & control analysis etc. for the purpose of aircraft conceptual design. Significant features developed and integrated in CEASIOM are geometry, aerodynamics, flight dynamics and aeroelasticity modules. The design 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 Transonic cruiser TCR from baseline design to Tier-I design. The baseline T-tail design 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. The flight dynamical analysis in CEASIOM of this configuration showed that trimming the aircraft required too large deflections in the design point so a new approach with a canard configuration was designed. A model of this configuration was built and tested in wind tunnel. The paper focuses on the validation of computational tools of different fidelity, from Tier I to Tier II RANS solvers, with test data to get a range of fidelity of the tools. The results showed that Tier I methods fail to reproduce experimental pitch moment already at moderate angles of attack. Euler methods give reasonably accurate predictions but only RANS offers good overall experimental agreement for all angles attack, in particular at higher angles where the flow starts to separate.

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 plan forms 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

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One major development is the software CEASIOM, a framework tool that integrates discipline-specific tools like: CAD & grid generation, CFD, stability & control analysis etc., all for the purpose of aircraft conceptual design. Significant features developed and integrated in CEASIOM as four core modules are: 1) Geometry module AcBuilder-SUMO, 2) Aerodynamic Model Builder AMB-CFD, 3) Stability and Control module S&C, and 4) Aero-elastic module NeoCASS. The AMB-CFD module replaces current handbook methods with new adaptable-fidelity methods: referred to as Tier I, Tier I+, and Tier II where Tier I is either the empirical digital DATCOM method or the steady and unsteady vortex-lattice code TORNADO for low-speed aerodynamics and aero-elasticity. Tier I+ is the inviscid EDGE CFD code for transonic aerodynamics and aero-elasticity. Tier II is a RANS flow simulator for high-fidelity analysis of extreme flight

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 aero-elastics. 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 aero-elastic 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 wind tunnel model. This evolution shows how CEASIOM is becoming a useful tool for aircraft design.

The aerodynamic database for the configuration is needed in order to study its flying and handling qualities. In the scope of SimSAC, this is done with the design system CEASIOM which contains an adaptive fidelity CFD simulation capability. This aerodynamic database is computed using the tools in CEASIOM, for example the vortex-lattice method TORNADO for the linear range of the flight envelope and the EDGE code for the nonlinear range. The paper focuses on the comparison between the computed results and wind tunnel static measurements to establish a range of validity of the computational tools. The computational tools compared are potential (VLM) TORNADO, the EDGE code for Euler and RANS using unstructured grids and the PMB and NSMB codes (mainly RANS) for structured multiblock grids.

In the next section the CEASIOM tool is described with its significant different parts. Following that the TCR is described from its original T-tail design to its final configuration with a canard being built and experimentally verified. The generation of the aerodynamic database with emphasis on the validation with low speed wind tunnel data and trimming at higher speeds are then given. This is followed by a summary and conclusions.

II. CEASIOM

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 presents an overview of the CEASIOM software, showing aspects of its functionality, process and dataflow. Significant features developed and integrated in CEASIOM as modules are

1) Geometry module AcBuilder-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 vortexlattice 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)



Figure 1. Core modules AcBuilder-SUMO, AMB-CFD, NeoCASS and S&C in the CEASIOM software.

package are among the major functionalities of this module.*Aero-elastic 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.

Some modules are further described below as they were used in the design of the TCR.

III. Design of the TCR configuration

A. Specification and Baseline Configuration

The TransCruiser (TCR) is a baseline design proposed by Saab for a civil passenger airplane flying in transonic regime. It is an excellent case study for CEASIOM, since little literature on such an unconventional configuration can be found, and traditional handbook methods fail to predict the flight characteristics with enough accuracy. The design specification for the TCR is the following:



Figure 2. Left: Mission profile. Right: Spreadsheet sketch and CAD sketch of the TCR

Payload: Nominal design for 200 PAX in economy class, pitch 36", 22,000 kg max payload. Baggage and freight in LD3-46W containers. Possibility to divide into three classes:

- 20 first class, pitch 44", width 19" (2+2 seats)
- 70 business class, pitch 38", width 19" (3+2 seats)

- 80 economy class, pitch 36", width 19" (3+3 seats)

Cabin and crew: Six lavatories and two galleys with a total of 40 full size trolleys. Two pilots and six cabin attendants.

Range: 5,500 nm, followed by 250 nm flight to alternate and 0.5 hour loiter at an altitude of 1,500 ft. Additional 5% of block fuel.

Design cruise speed: $M_D = 0.97$ at greater or equal altitude to 37,000 ft.

Climb: Direct climb to FL370 at max WTO.

Take-off and landing: Take-off distance of 2,700 m at an altitude of 2,000 ft, ISA+15 and maximum take-off weight. Landing distance of 2,000 m at an altitude of 2,000 ft, ISA and maximum landing weight with maximum payload and normal reserves.

Power plants: Two turbofans. **Pressurization**: According to EASA. **Noise requirement**: According to ICAO. **Certification** base: JAR25. **Mission profile**: This is shown in Figure 2.

B. CEASIOM refinement of baseline Design

i. Creating geometry in Geo & SUMO

In a multidisciplinary analysis environment such as CEASIOM, it is vital that the different modules share a unified geometrical description. In the industry, inconsistencies or discrepancies between the geometry models used for different analyses can be significant, due to the different requirements of these analyses. The aircraft geometry is described in CEASIOM by a relatively small set of parameters, O(100), originally based on Isikveren's doctoral thesis.² This geometry is unique for all modules and it is stored in an xml file. The xml file can be either created manually by the user or generated using the AcBuilder (see Fig. 3), a geometry builder with visual feedback.

At the next higher level of detail, the graphical surface modeling tool SUMO can be used to define a more detailed geometry based on a moderate number (often less than 30) of spline surfaces. SUMO can read the xml file in order to create the higher order of detailed geometry, and it also has a graphical user interface for creating or modifying the design (Fig. 3) and a large library for creating or changing wing profiles. The spline surfaces are created or modified via control points and spline curves, either through simple drag and drop or by typing in the exact coordinate or radius for points or shapes. This geometry could be used directly within SUMO creating meshes for 3D panel methods and for CFD solutions based on the Euler equations via Hang Si's TetGen.³ If one wants to go even further and acquire Navier-Stokes solutions the geometry can be exported as an IGES file.



Figure 3. Left: TCR geometry in AcBuilder. Right: TCR surface mesh in SUMO

ii. 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 DATCOM⁴), through linear singularity methods (Vortex Lattice Method,⁵ Panel Methods such as dwfSolve⁶) to full

non-linear Euler and RANS compressible flow CFD packages, see Fig. 4. 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.

The relevant part of the CEASIOM package is shown in Fig. 4. The geo.xml file defines the geometry with sufficient details for the Tier I computations. The lifting surfaces are assembled from quadrilateral plan forms, 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 laminar, and control surface deflections can be effected by actually changing the geometry or by just manipulating surface normals in the numerical flow tangency condition.



The geo.xml file is edited by the ACBuilder GUI **Geo to CFD grids.** 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 place 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^{6, 7} 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 TetGen3 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 IGES⁸ files to fully-edged mesh generator systems such as Ansys ICEM CFD.⁹ 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.

iii. Simulated Trim qualities (aerodynamics/Tornado)

Handbook methods predict that the TransCruiser trimability is poor. This section presents a low-speed rigidaircraft trim analysis carried out with CEASIOM.¹⁰ Once the aircraft geometry has been defined, aerodynamic data is computed using the Tornado VLM code, and trimability is studied using the stability & control module. The CEASIOM trim analysis confirms the guess of the handbook methods, see Fig.5. Considering a velocity of 160 m/s at sea level ($M_{\infty} \approx 0.47$), it seems clear that, although the angle of attack is not too big (around 3.5°), a tail plane deflection of 11° is required for trim which is unacceptable. Since the trim characteristics are so poor there is no use in designing a control system for this configuration. Therefore, in order to achieve a better trimability, different configuration variations have been analyzed with CEASIOM.



Figure 5. Required angle of attack (left) and tail deflection (right) for trim of TCR with T-tail at different airspeeds and altitudes. Negative angle of deflections corresponds to noose up.

iv. Predicted T-tail flutter (aero-elastics/NeoCASS)

The need of aero-elastic analysis within SimSAC has led to the development of a completely new module called NeoCASS (Next Generation Conceptual Aero-Structural Sizing Suite) to perform structural sizing, aero-elastic analysis and optimization. NeoCASS is compounded by three different tools:

- Weight and Balance (WB) to have a prediction of non-structural masses and their location mainly based on statistical handbooks;
- GUESS (Generic Unknowns Estimator in Structural Sizing) to have a first guess analytical sizing of the airframe based on ultimate loads estimated on simple structural principles, one-dimensional aerodynamics and inertia distribution predicted by WB;
- SMARTCAD (Simplified Models for Aero-elasticity in Conceptual Aircraft Design) which is the numeric kernel for aero-structural analysis and optimization and can be used to enhance the solution provided by GUESS).

All the sub-modules can be combined sequentially or used as stand-alone applications, providing data to different applications. Running through WB, GUESS and SMARTCAD it is possible to give a low to high fidelity estimation of inertia to the flight mechanics solvers. Once an input structural model is available, SMARTCAD can enhance the aerodynamic database of the aircraft with trimmed polars and corrections to aerodynamic derivatives for different flight regimes. Specific flight points chosen by the designer are given in the file states.xml and directly

used as ultimate load conditions by GUESS to perform the first sizing. Structural concepts and material properties adopted for modelling fuselage and lifting surfaces components when performing the sizing are given in the aircraft.xml file completely describing the aircraft under analysis. After the sizing process, a first estimate of the structural weight and stiffness distribution is available. A stick mesh model with all elements connectivity, material properties, non-structural lumped masses coming from WB is exported and used by the solver SMARTCAD for aerostructural analyses.

During the conceptual analysis of the TCR aircraft NeoCASS was used aiming at two main targets: the first estimation of aircraft weights, using GUESS and the initial assessment of aero-elastic characteristics, using SMARTCAD, especially important due to the initial T-tail configuration of TCR. Concerning the last one, once crated the aircraft stick model, composed by beam elements and



Figure 6. V-g plot of the TCR T-tail configuration.

concentrated masses, the first step is the calculation of the aircraft vibration modes and the matrix of unsteady aerodynamic forces using the ad hoc developed Doublet Lattice code.

For the investigation of flutter a complex matrix is solved algebraically for its eigenvalues and eigenvectors.¹¹⁻¹³ Looking at Fig. 6 where the V-g plot is reported for the TCR, it is possible to see a typical T-tail flutter, generated by fin bending and horizontal tail rolling, occurring at about 300m/s (sea-level).

v. Re-design to Canard Configuration

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 centre is located closer to the centre of gravity of the aircraft.

vi. Sizing of Canard Configuration

Many different configurations of the canard TransCruiser, obtained by varying the three parameters mentioned in the previous section, have been tested on CEASIOM. The goal is to find a configuration with better trim characteristics than the original one, but without making the aircraft unstable (i.e. the static margin must be positive).

Table 1 below shows the angle of attack, α , and canard deflection, δ , required to trim four different canard configurations, as well as the static margin, at a velocity of 160 m/s and sea level. x_w and x_c are, respectively, the apex position of the main wing and the canard wing, both in fraction of the total fuselage length, and SC is the canard area. Two of these configurations (TCR-C2 and TCR-C15) have the canard wing located in the fuselage (in the foremost position, in order to maximize the arm of the moment produced by the canard around the centre of gravity) and in the other two (TCR-C8 and TCR-C17) the canard is placed in the nose cone. The latter option has the inconvenience of the canard possibly interfering with several systems housed in the nose cone, such as the weather radar. Besides, it is not a very aesthetic configuration. However, the former option means that the doors cannot be located in the fore fuselage. A solution might be to place them in the mid-fuselage.

	$.x_{W}(m)$	$x_{C}(\mathbf{m})$	$S_C(m^2)$	α°	δ°	Static margin (%)
TCR-C2	0.26	0.13	72	2.4	6.6	4.42
TCR-C8	0.27	0.017	47	2.2	6.6	4.64
TCR-C15	0.26	0.12	72	3.2	5.9	3.12
TCR-C17	0.27	0.0017	65	2.2	4.2	-2.65

Table 1. Angle of attack and static margin for trim at 160 m/s and sea level, for four different canard
configurations of the TCR.

vii. Selection/Criteria of Final Design

Some general conclusions can be drawn from Table 1. When increasing the moment arm (i.e. the distance between the canard aerodynamic centre and the centre of gravity of the aircraft), the canard needs to produce a smaller lift force to obtain the same moment around the centre of gravity, so a smaller deflection is required. However, the aerodynamic centre of the whole aircraft is being placed closer to the centre of gravity. Thus, the aircraft will become less stable. This can be observed comparing the TCR-C2 and the TCR-C17. Featuring a larger distance between the canard and the main wing, the TCR-C17 requires a smaller canard deflection for trim, but it is also less stable than the TCR-C2 (in fact, it becomes unstable).

The effect of increasing the canard area is similar. A larger canard area means that, to obtain the canard lift needed to trim the aircraft, a smaller canard deflection is required. However, a larger canard area also moves the aerodynamic centre of the aircraft further fore, resulting in less stability. This is appreciated when comparing the TCR-C8 and the TCR-C17. The latter one has a larger canard area, so the canard deflection for trim is smaller, but the aircraft is more unstable.

To summarize, increasing the canard area or the distance between canard and main wing results in a smaller

canard deflection for trim, but also in a less stable aircraft. Therefore, a compromise between good trim characteristics and acceptable stability must be reached. For that reason, the TCR-C15 was chosen as the most appropriate configuration. It considerably reduces the trim deflection with respect to the original T-tail configuration (around 50%), and the aircraft is slightly stable. The aerodynamic centre is expected to be shifted further aft in the transonic regime, improving the aircraft stability but slightly worsening the trimability.



Figure 7. TransCruiser canard configuration TCR-C15.

viii. Wind tunnel model of TCR-15

A wind tunnel model of the TCR-C15 configuration has been built and the model has been tested in the TsAGI T103 wind tunnel at a speed of 40 m/s. This is the wind tunnel of continuous type of action with open working section (elliptical cross section of 2.33×4.0 m). The static test in the wind tunnel campaign include a variation of pitch and slide-slip angles from -10° to 40° with step of 2° and of the canard deflection angle of incidence from -15° to 15° with step of 5°. The campaign also includes dynamic tests of low and high amplitude oscillations for pitch, roll and yaw at selected frequencies. The length of the model is 1.5 m which corresponds to a scaling factor of 1:40 to the real aircraft. The wind tunnel campaign will be reported in a separate publication.¹⁴

IV. Computing TCR-C15 aerodynamics

The aerodynamic database is filled with computations from four partners with in-house tools of different fidelity. The aerodynamic analysis is carried out using the vortex-lattice potential solver TORNADO (Tier 1), the CFD codes NSMB and the PMB codes for structured multiblock grids and the EDGE code for unstructured grid with inviscid Euler calculations (Tier I+) and RANS calculations (Tier II). Calculations have been performed with the various codes in the entire speed range from low-speed up to transonic cruise conditions at $M_{\infty} = 0.97$ in order to fill up the aerodynamic database. The focus of the analysis reported here is on the comparison between computed and measured wind tunnel data at low speed to establish the confidence and range of validity of the different tools. Another focus is the trimming of the aircraft in the entire flow regime based on computed results.

CEASIOM offers two ways to compute the canard deflections. The first one, and the one used here, is to generate different meshes for each canard deflection. This slows down the calculation process, but ensures more accurate results. The second way uses one single mesh of the aircraft, with no canard deflection, for all the cases, and the deflection is achieved by a transpiration boundary condition which usually offers good results for moderate deflections $\delta \leq 10^{\circ}$ but it is only available for Euler calculations.

Three sets of computational grid were generated for, one set for each of the CFD tools NSMB, PMB and EDGE. Separate grids were generated for different deflection angles $[0^{\circ}, 5^{\circ}, 10^{\circ}]$ of the canard to compute the trimmed conditions. The RANS grids were generated with a sufficient wall normal resolution to obtain $y^+ \leq 1$ for all computed speeds. The table below summarizes the grid data of the CFD grids used for a half model. The RANS grids for NSMB and EDGE are similar in size on the surface but the unstructured volume grid is substantially smaller in size. The NSMB and PMB grids have volume grids of similar size but the surface grid of PMB is twice as fine as for NSMB.

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Solver	Туре	Inviscid/ RANS	# nodes	# surface node
NSMB	Structured	Inviscid	6×10 ⁶	25×10 ³
NSMB	Structured	RANS	10×10^{6}	49×10 ³
PMB	Structured	RANS	8.5×10^{6}	100×10 ³
EDGE	Unstructured	Inviscid	0.3×10^{6}	50×10 ³
EDGE	Unstructured	RANS	2×10^{6}	50×10 ³

The computational tools and generated grids are briefly described below.

1. TORNADO

The Tornado VLM code (www.redhammer.se/tornado/) is an open source Matlab implementation of a modified horse-shoe vortex singularity method for computing steady and low reduced frequency time-harmonic unsteady flows over wings.⁵ The lifting surfaces are created as unions of thin, not necessarily flat, quadrilateral surface segments. Effects of airfoil camber are modeled by surface normal rotation. Leading edge control surfaces are modeled likewise. The modification to the horseshoe vortices allows trailing edge control surface deflection by actual mesh deformation.

The steady wake can be chosen fixed in the body coordinate system or follow the free stream. Overall effects of compressibility at elevated Mach-numbers are assessed by the Prandtl-Glauert scaling, and zero-lift drag estimates are obtained by Eckert's flat plate analogy. Fuselages may be modeled by combinations of flat plates or Munk's slender body singularity method. However, choice of proper geometry for such models requires experience, and most analyses are done by simply replacing the portion of the lifting surface covered by the fuselage by a flat plate with zero incidence. The basic flow solver is wrapped by user interfaces to create tables of aerodynamic coefficients and derivatives, for export to flight simulators and flight control system design software.

2. NSMB

The Navier Stokes Multi Block solver (NSMB) was developed from 1992 until 2003 in a consortium which included Airbus France and SAAB Military Aircraft.¹⁵ Since 2004 NSMB is further developed in a new consortium lead by CFS Engineering and composed of RUAG Aviation (Emmen), Astrium Space Technologies (France), EPFL (Lausanne), EHTZ (Zürich), IMFT (Toulouse), IMFS (Strasbourg), the Technical University of München and the University of the Army in München.

NSMB employs the cell-centred Finite Volume method using multi block structured grids to discretize the Navier Stokes equations. Various space discretization schemes are available to approximate the inviscid fluxes. The time integration is carried out using either the explicit Runge Kutta scheme or the semi-implicit LU-SGS scheme. Various convergence acceleration methods are available, among them local time-stepping, preconditioning, grid sequencing and multigrid. Well tested turbulence models in NSMB include the Spalart-Allmaras one-equation model¹⁶ and different variants of the k- ω models including the Menter Shear Stress variant.¹⁷ NSMB has been used to simulate a wide variety of different flow problems, among them flows over re-entry space vehicles including air dissociation and unsteady flows with fluid-structure interaction.¹⁸

The TCR calculations were made using a 4^{th} order central space discretization scheme. The LU-SGS semiimplicit scheme was used for the time integration. Local time stepping and low-speed preconditiong were used for acceleration to steady state. The Navier Stokes calculations employ the Menter k- ω SST to model the turbulence.

The TCR grid was generated using ICEM-CFD Hexa. All grids had 666 blocks for half a configuration. The Euler grid had 6×10^6 cells, the Navier Stokes grid 10×10^6 cells. The grid points were clustered near the leading and trailing edges of canard and wing. The O-grid strategy was used to cluster grid points in the boundary layer for the Navier-Stokes calculations.

3. PMB

The PMB flow solver (Parallel Multi-Block) for block structured grids originates from University of Liverpool. The Euler and RANS equations are discretized on curvilinear multi-block body conforming grids using a cellcentred finite volume method with a fully implicit time integration approach. Numerous spatial discretization schemes are available as well as turbulence models including the Spalart-Allmaras model and several variants of the k- ω model. A wide variety of unsteady flow problems, including aero-elasticity, cavity flows, aerospike flows, delta wing aerodynamics, rotorcraft problems and transonic buffet have been studied by means of this code. A validation against flight data for the F-16XL aircraft has also been performed.¹⁹ The main features of the CFD solver are detailed in Badcock *et al.*²⁰

The TCR model was computed using PMB on a structured multiblock grid generated using ICEM CFD Hexa. The model consists of an 8.5×10⁶ nodes for the half configuration arranged in 675 blocks. The tips of the wing and the canard of the TCR model are both blunt, for which the same block topology was chosen. Here, a diamond shaped block fits into the leading edge part and another on the trailing one. The quality of the cells in these two areas is slightly compromised in order to allow the C-blocking around the wing.

4. EDGE

The EDGE CFD solver (<u>http://www.edge.foi.se/</u>) is an edge- and node-based Navier-Stokes flow solver applicable for unstructured grids.²¹⁻²³ Edge is based on a finite volume formulation where a median dual grid forms the control volumes with the unknowns allocated in the centers. The governing equations are integrated to steady state, with a line-implicit approach²³ in areas with highly stretched elements and explicitly elsewhere with a multistage Runge-Kutta scheme. The steady state convergence is accelerated by FAS agglomeration multigrid. Fully developed turbulent flow is assumed in the computations. The effect of turbulence is modeled by an Explicit Algebraic Reynolds Stress Model (EARSM) formulation based on a two-equation k- ω model.^{24,25}

The unstructured Euler grids used in the investigation were created with SUMO tool for different deflection angles, the grids were generated for the full model. The Euler grids were refined with the adaptation module in Edge resulting in meshes with resolution given in Table 2. The unstructured RANS grids were generated with an in-house tool Tritet^{26, 27} sharing the Euler surface grids.

A. Validation of low speed data against wind tunnel data

The wind tunnel campaign was carried out at low speed at 40 m/s corresponding to the flow conditions $M_{\infty} = 0.115$, Re = 0.74×10^6 , where the Reynolds number is based on the mean aerodynamic wing chord (11.77/40 = 0.29 m). Although the Reynolds number is rather low, all RANS calculations assume fully turbulent flow. Figure 8 displays the numerical results of the integrated forces and pitching moment with no side slip, $\beta = 0^\circ$, and deflection angle $\delta = 0^\circ$. The computed results are compared to experimental measurements. The VLM results are only applicable for lower angle of attacks, $\alpha \le 10^\circ$.

The prediction of the normal force is rather good with all approaches, some differences are observed at the highest angles of attack where inviscid calculations over-predict the lift which is to be expected at these high incidences. The tangential force, not available from experiments, show a clear difference between inviscid and RANS results. The VLM TORNADO results follow the inviscid EDGE results at lower incidences. In comparison to the EDGE Euler results the NSMB Euler results are much closer to the three RANS solutions with a vertical shift. The three RANS solutions predict similar tangential forces with an increase in the differences at higher incidences.



Figure 8. Integrated normal force (left), tangential force (mid) and pitch moment (right) for the TCR-C15 canard configuration with experimental comparisons. $M_{\infty} = 0.115$, $\beta = 0^{\circ}$, $\delta = 0^{\circ}$.

The most interesting quantity for the stability and control is the pitching moment. The experimental results show that there are two breaks in the pitch moment curve. The first break occurs at about $\alpha = 8^{\circ}$ and results in an increased slope of the curve. The second break occurs at about $\alpha = 20^{\circ}$ where the pitch moment suddenly drops and then continues to grow again with about the same slope. The VLM TORNADO does not pick up the first break and change of slope in the pitch moment. The Edge Euler results predict a change of slope but at a too high incidence. The NSMB Euler results predict the first break very well which probably indicate that the EDGE grid is not sufficiently resolved. All RANS Tier II results predict this phenomenon well. The RANS results differ in the vicinity of the second break though. EDGE does not predict the break at all, NSMB seem to predict it a bit early. The best experimental agreement is obtained from the PMB calculations.

By inspecting the RANS results more closely from NSMB and EDGE in Fig. 9, it is evident that the difference at the second break in the pitch moment is due to differences in moment from the canard where NSMB predicts a reduction in moment at starting at about $\alpha = 18^{\circ}$ where moments from EDGE continues to grow until about $\alpha = 22^{\circ}$ where a reduction is seen. A corresponding difference and divergence of the normal force curves over the canard is also visible.

Figure 10 displays the xcomponent of the skin-friction distribution from EDGE in which a blue color denotes negative values and flow separation. The flow separation



distribution from EDGE in which a Figure 9. Integrated normal force (left) and pitch moment (right) for blue color denotes negative values and TCR-C15. $M_{\infty} = 0.115$, $\beta = 0^{\circ}$, $\delta = 0^{\circ}$. RANS results NSMB and EDGE.

on the canard starts at its tip and leading edge and the separated area grows with increasing incidence. The onset of separation occurs at an angle of attack where the normal force stops to grow, at about $\alpha = 22^{\circ}$. There is a massive separation at $\alpha = 26^{\circ}$. The main wing has mostly attached flow except for a small spot at inboard span that reduces in size with increasing angle of attack. There is a small leading edge separation at the outer part of the wing that seems fairly constant with angle of attack.



Figure 10. Surface skin friction (x-component) distribution from EDGE. From left to right: angles of attacks [18°, 20°, 22°, 24°, 26°]. $M_{\infty} = 0.115$, $\beta = 0^\circ$, $\delta = 0^\circ$. Blue color denotes reversed flow.



Figure 11. Surface skin friction (x-component) distribution from NSMB. From left to right: angles of attacks [16°, 18°, 20°, 22°, 24°]. $M_{\infty} = 0.115$, $\beta = 0^\circ$, $\delta = 0^\circ$. Blue color denotes reversed flow.

The corresponding results with NSMB displayed in Fig. 11 show also that the flow starts to separate over the canard but at an earlier angle of attack, there is a larger separated area already at about $\alpha = 20^{\circ}$ that grows with

increasing incidence. Another noticeable difference between the results from NSMB and EDGE is that the outer part of the wing is clearly separated as predicted by NSMB and which seems more realistic and expected at these high angles of attack. At the inner part of the wing the flow is attached in both calculations with the exception of the small spot of negative skin friction values. A possible explanation of the differences between the computed results may be that a substantially finer volume grid is employed in the NSMB calculations as given in Table 2.

It then seems likely that the second break in the pitch moment curve is due to that the flow starts to separate of the canard which is better represented by the calculations using structured grids.

B. Trimming TCR-C15

The trimming has been carried out based on a mixture of VLM and CFD results. The trim analysis is based on a linear assumption for the variation of lift and pitch moment as function of the angle of attack and canard deflection angle. As mentioned, the trim characteristics of the TCR canard configuration improve with respect to the original T-tail configuration. The canard deflection is smaller and the angle of attack remains about the same. This is demonstrated in Fig. 12 where the required angle of attack and deflection angles at low speeds and different altitudes to trim the TCR-C15 aircraft are demonstrated based on CFD results with EDGE.

The trimmed conditions are compared to results obtained from trimming based on wind tunnel data where the dynamic pressure is altered to extrapolate to higher speeds from the low speed in the experimental campaign. There is a reasonable agreement between the extrapolated wind tunnel data and the CFD results. The angle of attack is decreased as the speed increases, the canard deflection angle increases slightly but varies around the design conditions of about $\delta \sim 6^{\circ}$ as given in Table 1 at 160 m/s.

The aerodata for the TCR-C15 in transonic speed has been computed using a combination of results obtained with EDGE and NSMB with the meshes described above. Figure 13 presents the trim conditions at transonic speed and high altitudes. The deflection angles remain fairly constant until the speed of sound is approached where there is a dip with increased noose up and then returns to about the same deflection at higher speeds. The cruise Mach number $M_{\infty} = 0.97$ corresponds to a speed of 286.2 m/s at 11 km altitude where a deflection of about 12° is found.



Figure 12. Trim conditions at low speed for TCR-C15. Left: Angle of attack α° . Right: Deflection angle δ° where negative value refers to noose up.



Figure 13. Trim conditions at high speed for TCR-C15. Left: Angle of attack α° . Right: Deflection angle δ° where negative value refers to noose up.

A closer inspection of the lift and pitch moment in Fig. 14 shows that there is a sudden increase in lift approaching the cruise Mach number with a corresponding decrease of pitch moment.

Figure 14 reveals that the change in lift and moment comes from the wing and a visualization of the surface pressure distribution in Fig. 15 shows that the suction on the outer part of the wing increases with increasing Mach number. There is in particular a large jump in the pressure suction from Mach 0.85 to Mach 0.92. The suction occurs at the outer part of the wing which is at the rear part of the aircraft and behind the center of gravity contributing to a more negative pitch moment.

Trimming the aircraft in this highly transonic regime will then requires an increase of lift from the canard at the forward part to balance the aircraft and that increases the pitch in Fig. 14. This explains the dip to larger deflections of the canard in Fig. 13.



Figure 14. Integrated lift (left) and pitch moment (right) for TCR-C15 as function of speed, 11 km altitude, $\delta = 0^{\circ}$. RANS results with EDGE. Cruise at M_{∞} =0.97, equivalent to U=286.2 m/s.



Figure 15. Upper surface pressure distributions from EDGE. , $\delta = 0^{\circ}$. From left to right: Mach numbers 10.75, 0.85, 0.92, 0.971, corresponding to [221.3, 250.8, 271.4, 286.2] m/s.

V. Summary and conclusions

This paper has described the DSE case Transonic cruiser TCR from baseline design to Tier-I design with Tier II verification. The baseline, a T-tail design, was analyzed with the CEASIOM tools for aerodynamics, mass properties, flight mechanics and aeroelastics. The flight dynamical analysis showed that there is a problem with trim, and the aeroelastic module showed that the T-tail would flutter. The CEASIOM analysis indicated that a canard configuration would have better flying qualities. This configuration is judged to be better than the T-tail configuration and has been built as a model and tested in the wind tunnel to verify the entire design functionality.

The paper focuses on the comparison between computed results and low speed wind tunnel results of the TCR, so far only steady results are compared although dynamic test were carried out. The computed results are carried out with the Tier I tool based on VLM and CFD tools based on Euler (Tier-I+) and RANS (Tier-II). Three CFD tools, namely NSMB, PMB and EDGE, are compared with the purpose to establish the confidence and range of validity of the tools. The emphasis is put on how well the experimental pitch moment is reproduced by the computations.

All computational tools show a good agreement with experimental forces and moments at lower angles of attack. The experimental pitch moment curve show two breaks. The first break occurs at a fairly low angle of attack of about $\alpha = 6^{\circ}$ where the slope of the curve increases. This break is well reproduced by Euler and RANS computations. The VLM tool does not predict the break at all, the pitch moment continues to grow linearly with the slope before the break. The second break occurs at high angles of attack and is due to onset of flow separation on the canard. This phenomenon is not well predicted by Euler methods but fairly well predicted by RANS methods, in particular by PMB and NSMB using structured well-resolved computational grids.

Trimming of the aircraft is carried out in the entire regime of speed based on aerodata from computed results.

The trimmed results are based on a combination of VLM and EDGE results in low speed and on EDGE and NSMB results at high speed in the transonic regime and where VLM is not applicable. The trimmed data shows that the designed TCR configuration trims at expected canard deflection angles at lower speeds. The trim analysis also revealed a non-linear increase in lift close to the cruise Mach number $M_{\infty} = 0.97$ leading to a dip in the deflection angle with a larger angle in the vicinity of the speed of sound.

The construction of the TCR configuration with CEASIOM demonstrates its potential and usefulness as a tool for aircraft design. The TCR design has also demonstrated that CFD methods should be incorporated at an early stage where low fidelity methods fail to produce realistic predictions. The design and verification of the TCR configurations described here is a first step towards a flying concept. Many steps in the design are still needed to account for like structural aspects, aeroelastic verification, stability & control etc.

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