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DEVELOPMENT AND VALIDATION OF A NEXT-GENERATION CONCEPTUAL AERO-STRUCTURAL SIZING SUITE

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Abstract

An overview of a novel variable-fidelity aero-structural computational suite targeted for prediction at the conceptual design phase is presented herein. The computational suite consists of two primary modules known as CADac (Computer Aided Design Aircraft) and NeoCASS (Next generation Conceptual Aero-Structural Sizing Suite). The methodology is based upon the integration of geometry construction, aerodynamic and structural analysis codes that combine depictive, computational, analytical, and semi-empirical methods, validated in an aircraft design environment. The aerodynamics sub-space is analyzed using methods based upon a Vortex-Lattice Method used to examine large structural deformations, a Doublet Lattice Method in order to predict flutter boundaries in the subsonic speed regime, and, an Euler based method to cater for identification of flutter points in the transonic regime. A quasi-analytical method that provides accurate weights estimation and refined prediction of airframe moments of inertia data has also been introduced, thus facilitating a more comprehensive investigation of the quasi-static aeroelastic problem. To illustrate the new computational system capabilities, the methodology was applied to a complete flexible structural model of the B747-100 transport aircraft. The quasi-analytical weight prediction of the NeoCASS suite was found to generate an accuracy of less than 0.5% error compared to published results.

1 Tool layout

The aircraft design is an interdisciplinary activity governed by simultaneous considerations of complex, tightly coupled systems and functions. The final task is to achieve an optimal integration of all components into an efficient, robust and reliable aircraft with high performances that can be manufactured with low technical and financial risks at an affordable cost over its whole lifetime. The design process of modern transport aircraft generally occurs in three phases: conceptual, preliminary and detailed design. Most of the life-cycle cost is incurred during the conceptual design phase and therefore, the earlier an appropriate conceptual morphology can be found, the more economical the whole design process will be, avoiding costly redesign and corrections. In the conceptual design phase, the aircraft is defined at a system level, where many variants of aircraft are investigated; the need for fast computation of feasible solutions implies the use of semi-analytical, statistical, semi-empirical or low fidelity tools. Thus the aircraft structure is practically not considered until the preliminary design phase and it is almost impossible to take into consideration aeroelastic requirements that appear later during the design process. But new generation transport aircrafts are very flexible and aeroelastic effects must be taken into account right from the beginning of the design phase in order to avoid expensive redesign during preliminary design or weight penalties re-

sulting from unforeseen aeroelastic requirements. The 6^{th} European Framework project SimSAC (**Sim**ulating Aircraft **S**tability **A**nd **C**ontrol Characteristics for Use in Conceptual Design) started in 2006 and aims at enhancing the conceptual design and early preliminary design processes by developing the integrated digital design and decision making environment CEASIOM (**C**omputerised **E**nvironment for **A**ircraft **S**ynthesis and **I**ntegrated **O**ptimisation **M**ethods), where the aerodynamic information for stability and control assessment can be computed at some user nominated fidelity in the conceptual design. SimSAC includes a complete suite for the development and validation of the aero-structural configuration, able to take into account aeroelastic requirements right from the conceptual design phase.
This aero-structural suite is based on two main modules: a geometry module, called CADac (**C**omputer **A**ided **D**esign **A**ir**c**raft) and an aeroelastic module, called NeoCASS (**N**ext generation **C**onceptual **A**ero-**S**tructural **S**izing Suite). The geometry description is the first issue to be addressed since a complete description of the aircraft to be designed is required. CADac adopts a set of geometrical parameters which are general enough to ensure that a wide array of aircraft morphologies can be represented and analyzed. From this geometrical description, the structural and aerodynamic module use the appropriate parameters that are required for the method at hand. These parameters also drive an automatic CAD (Computer Aided Design) solid model generator using the middleware CAPRI® [1]. NeoCASS contains two different tools: a first one, called GUESS (**G**eneric **U**nknowns **E**stimator in **S**tructural **S**izing), based on a semi-analytical description of aircraft structure, is used to define a first try stiffness distribution able to satisfy some global design requirements; the second one, called SMARTCAD (**S**implified **M**odels for **A**eroelasticity in **C**onceptual **A**ircraft **D**esign), includes different tools for the complete aeroelastic analysis of aircraft, including flutter clearance, divergence speed, aerolastic trimming and corrections of stability derivatives. Two classic lifting surface methods are implemented: the Vortex Lattice Method (VLM) is used for subsonic steady aerodynamic and aeroelastic calculations and the Doublet Lattice Method (DLM) is used for subsonic flutter analysis and harmonic stability derivatives prediction. For higher fidelity and for aerodynamic analysis at higher Mach number where the VLM and the DLM fail to give accurate results, the Edge [2] CFD (Computational Fluid Dynamics) flow solver, developed by the the Swedish Defense Research Agency FOI, is run, using the CAD solid models generated by CADac. In the following, a detailed description of all the modules, including some application examples, is presented.

2 Geometry module

2.1 Parametric geometry description

The aero-structural analysis of a new aircraft design covers the interaction of aerodynamics, weight, balance and loads, each of these requiring a peculiar description of the morphology, yet referring to the very same aircraft. In addition, with growing design maturity, the geometric description of the aircraft evolves substantially, offering more and more details. Such a complex multi-disciplinary and multi-fidelity problem calls for a geometric description that is flexible enough to suit all the separate study domains and levels of fidelity, yet remains simple enough to be intuitive to the user and to enable easy optimization and trade study analyzes.
Such a geometric description is obtained by an appropriate parameterization of the different aircraft components and of their relative positioning. For the wing for example, a two kinks description has been adopted with parameters such as aspect ratio, area, sweeps, dihedrals, twists and airfoil sections. An aircraft design geometry is fully described in a unique *XML* file to which all the different analysis module refer (see Fig. 1). In this *XML* file appear in a structured way the different parts of the aircraft and the associated parameters. The choice of the *XML* format facilitates the sharing of data as well as the expansion

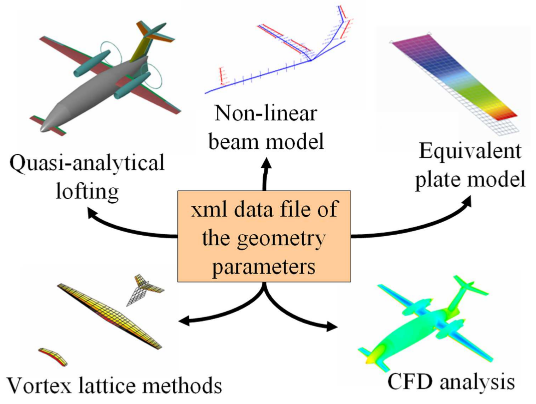


Fig. 1 Geometry centric conceptual design.

of the dataset, i.e. the number of components of the aircraft can be expanded at will and it is possible to introduce new components as well as new parameters, thus enlarging the array of morphologies that can be modeled.

2.2 The CADac tool

It is nowadays conceivable to use CFD very early in the conceptual design of an aircraft, thus giving more accurate aerodynamic prediction, in particular in the case of atypical or unconventional geometries for which experimental data and intuitive understanding of the flow are lacking. But, compared to low fidelity method, CFD is very demanding since it requires a closed and consistent CAD model. In addition, consistency between the designer's layout and the CAD model is pivotal; but CAD-based geometry models are usually built from splines surfaces whereas a designer works with intuitive parameters such as aspect ratio, area, sweep, etc. The translation from the designer's desiderata to a CAD-model usable for CFD computation is therefore a time-consuming and tedious exercise. CADac is designed to shortcut this transformation by creating a proper CAD model from the finite set of intuitive parameters used in the geometry module of SimSAC.

CADac is based on the Master Model concept: the different parts of an aircraft have been created in a parameterized way and are stored in component libraries. Such libraries have been created for the four major CAD systems: Catia V5®, SolidWorks®, Unigraphics® and Pro Engineer®; and CADac is using the Application Programming Interface CAPRI® that provides a common interface to these four CAD systems. CADac loads the *XML* file containing the geometry description of the aircraft, and, through CAPRI®, accesses the CAD component library, loads the relevant CAD "rubber" components, scales and positions them and finally performs a Boolean union of all the parts to produce a closed and consistent solid model of the aircraft design to be analyzed using CFD, as shown in Fig.2. Since this process is fully automated and CAD-vendor neutral, no expertise in CAD is required and it is possible to use any of the four above-mentioned CAD environments.

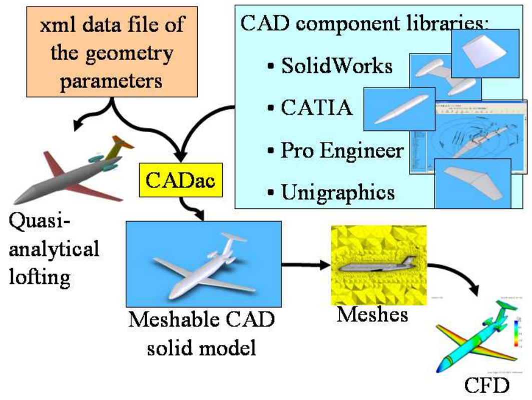
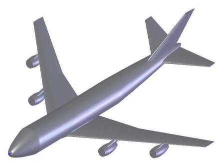


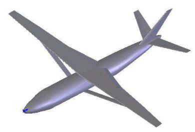
Fig. 2 Emulation of quasi-analytical lofting in CAD.

2.3 Automatic CAD model generation: examples

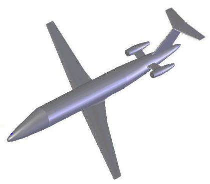
To show the versatility of CADac and the variety of morphologies that can be modeled by the chosen parameterization, Fig. 3 shows a few examples of automatically generated CAD models for very varied aircraft morphologies and dimensions, some spanning more than 60 meters (Transonic cruiser, B747) whereas the strut-wing aircraft is a CAD model for a 2 meters long wind-tunnel model. It is highlighted that each of these CAD solid models is "water-tight", i.e. closed and consistent and it is therefore easy to create a mesh suitable for CFD analysis without need for time-consuming geometry repair.



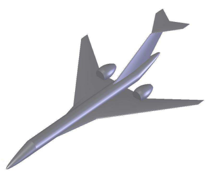
(a) Boeing 747-100.



(b) Wind tunnel model with struts.



(c) Oblique wing regional jet.



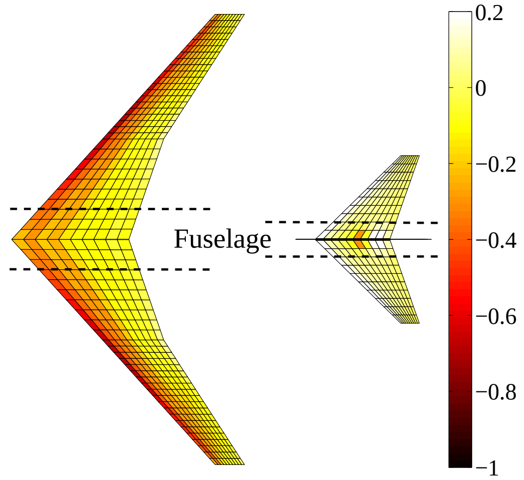
(d) Transonic cruiser.

Fig. 3 Sample of automatically generated parametric CAD models.

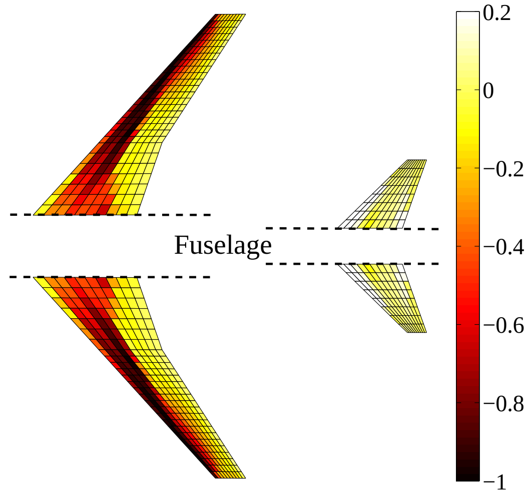
2.4 Application to low and high fidelity aerodynamics

To illustrate the value and utility of the CADac tool in the SimSAC project and in NeoCASS, an example case has been run for the Boeing 747-100 without engines. Two aerodynamic analysis have been performed based on exactly the same geometry *XML* input file; the first one using the vortex lattice method Tornado [3]; the second one using the CAD model automatically generated by CADac and running the Edge solver in Euler mode. The results for the pressure distribution are shown in Fig 4. It is highlighted that the whole process, from *XML* file to CFD solution and visualization, took less than one hour and a half with minimal user intervention. The Tornado solution is obtained within minutes.

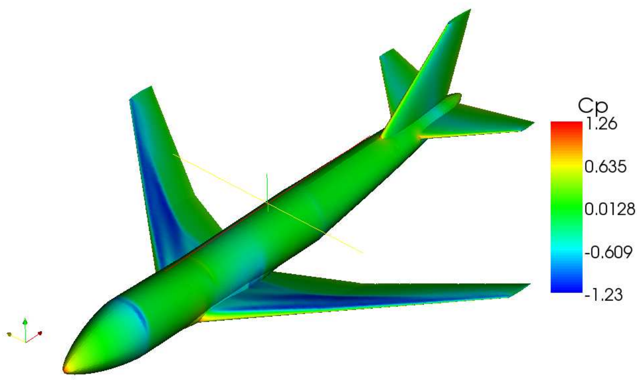
Fig.4(a) shows the Tornado computation of the distribution of the pressure difference between lower and upper surfaces for the wing and horizontal tail. For comparison purposes, the pressure difference has been extracted from the Edge pressure distribution results (see Fig.4(c))



(a) Tornado ΔC_p distribution.



(b) Edge ΔC_p distribution.



(c) Edge C_p visualization.

Fig. 4 Aerodynamics study of the B747-100 in cruise condition.

and projected on the same surface mesh as the one used for Tornado computations; the result is shown in Fig.4(b). The comparison of Fig.4(a) and Fig. 4(b) clearly highlights the advantages of being able to run both low fidelity methods as well as CFD simulations early in the design process. Although Tornado predicts correctly the total lift coefficient and averages well the ΔC_p distribution over the wing and the pressure drop at the leading edge, it cannot model shock waves for example and therefore fails to describe accurately the sudden drop of ΔC_p in the midboard region as well as some finer details of the distribution. Indeed, Tornado is a vortex lattice method modeling only the camber of the lifting surfaces and not their thickness distribution. It is therefore useful to be able to run CFD computations in order to have a better understanding of the aerodynamics; and this will be particularly relevant in the flutter prediction in transonic regime performed in SMARTCAD (see section 5).

3 Weight and balance prediction

Once an appropriate geometry description has been defined, the next step is to be able to get a first estimation of weight and balance. At conceptual stage, aircraft weight estimation is not a trivial task, especially if new unconventional design are investigated: lack of data and continuous design changes are two main issues a designer has to face. Many aeronautical common approaches like Raymer's[4] or Torenbeek's[5] rely on semi-empirical formulas and need extensive tables usage to search and set correction coefficients, making the process hard to automate. The procedure here implemented, based on A.T. Isikveren's PhD Thesis [6], allows to calculate aircraft major components weights and arms, still relying on statistical formulas but minimizing user's intervention.

First of all, weights of the different aircraft components can be classified in three principal groups: first those directly related to Maximum Take-Off Weight (MTOW), i.e. wing or fuselage weight; second, what is defined as "fixed" equipment, function only of passengers accommodation and held constant; and third the fuel and payload weights. These three groups concur to final MTOW by means of an iterative method (for more details, see[6]): a user's defined fuel amount acts as control variable on the process leading to a minimum MTOW that fulfills airframe strength requirements at a fixed payload. Following this classification, the input set is restricted to external geometry data, such as span or fuselage length, and a few internal layout information, i.e. cabin length, fuel and payload, which includes passengers, crew and baggage (design specifications). Statistical formula validity is considered with care, especially for novel designs, but the main target of the weight and balance module is a first reasonable estimate, which will be later refined with the GUESS module (see section 4).

The weight and balance module estimates the weight, the position of the center of gravity and the moment arm for each component of the aircraft. Arms calculation, either for external or internal geometry, is made using volume information, thus implying constant density for each component but it is possible to add concentrated mass separately: if available: additional data such as such APU's (**A**uxiliary **P**ower **U**nit) weight or auxiliary fuel tank capacity and position can be set manually improving the accuracy and realism of the weight prediction. A key factor for weight calculation is the maximum fuel value (and its distribution in the different tanks) that is a required user input; but for internal layout, with the exception of cabin extent (which although can be roughly estimated to 0.7-0.8 of fuselage length), the required data can be automatically estimated by the weight and balance module from statistical and semi-empirical methods.

It also computes the Green Manufacturer's Empty Weight (MEW) and the MTOW and the related positions of the center of gravity. These values set center of gravity range limits, because the first is airframe weight comprising also propulsion, furnishing, miscellaneous contribu-

tions and any manufacturer's tolerances but without fuel and payload, while the latter is the maximum take-off weight at brake release.
A dedicated routine calculates the inertia matrix using either a coarse approximation, which treats the whole aircraft as solid with constant density (thus using simple formulas with correction coefficients; an example can be found in [4]), or a refined method based on the Mitchell code [7].
Both methods make approximations and give a first estimate of the inertia matrix that will be improved in using GUESS. The example case of the B747-100 is considered to illustrate the relevance of the first results given by the weight and balance module. Averaging the MTOW of the various versions, it has been found 364000 kg while weight and balance prediction has given 382274 kg, leading to 5% error considered acceptable at this design stage. Due to the lack of data about the inertia matrix on the chosen aircraft, we refer to a similar example on B747[8] and the comparison is shown in table 1:

	Prediction	From [8]	Error
I_{xx}	$2.3.10^7 kgm^2$	$2.47.10^7 kgm^2$	6.9 %
I_{yy}	$3.6.10^7 kgm^2$	$4.48.10^7 kgm^2$	19.6 %
I_{zz}	$5.6.10^7 kgm^2$	$6.74.10^7 kgm^2$	16.9 %

Table 1 *Boeing 747-100 main moments of inertia.*

And the estimated position of the center of gravity along the longitudinal axis (aircraft fuselage length is 68.5 m) is:

$$x_{MTOW} = 29.51 \text{ m} \quad (14.8\%\ MAC\ w.r.t.\ MAC\ apex)$$

4 GUESS: Generic Unknowns Estimator in Structural Sizing

4.1 Description of the tool

GUESS is used to refine the weight prediction described previously (see section 3) and to determine a stick beam model to be used by the numerical aero-structural module SMARTCAD that will be described in paragraph 5. NeoCASS provides a method based on fundamental structural principle for estimating the load-bearing airframe for fuselage and lifting surfaces.
This method is particularly useful in the preliminary weight estimation of aircraft since it represents a compromise between the rapid assessment of component weight using empirical methods, based on actual weights of existing aircraft, and the detailed but time-consuming finite-element analysis. Both methods have particular advantages but also limitations which make them not completely suitable for the preliminary design phase.
Different approach are commonly adopted to estimate the weights; the empirical one is the simplest but its accuracy depends on the quality and quantity of available data, its results will not applicate to unconventional geometries nor assess the impact of advanced technologies and materials. Finite-element methods are not appropriate for conceptual design. It is also conceivable to create detailed analysis models at a few critical locations on the fuselage and wing, to successively extrapolate the results to the whole aircraft. This approach can be misleading due to the great variety of structural, load and geometric characteristics in a typical design. Creating a coarse model of the aircraft is also an used method, but this scheme may miss key loading and stress concentrations.
But an alternative approach exists, based on beam theory. This results in a weight estimate which is directly driven by material properties, load conditions, and vehicle size and shape, thus being not confined to an existing data base. NeoCASS starts from this last approach and extends it to the sizing of horizontal and vertical tail planes to have a complete view of the airframe of the whole aircraft. The distribution of loads and the vehicle geometry are accounted for, since the analysis is done station-by-station along the vehicle longitudinal axis and along the lifting surface structural chord, giving an integrated weight which depends on local conditions. Nevertheless, an analysis based solely on fundamental principles will give an accurate estimate of structural weight only. Thus, weights for the secondary structures of the fuselage and the lifting surfaces (including

leading and trailing edge control surfaces) and items from primary structure (such as doublers, cutouts and fasteners) must be estimated by a correlation to existing aircraft.

4.2 Application to *Boeing 747-100*

To demonstrate GUESS capabilities to predict weights for the major components of a real aircraft, an example has been run with the *Boeing 747-100*. The results are briefly summarized in Table 2. Fuselage and wing total structural weight computed by means of GUESS are compared with available data. Moreover, estimation of MTOW is compared with the averaged MTOW already indicated in weight and balance section.
Table 2 illustrate that a detailed parametric geometry description of the aircraft, through use of the input geometry *XML* file as described in section 1, a reasonable first estimation of the weight (5%error) and balance and a correct determination of loads condition performed within the solver GUESS are necessary conditions to achieve very good agreement between the estimated and the actual weights with error of less than 0.5 % for the main components.

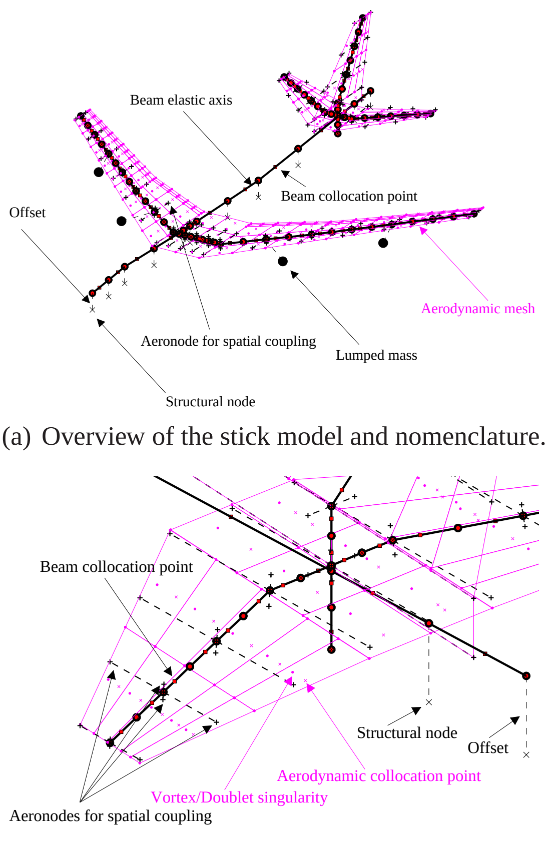
	GUESS	*B747-100*	Error
fuselage [kg]	32941	32958	0.05 %
wing [kg]	39169	40008	0.2 %
MTOW [kg]	362880	364000	0.3%

Table 2 Structural weight estimation of the *Boeing 747-100* main components using GUESS.

5 Aeroelastic analysis: SMARTCAD

In order to carry out aeroelastic analysis, the distributions of stiffnesses determined by GUESS module on prescribed sizing maneuver is converted to a stick model for the whole aircraft airframe with the adoption of a semi-monocoque scheme. SMARTCAD (**S**implified **M**odels for **A**eroelasticity in **C**onceptual **A**ircraft **D**esign) is the core module dedicated to aeroelastic analysis and allows the creation of low-order, high fidelity models which can take into account most of the higher order/nonlinear effects and couplings for the aircraft to be designed. More details about its implementation can be found in [9].
Two main elements are used for structural modeling:

- linear equivalent plates for low aspect ratio structures [10];
- linear beams for high aspect ratio structures and non-linear beams to include geometric effects when large displacements are involved (see Fig.5(a)). The beam used here is based on a finite-volume formulation which does not require numerical integration but only the evaluation of equilibrium at collocation points[11] and is free of shear-locking problems.



(a) Overview of the stick model and nomenclature.

(b) Detailed overview for tail planes.

Fig. 5 Stick model for Boeing 747 aircraft.

These models have a long tradition in the aerospace industry and are certainly important tools for preliminary structural analysis since they represent a relatively simple model that only requires a few geometric details, hiding the real structural geometry up to the point of making the aircraft external shape partially or completely disappear. Despite the computational power available nowadays, these simplified models will be used for some time to come in aerospace industry, especially in early design stages where SMARTCAD is intended to be used. They are indeed relatively accurate and enable to quickly determine aeroelastic performances of the aircraft under design and to perform aero-structural optimization within a Multi-Disciplinary Optimization (MDO) environment.
As for aerodynamic modeling, a hierarchic set of tools is available according to the fidelity to be pursued:

- Vortex Lattice Method (VLM) for static aeroelasticity with camber contributions and deformable mesh when non-linear beams are used to account for large displacements effects;
- Doublet Lattice Method (DLM) [12] to create Reduced Order Models (ROM) for unsteady generalized aerodynamic forces and rapidly discover flutter points at different Mach numbers in subsonic regime;
- Edge code to solve for Euler equations and predict flutter instabilities in the transonic regime, overcoming the non-conservative flutter prediction (transonic dip) when linearized aerodynamic theories are used[13]. Fig.6 shows the results for the classic AGARD 445.6 wing aeroelastic benchmark[14].

In order to use a staggered approach as the one adopted in SMARTCAD, where two independent codes, each one optimal for its purpose, are used for each field and must interact, a spatial coupling scheme is required. The adoption of a partitioned approach [15] requires the definition of an interface scheme to exchange displacements, velocities and loads between the structural grid and the CFD boundary surfaces. The two models are typically discretized in very different, often incompatible, ways. Structural models usually present complex geometries, including many discontinuities and they may lack many geometric details as introduced above. On the contrary, CFD meshes require an accurate description of boundary surfaces and panel meshes require a scheme able to transfer data from one-dimensional beam elements to a two-dimensional lifting surface. In this last case, an extra set of nodes (defined as *aeronodes* in Fig. 5) is introduced. Each aeronode is associated to a real node of the structural mesh and undergoes a rigid body motion under the classic hypothesis of rigid section that a beam model assumes. Two spatial coupling methods are available:

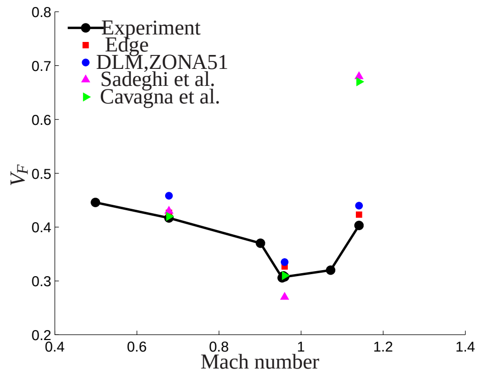
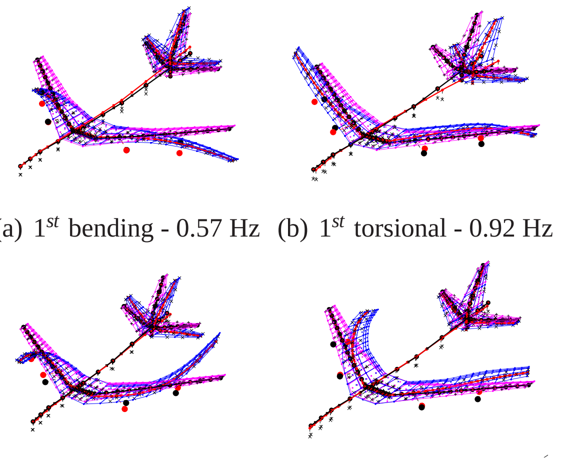


Fig. 6 Flutter speed index V_F and frequency ω_F for the AGARD 445.6 wing by Edge solver

- an innovative scheme, based on a "mesh-free" Moving Least Square (MLS) method [16];
- the Radial Basis Function (RBF) method, which is one of the most adopted methods in computational aeroelasticity.

Both methods ensure the conservation of energy transfer between the fluid and the structure and they are suitable for the treatment of complex configurations. Therefore, no spurious energy is introduced in the system that may



(a) 1^{st} bending - 0.57 Hz (b) 1^{st} torsional - 0.92 Hz

(c) 2^{nd} bending - 1.56 Hz (d) 1^{st} inplane - 1.72 Hz

Fig. 7 Boeing 747 vibration modes for maximum take-off configuration.

alter numerically its aeroelastic stability. As for mass distribution, the GUESS module directly includes, during the stick model generation, lumped masses (such as engines as showed in Fig. 5(a), landing-gears or system whose value and location is provided by the Weight and Balance module) or by introducing non-structural densities on the beams where non-structural mass is distributed (such as fuel stored in the wing-box, passengers, furniture, paint). This enables to have a structural model as faithful as possible with the correct inertial load distribution.
Different analysis can be carried out:

- vibration modes calculations and flutter analysis (see Fig.7);
- linear/non-linear static aeroelastic analysis, trimmed calculation for a free-flying rigid or deformable aircraft
- steady and unsteady aerodynamic analysis to extract derivatives for flight mechanics applications.

6 Conclusions

The development and application of a new variable-fidelity aero-structural sizing and optimization capability specially suited to the conceptual design phase has been presented in this paper. The computational suite consists of two primary modules related to geometry construction and aero-structural sizing; these are known as CADac (**C**omputer **A**ided **D**esign **A**ir**c**raft) and NeoCASS (**N**ext generation **C**onceptual **A**ero-**S**tructural **S**izingvSuite) respectively. The geometry construction expert module has been found to greatly expedite the generation of consistent, closed solid models appropriate for high-fidelity computational aerodynamic analysis. This has been achieved via the utilization of the CAPRI application programming interface in conjunction with an array of popular Computer Aided Design (CAD) commercial packages, i.e. Catia V5®, SolidWorks®, Unigraphics® and Pro Engineer®. The aerodynamic prediction portion of the NeoCASS module comprises three specialist codes which include: TORNADO (a Vortex-Lattice based code), a Doublet Lattice Method based code, and, EDGE (an Euler based code). Each of the aerodynamic specialists codes have been selected in order to produce as inexpensively as possible an acceptable level of conformity in the aero-elastic borne result. In terms of coupling the aerodynamics code with a structural sizing capability in NeoCASS three expert sub-modules have been created. The TORNADO code has been coupled with non-linear beams in order to predict large displacements in the structure. The Doublet Lattice Method has been utilized to permit the creation of Reduced Order Models (ROM) using unsteady generalized aerodynamic forces with intent to identify flutter points during subsonic flight. Finally, the EDGE code has been employed to predict flutter instabilities in the transonic flight regime. As an indication of the capabilities produced by this newly proposed computational aero-structural suite a complete flexible structural model of the B747-100 transport aircraft was analyzed. The quasi-analytical weight prediction portion of the NeoCASS suite was found to generate an accuracy of less than 0.5% error compared to published results.

6.1 Acknowledgments

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6.2 Copyright Statement

References

[1] Haimes R. Capri: Computational analysis programming interface. a solid modeling based infrastructure for engineering analysis and design. *Massachusetts Institute of Technology*.

[2] www.foi.se/edge.

[3] T. Melin. Tornado a vortex-lattice matlab implementation for linear aerodynamic wing applications. Master's thesis, Royal Institute of Technology (KTH), 2000.

[4] Raymer D. P. *AIRCRAFT DESIGN: A Conceptual Approach, Fourth Edition*. AIAA Education Series, New York, 2006.

[5] Torenbeek E. *Synthesis of subsonic airplane design*. Delft university press ,Kluwer academic publishers, New York, 1982.

[6] A.T. Isikveren. *Quasi-analytical modelling and optimization techniques for transport aircraft design*. PhD thesis, Royal Institute of Technology (KTH), 2002.

[7] Mitchell C.G.B. Technical Report TR 73079, Royal Aircraft Establishment, Procurement Executive, Ministry of Defence.

[8] Nelson R. C. *Flight stability and automatic control, Second edition*. McGraw-Hill, 1998.

[9] L. Cavagna, P. Masarati, P. Mantegazza, and S. Ricci. Development and validation of an investigation tool for nonlinear aeroelastic analysis. In *Proceedings of the* 26^{th} *ICAS Congress*, Anchorage, Alaska, 14–19 September 2008.

[10] Gary L. Giles. Equivalent plate analysis of aircraft wing box structures with general planform geometry. *Journal of Aircraft*, 23(11):859–864, November 1986.

[11] Gian Luca Ghiringhelli, Pierangelo Masarati, and Paolo Mantegazza. A multi-body implementation of finite volume beams. *AIAA Journal*, 38(1):131–138, January 2000.

[12] E. Albano and W. P. Rodden. A doublet–lattice method for calculating the lift distributions on oscillating surfaces in subsonic flow. *AIAA Journal*, 7(2):279–285, 1969.

[13] Luca Cavagna, Giuseppe Quaranta, and Paolo Mantegazza. Application of Navier-Stokes simulations for aeroelastic assessment in transonic regime. *Computers & Structures*, 85(11-14):818–832, 2007. Fourth MIT Conference on Computational Fluid and Solid Mechanics.

[14] E. C. Yates. AGARD standard aeroelastic configurations for dynamic response. I wing 445.6. R 765, AGARD, 1985.

[15] Charbel Farhat and Michael Lesoinne. Two efficient staggered algorithms for the serial and parallel solution of three-dimensional nonlinear transient aeroelastic problems. *Computer Methods in Applied Mechanics and Engineering*, 182:499–515, 2000.

[16] Giuseppe Quaranta, Pierangelo Masarati, and Paolo Mantegazza. A conservative mesh-free approach for fluid-structure interface problems. In M. Papadrakakis, E. Oñate, and B. Schrefler, editors, *International Conference on Computational Methods for Coupled Problems in Science and Engineering*, Santorini, Greece, 2005. CIMNE.