NEOCASS: AN OPEN SOURCE ENVIRONMENT FOR THE AEROELASTIC ANALYSIS AT CONCEPTUAL DESIGN LEVEL

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Abstract

This paper, after a brief introduction describing the NeoCASS suite for aircraft conceptual design, reports the recent developments introduced into the software. Typical examples of results obtainable using NeoCASS are also reported.

1 Introduction

It is well known the importance to be able to predict as early as possible the performances of a future aircraft and to study quickly but accurately a wide range of designs at conceptual stage before going to further steps such as the preliminary and detailed ones when the design freedom is considerably restricted. Most of the life-cycle cost of an aircraft 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 later redesign and corrections.

Conceptual design systems nowadays adopted for the design of contemporary commercial aircraft make extensive use of handbook methods based on semi-empirical theory and data. Although these techniques are now well proven and developed, they are not exhaustive and, considering today's computer performances, it is now conceivable to bring higher fidelity methods earlier in the design process. From 2006 to 2009 a research project funded by the 6th European Research Framework named SimSAC (Simulating Aircraft Stability And Control Characteristics for Use in Conceptual Design) aimed at this goal, i.e. the development of a design tool based on multi-fidelity semi-empirical, computational and analytical methods for the aero-structural analysis of an aircraft layout at conceptual design stage, called CAESIOM. Inside CEASIOM tool, a dedicated suite for the structural sizing and aeroelastic analysis, named NeoCASS (Next generation Conceptual Aero-Structural Sizing Suite) has been developed by the Department of Aerospace Engineering of Politecnico di Milano, having the following main goals: to provide a more realistic estimation of structural weight; to allow for aeroelastic analysis and optimization since the conceptual design level. The geometrical representation of the aircraft adopted by CEASIOM and by NeoCASS as well, is fully described by a unique parametrization file based on the Extensible Markup Language (XML) format to which all different analysis modules refer. The geoemtry database is easily generated and managed in a visual environment by a dedicated module, named AcBuilder. The adopted format allows storing each component of the aircraft and its parameter in a hierarchical and sorted way. It eases data sharing as well as the expansion of the dataset, i.e. the number of components of the aircraft can be modified at will by introducing new components as well as new parameters, thus increasing the family of morphologies that can be modeled.

After the end of SimSAC project the development of NeoCASS tool continued along different directions, such as the development of a dedicated module for the gust response analysis, named NeoRESP, the enhancement of data transfer from NeoCASS to higher fidelity tools like CFD codes or advanced CAD systems like Catia v.5. Finally, September 2011, NeoCASS became an open source project open to the contributions of external users and developers.

The paper, after a brief description of NeoCASS structure, will introduce the recently introduced capabilities concerning one of its module. i.e. GUESS, with the help of some numerical examples.

2 NeoCASS Structure

NeoCASS is a suite of modules that combines state of the art computational, analytical and semi-empirical methods to tackle all the aspects of the aero-structural analysis of a design layout at conceptual design stage [1; 2; 3; 4]. It includes two main modules, respectively named GUESS (Generic Unknowns Estimator in Structural Sizing) and SMARTCAD (Simplified Models for Aeroelasticity in Conceptual Aircraft Design) as shown in figure 1. An external module is included, called W&B (Weight and Balance), used also by other modules of CAESIOM procedure, necessary in order to have a first estimate of the non-structural masses and their location for the estimation of inertial loads.

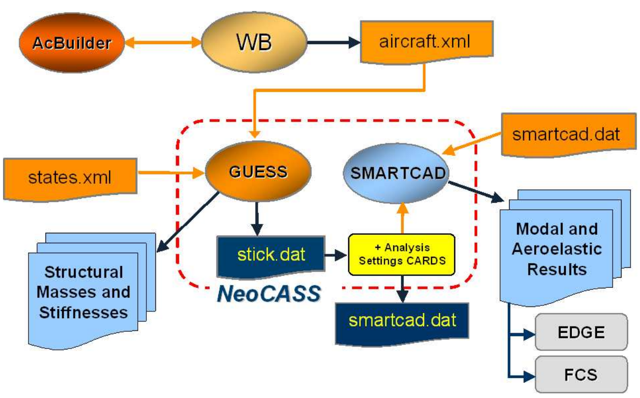


Fig. 1 The layout of NeoCASS suite.

In order to start the aeroelastic analysis, a semi-analytical module named GUESS (Generic Unknowns Estimator in Structural Sizing), based on a modified version of the AFaWWE code (Analytical Fuselage and Wing Weight Estimation) [5], is run to produce for the whole airframe an initial estimate of the stiffness distribution on the basis of user-defined sizing parameters. The initial structural sizing is performed in a fully stressed design condition and introduces structural instability limits for compressed panels and stiffeners. However, no aeroelastic effects are considered during this sizing phase. Once the initial structural sizing and the first stiffness distribution is determined by GUESS, a structural and aerodynamic mesh is automatically generated to allow for the subsequent aeroelastic assessment and optimization together with all the requested information for the fluid-structure interfacing.

The second main module is named SMARTCAD (Simplified Models for Aeroelasticity in Conceptual Aircraft Design) and it is dedicated to the aeroelastic analysis. SMARTCAD is based on different analysis tools with increasing fidelity and computational costs. Two classic lifting surface methods are implemented: the Vortex Lattice Method (VLM) for subsonic steady aerodynamic and aeroelastic calculations and the Doublet Lattice Method (DLM) for the prediction of harmonic aerodynamic generalized forces and subsonic flutter analysis [6; 7]. An interface to high-fidelity CFD codes is also available: further details can be found in [2] . Since at the conceptual level indeed, the primary focus is on determining and representing at least structural/non-structural mass and stiffness distribution to satisfy strength, stiffness and stability requirements. Few simple lumped structural elements capable of giving equivalent structural behavior can be used for this purpose such as a linear equivalent plate, linear beam or non-linear beam to introduce geometrical non-linear effects. These models lead to low-order algebraic problems, keeping the computational cost very low and allowing several configurations to be examined quickly. NeoCASS includes also a dedicated Multi Disciplinary Optimization (MDO) tool used to refine the initial structural sizing so that different aeroelastic constraints can be satisfied as limits on: divergence speed, aeroelastic aerodynamic derivatives, maximum deformed shape under loading due to structural flexibility, flutter speed.

Recently a third module has been added to the Neo family, called NeoRESP, for the dynamic aeroelastic response. The aeroelastic dynamic model combines the beam model with a DLM model which provides for the oscillatory aerodynamic forces. Specifically, the DLM gives the forces directly in frequencies domain. Thus, the simplest way to solve for the problem in the time domain is to transform the frequency responses by a FFT. NeoRESP, in the actual version, includes the discrete gust response only, thus assuming that: the gust features an assumed spatial distribution for its perturbation velocity; the perturbation travels along the flight path and stays constant in time; the perturbation field is not sensitive to the aircraft passing and flow interfering phenomena [8].

In the following images typical outputs of NeoCASS analysis are reported.

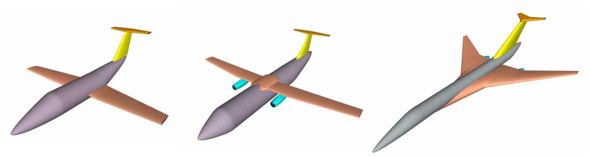


Fig. 2 Examples of aircraft configurations that can be analyzed using NeoCASS: a small size trainer (left), a twin engine regional aircraft (middle) and a transonic cruiser (right).

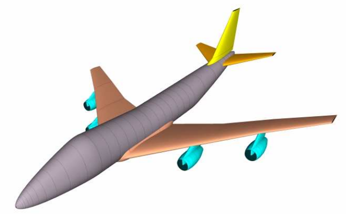
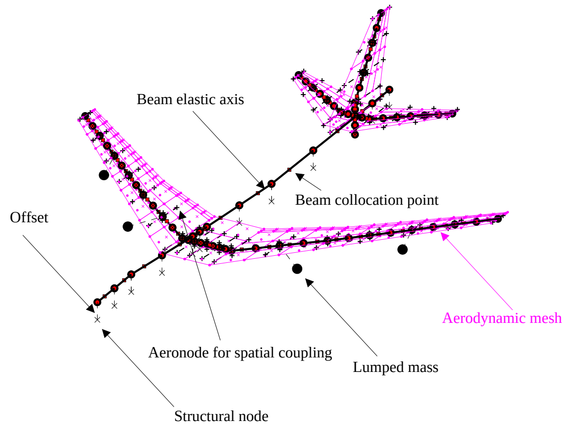
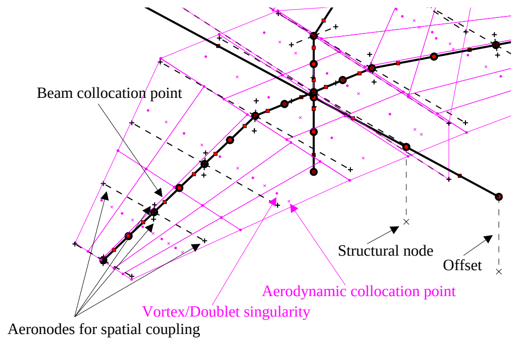


Fig. 3 Geometry representation of Boeing 747-400 aircraft.



(a) Overview of the stick model and nomenclature.

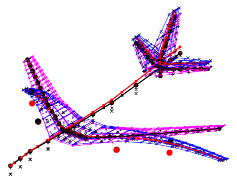


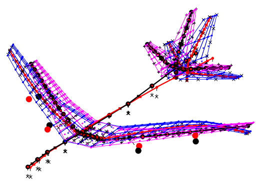
(b) Detailed overview for tail planes.

Fig. 4 Stick model for Boeing 747 aircraft.

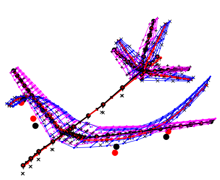
3 The New GUESS Module

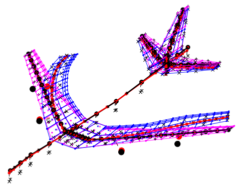
GUESS module, since its first development, included two different analysis approaches or so called modes, i.e. Standard and Modify modes. In the Standard mode the sizing is based on a limited, predefined set of maneuver and simplified aerodynamic theory, namely strip theory, for load calculation. In the Modify mode the user had the freedom to specify user-defined maneuvers and the sizing required at first a trim analysis. In the new version of NeoCASS 2.2, online since June 2012, a totally new GUESS Standard module was included, where the original one derived from Ardema's original work [5] has been massively revisited to improve accuracy. GUESS Standard is now named GSTD





(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. 5 Boeing 747 vibration modes for maximum take-off configuration.

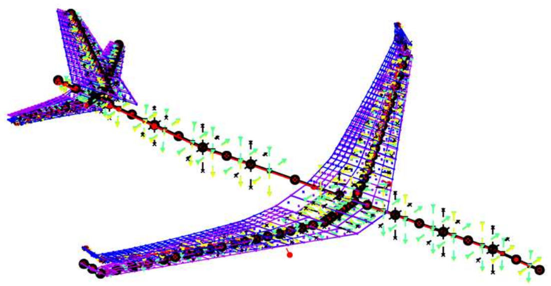


Fig. 6 Large transport aircraft in the trimmed configuration for a 2.5g pull-up maneuver.

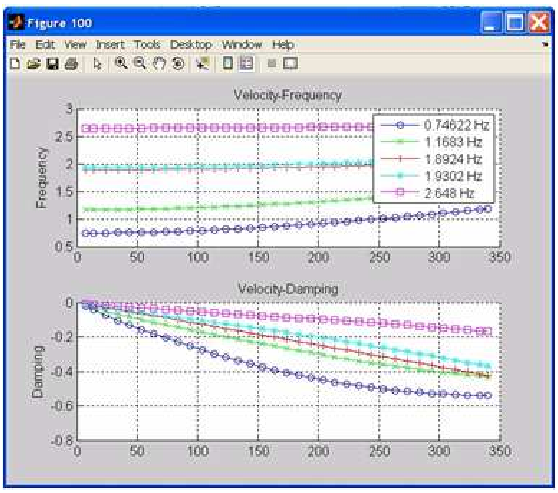
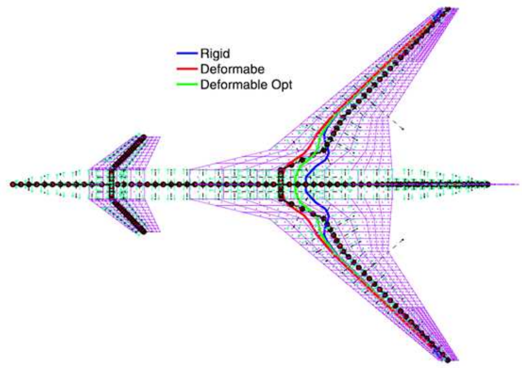
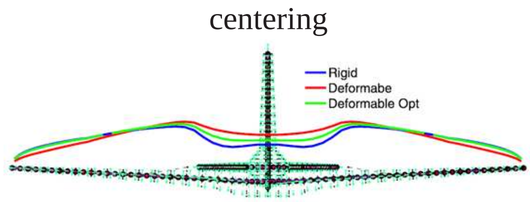


Fig. 7 Typical V-g plot obtained with the flutter analysis module of SMARTCAD.



(a) Top view



(b) Front view

Fig. 8 Comparison between rigid and elastic load distribution over a transonic cruiser.

and in analogy GUESS Modify is named GMOD. The main improvement relies in the possibility of performing a set of steady user-defined maneuvers solved directly by SMARTCAD. The previous release was limited in aerodynamic and structural modeling and in the sizing maneuvers. Strip theory was adopted for spanwise aeroloads and the softwares TORNADO and LDSTAB were used respectively for longitudinal and for latero-directional derivatives to enable trim solution. Structural concepts were based on Ardema's original models, and only closed set of pre-defined maneuvers, i.e. pull-up, sideslip and landing could be used. The user had a very limited control on the parameters of the maneuver.

The new release of GUESS overcomes the limitations of the first release. A new concept of lifting surface section has been added to ones from Ardema's work. This concept adopt a physically based wingbox structure based on the classical semi-monocoque theory. A numeric optimization process is carried out for each spanwise section of lifting surfaces to find the optimal stringer-area, web and skin thicknesses so that the section features the minimum weight and satisfies stress, global and local instability constraints. The trim process is general and is determined numerically by considering a simple rigid model with one lumped mass coupled to a vortex lattice aero mesh. Any kind of maneuver can be defined in terms of control inputs, accelerations or angular rates. Static gusts and taildown landing can be considered as well.

A new GUI panel has been included to raise the fidelity. It allows to define all the maneuvers to be considered during the sizing. To further aid the designer, the panel can be used to define a maneuver according to few selected points of flight certification rules. For each trim condition, aero loads from the internal VLM mesh are transferred to the underlying stick model through beam-like splines. When the sizing process is completed, the mass distribution is updated along the internal structural mesh during the sizing process. The lumped mass is updated and one more sizing step is repeated until overall convergence.

4 GUESS Standard vs. Modify

As already pointed out NeoCASS has two tiers for GUESS: GUESS Standard (GSTD) and GUESS Modify (GMOD). After the recent improvements, GSTD is fully based on SMARTCAD as numerical solver for trim, aerodynamic loads and structural analysis, in analogy with GMOD. Nevertheless, different assumptions make GSTD a first level approach if compared to GMOD:

1. GSTD assumes the aircraft as rigid and its structure to be statically determinate. Thus, configurations with tailbooms or joined wings cannot be considered here. For this reason, GSTD is also referred as Rigid/Force GUESS. The model is represented by a lumped mass which is iteratively updated. At the first iteration mass and inertia are directly recovered from Weight and Balance (WB) predictions. During the iterative process, the weight for lifting surfaces and fuselage are updated and the new loads to guarantee a trimmed flight for each selected maneuvers are found. An underlying stick mesh is created; loads are recovered at each node and each section sized according to the structural concept adopted. Inertial loads for distributed and lumped masses are accounted for as well. Diagrams of internal loads are recovered along each component for each maneuver. Sizing loads are then recovered taking the maximum of bending, torque and shear at each section.

2. GMOD is the second level and overcomes the limitations of the first level. It is referred as Elastic/Displacement GUESS. In this case the stick mesh is used . The global stiffness matrix is recovered and a finite element solution is carried out to determine the trim flight state. A displacement approach is adopted. The solution hence does not depend on the constraints of each component. Statically indeterminate configurations such as tailbooms or joined wings can be considered. GMOD allows to use rigid elements and to rule the way the components are mutually linked. This will affect the stress distribution of course. By default the wing is connected to the fuselage though pins while tail planes are clamped.

4.1 Application Example of New GUESS Module

In the following a twin prop regional aircraft is used as application example of new GUESS module. After loading the XML file containing the properties describing the aircraft layout, the sizing process is defined through the panel shown in Fig. 9.

Prescribing a suitable set of maneuvers to consistently size the aircraft is not an easy task. An experienced designer can define his own set of maneuvers by checking on Maneuver set definition. On the other hand, GUESS simplifies the task by following few excerpts of flight regulations. The designer selects which EASA regulation has to be used between CAS23 and CAS25. A third option is to let the software choose which

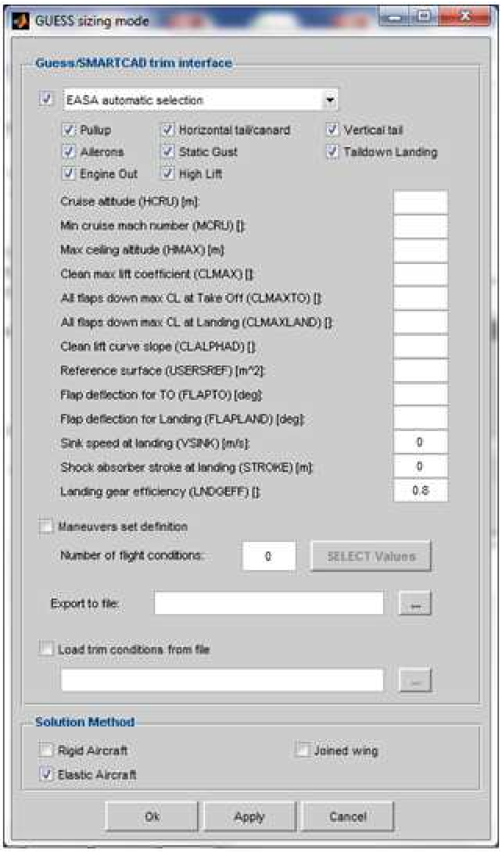


Fig. 9 GUI panel for sizing definition.

is the most suitable for the aircraft under investigation according to its weight, number of passengers and propulsion. If this last choice is adopted, some inputs are required to define main aircraft speeds and the value of the few fixed variables for each maneuver. Table 1 summarizes the aircraft speeds at which the different maneuvers are performed. Depending on the inputs given, few of them cannot be defined. In this case, the solver will skip the relative maneuvers. In the following Fig. 10, an example of the typical output produced by GUESS once completed the input data is reported.

The main features of the aircraft are summarized by the Placard and the Load factor (nV) diagrams shown in Figs 11 and 12. The former shows the value of cruise speed V_C and dive speed V_D with altitude as EAS, TAS or CAS. The latter reports the main speeds and the limit positive

Table 1 Aircraft speeds used for sizing.

Speed	Description
V_A	Maneuver speed
V_B	Rough air gust speed
V_C	Cruise speed
V_D	Dive speed
V_S	Stall speed in clean conf.
V_{FLAND}, V_{FTO}	Stall speed with flaps

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SPEEDS (EAS):
 - Maneuvering          VA:     92.6302 [m/s]
 - Rough air            VB:     67.4232 [m/s]
 - Design min cruise    VC:     140.578 [m/s]
 - Design cruise        VMO:    149.013 [m/s]
 - Design dive          VD:     190.01 [m/s].
 - Stall clean conf.    VS:     58.5845 [m/s]
 - Stall take-off conf. VFTO:   54.9571 [m/s]
 - Stall landing conf.  VFLAND: 47.0328 [m/s]
      Percentage MTOW used: 79.1%

MACH:
 - Design cruise MMO:  0.583.
 - Design dive    MD:  0.594717.

LOAD FACTORS:
 - Max nz: 2.5.
 - Min nz: -1.

REFERENCE DATA used:
 - Design weight: 282114 [N]
 - Reference surface: 61 [m^2]
 - Reference chord: 2.2443 [m]
 - Reference span: 27.18 [m]
 - Reference cruise altitude: 4572 [m]
 - Max ceiling altitude: 6000 [m]
```

Fig. 10 Example of aircraft data summary output from GUESS.

load factor and is automatically saved by GUESS in a $.fig$ file for post-processing purposes. Finally, Fig. 13 shows the summary of sizing maneuvers in the Mach vs. altitude diagram.

Once the GUESS analysis, i.e. the sizing process, is complete, the internal database is automatically saved and used for post processing. Dedicated functions are available to produce the relevant information concerning the sizing process. For example, it is possible to plot the initial n-v diagram saved by GUESS together with the load factor of each maneuver for a given mass configuration, like shown in Fig. 14, where for each point, the ID of the corresponding maneuver is reported. Indeed, the designer can plot the load factors of each maneuver and have a rapid estimate of which ones are limiting. In this case, the maneuvers do not exceed the limit value of 2.5 since all of them have a prescribed value of load factor. The only cases when the load factor results from the trim problem so that it could exceed the maximum prescribed value are gust and landing maneuvers.

A second function helps the designer to estimate how each maneuver affects the internal loads along each section of fuselage, wing and tailplanes. Figure 15 shows for the first mass configuration, the critical maneuver along wing axis. The x axis gives the ID of each maneuver while y axis gives the section index, starting from the root. In this simple case, the maneuver 3, a pullup at maximum load factor at V_C, is critical for all sections. Finally, it is possible to plot the 2D envelope diagrams for each station along wing, fuselage or tailplanes. Figure 16 shows the envelope for bending and torque for each maneuver for a section at 50% of wing-span. The red dots are the maximum and minimum value of each load component; they are currently used for the sizing of the section.

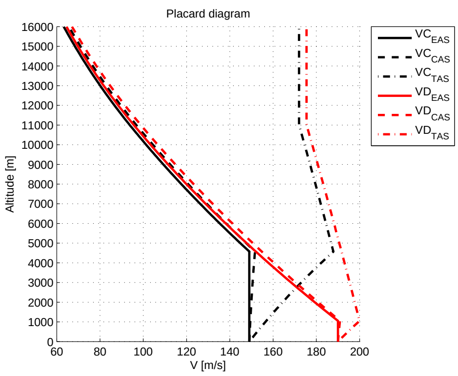

Fig. 11 Placard diagram.

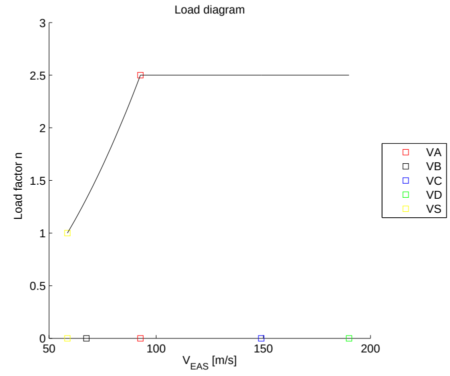

Fig. 12 n-V diagram.

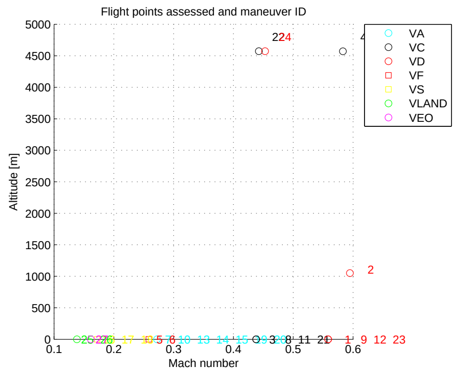

Fig. 13 An overview of maneuvers adopted for sizing in the Mach vs. altitude diagram.

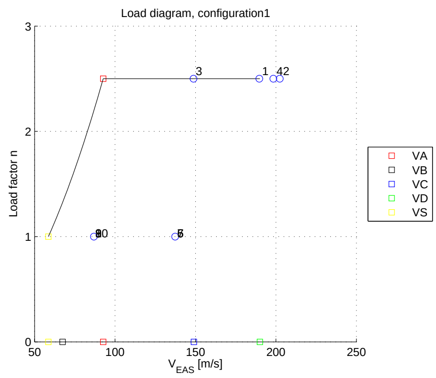

Fig. 14 n-V diagram with defined maneuvers.

5 Conclusions

NeoCASS is a suite of Matlab codes specifically tailored for structural sizing and aeroelastic analysis at conceptual design level. It includes two main modules, i.s. GUESS and SMARTCAD for the initial sizing, the first, and for the aeroelastic analysis and optimization, the latter.

Since September 2011 NeoCASS became an open source project, and its homepage is reach-

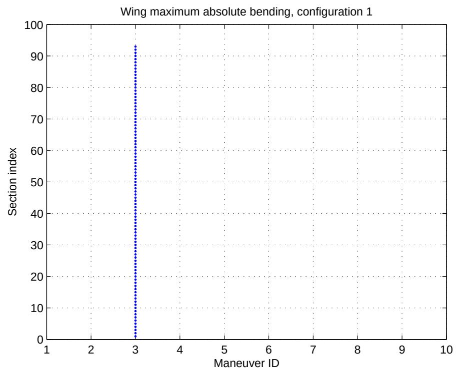

Fig. 15 Critical maneuvers for sizing.

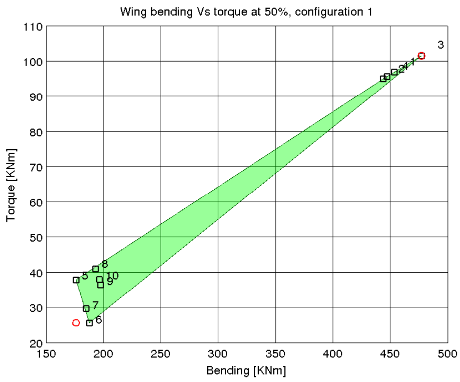

Fig. 16 2D loads envelope diagram.

able at the following link: www.neocass.org. NeoCASS has been tested on different kind of aircraft configurations and is adopted as research tools in the framework of different European Projects.

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