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ORIGINAL PAPER

On the Preliminary Structural Design Strategy of the Wing of the Next-Generation Civil Tiltrotor Technology Demonstrator

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Abstract

The T-WING project is a Clean Sky 2 research project aimed at designing, manufacturing, qualifying and flight-testing the new wing of the Next-Generation Civil Tiltrotor Technology Demonstrator (NGCTR-TD), as part of the Fast Rotorcraft Innovative Aircraft Demonstrator Platforms (FRC IADP) activities. Requirements, design strategy, methodology and main steps followed to achieve the composite wing preliminary design are presented. The main driving requirements have been expressed in terms of dynamic requirements (e.g., limitations on natural frequencies), aeroelastic requirements, i.e., compliance with European Aviation Safety Agency (EASA) CS-25 and CS-29 Airworthiness Requirements), structural requirements (e.g., target wing structural mass), functional requirements (e.g., fuel tanks, accessibility, assembly and integration, etc.) and wing preliminary loads. Based on the above-mentioned requirements, the first design loop is performed by targeting an optimal wing structure able to withstand preliminary design loads, and simultaneously with stiffness and inertia distributions leading to a configuration free from flutter within the flight envelope. The outcome from the first design loop is then used to refine the model and compute more reliable flight loads and repeat aeroelastic analysis, returning further requirements to be fulfilled in terms of wing stiffness and inertia distributions. The process is iterated till the fulfillment of all the project requirements.

Keywords Civil tiltrotor · Wing · Design · Aeroelasticity · Flutter · Multi-objective optimization

Abbreviations

CFRP	Carbon fiber-reinforced plastics
DLM	Double lattice method
DMU	Digital mock-up
FEA	Finite element analysis
FEM	Finite element method
FRC	Fast rotorcraft
IADP	Innovative aircraft demonstrator platforms
IPS	Infinite plate splines
MS	Margin of safety
NGCTR-TD	Next-generation civil tiltrotor technology demonstrator
RSM	Response surface methodology
SUAV	Smart unmanned aerial vehicle
VABS	Variation asymptotic beam sectional
WAL	Work area leader

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Fig. 1 NGCTR

1 Introduction and Scenario

Horizon 2020 (H2020) Clean Sky 2 FRC IADP NextGenCTR will be dedicated to the design, construction and flying of an innovative Civil Tiltrotor technology demonstrator [1], the configuration of which will go beyond current architectures for this type of aircraft. NextGenCTR's demonstration activities, led by Leonardo Helicopters, will aim to validate its architecture, technologies/systems and operational concepts, with significant improvement with respect to the current state-of-the-art tiltrotors. The NGCTR-TD is characterized by a different concept for the tilting mechanism with respect to the upcoming Leonardo civil tiltrotor platform: a fixed engine installation with a split gearbox to provide the proprotor tilting mechanism, based on new capabilities in aerodynamic and structural analysis, design, and next-generation manufacturing and assembly principles. This will also allow important operational cost reduction to address the competitiveness of the architecture and solutions adopted (Fig. 1).

T-WING consortium is working on the composite wing of the NGCTR-TD planned to be flying in 2023. The consortium, led by the Italian Aerospace Research Center, is composed of industrial partners Magnaghi Aeronautica and Salver (IT), SSM (IT), SMEs OMI (IT) IBK Innovation (DE) and Università degli Studi di Napoli Federico II (IT).

The task undertaken by the consortium is aimed at designing, manufacturing, qualification and flight-testing of the wing and moveable surfaces of the NGCTR-TD. The logic behind the development of wing and moveable surfaces, which is illustrated in Fig. 2, foresees a design phase based on the requirements, driven by airworthiness and defined in cooperation with the Work Area Leader (WAL). Once the design phase is completed, the toolings to be used for the manufacturing of the wing will be designed and produced and the wing itself will be manufactured, and qualified. After a successful qualification, the wing will be assembled to all the other components of the NGCTR-TD. The last step of the development is the instrumentation of the wing, by the use of accelerometers and strain gauges, and the flight test campaign which will lead, among others, to the validation of the flight loads used for the preliminary design of the wing.

The NGCTR-TD is a demonstrator aimed at testing various technologies for use on the Next-Generation Tiltrotor aircraft by Leonardo Helicopters.

Among the major improvements related to these technologies are:

- Development of a new high lift and low drag wing which is optimized to improve downwash impingement in helicopter mode (Hovering). As shown in Fig. 3, downwash impingement is improved by the introduction of two surfaces, an outboard flaperon and a large morphing surface which rotates downwards in helicopter mode to reduce the wing area beneath the rotors.
- Development of a highly integrated composite wing structure.
- Development of a compact structural wing box, since almost half of the wing chord length is dedicated to the moveable surfaces.

2 State-of-the-Art Assessment

In the last few years, for a fast and reliable point to point connection or intercity flights and to improve public mobility and access to air transportation, Runway-Independent Aircraft concept is progressively becoming more prominent in civil aviation. Moreover, the market prospects predict an increasing demand of Disc-Rotor technologies for business flights, air medical, search and rescue application, and others. The helicopter is currently the best solution in all operative conditions where low-speed capabilities are essential, mainly thanks to the efficiency connected to the physics of low disk loading, the high-payload carriers, due to efficiency and low empty weight and the high maneuverability and agility, using thrust for control power. Nevertheless, the intrinsic characteristics of rotor aerodynamics limit both the maximum reachable speed from the helicopter and the maximum altitude and service ceiling. The solution to the helicopter's limitations has been to combine the maximum cruising speed, range, endurance, payload, manoeuvrability, and superior survivability of the airplane with the vertical lift capabilities of a helicopter. Much research worldwide has yielded many tiltrotor concepts but very few have actually taken flight, including some NASA prototypes, the pioneer XV-3 and then the successful XV-15 program, the Bell's military tiltrotors V22 and V280 and, finally, the AW609, currently subjected to certification process for use in the civil sphere. The following are some important performances in terms of GTOW, disk loading, maximum and cruise speeds, ser-

Fig. 2 Wing development logic

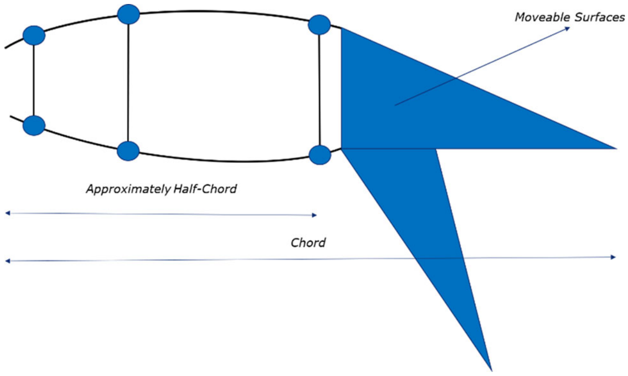


Fig. 3 Scheme of the NGCTR-TD structural wing box

vice ceiling and range to provide an approximate comparison between the main design parameters of the aforementioned tiltrotors (Table 1).

Generally, the Preliminary Tailored Wing Design depends on the specific tiltrotor flight mission, in terms of payload, range and cruise speed and consist of an iterative process during which a design concept is settled to match the potential customer's requirements [2]. The design concept is then subjected to design analysis and the results, in terms of trade-off and optimization, output a reviewed design solution. This process is repeated until a solution deemed to be the best is economically sustainable and meets the desired requirements. So, the final design proposal only evolves after a systematic interaction between the requirements, detailed design tools and historical database of similar existing article produced and/or in operating conditions. The design of a composite wing for a tiltrotor aircraft is strongly connected to the flight mission requirements so the fuel tanks, the rotor-drive system and other components must be included inside of the wing structure preliminary sizing. Sometimes, because related to project requirements or manufacturing technologies, it could be required that geometric configurations are kept fixed, such as the spar location, when other component location or shape change. For this reason, to find the best design solution that minimizes the structural weight of the wing while satisfying a series of design constraints, an opti-

Table 1 Main performances and maximum take-off weight of existing tiltrotors

	XV-3	XV-15	V22	V280	AW609
$GTOW_{Max}$	4890 lb (2218 kg)	13,248 lb (6009 kg)	52,600 lb (23,859 kg)	57,320 lb (26,000 kg)	16,799 lb (7620 kg)
Disk loading	5.66 lb/ft^2 (27.5 kg/m^2)	13.2 lb/ft^2 (64.3 kg/m^2)	20.3 lb/ft^2 (99 kg/m^2)	16 lb/ft^2 (78 kg/m^2)	15.9 lb/ft^2 (77.4 kg/m^2)
Maximum speed	160 kts (296 km/h)	300 kts (557 km/h)	305 kts (565 km/h)	304 kts (560 km/h)	275 kts (509 km/h)
Cruise speed	145 kts (269 km/h)	165 kts (425 km/h)	241 kts (446 km/h)	278 kts (520 km/h)	260 kts (482 km/h)
Service ceiling	15,000 ft (4600 m)	29,500 ft (8840 m)	25,000 ft (7620 m)	15,092 ft (4600 m)	25,000 ft (7620 m)
Range	255 mi (411 km)	515 mi (825 km)	1011 mi (1627 km)	2485 mi (4000 km)	863 mi (1389 km)

mization process is necessary. It also expected that the best design solution must also minimize costs, time and computational efforts.

The following is a brief general overview of some operating flows concerning the preliminary design of a composite wing for tiltrotor. The purpose is to provide a state of the art, differences and similarities on methods and algorithms, compared to the work presented in the following paragraphs. In particular, reference is made to some optimization studies that have aeroelastic stability and integrity of the wing as their final goal or constraints.

The first example of design optimization framework regards the design optimization of the SUAV TRS4 composite wing [3]. SUAV is short for Smart Unmanned Aerial Vehicle and it consists of a three-blade tiltrotor whose Gross weight is 2204.6 lb (1000 kg), with a maximum speed of 270 kts and a wing span length of 22.3 ft (6.8 m). It was developed by the Korea Aerospace Research Institute (KARI). The mathematical optimization process comprises a number of numerical analysis modules, integrated in a single MATLAB environment. Briefly, this MATLAB tool works as a gradient-based optimizer design that implements three important analysis steps: a 2D linear beam cross-section analysis, a flutter analysis and finally a 3D stress/strain analysis.

As a mathematical optimization algorithm, the ‘*fmincon*’ command provided in MATLAB Optimization Toolbox is used. This optimizer attempts to find a constrained minimum of a scalar function composed of several variables starting with an initial estimate. At the beginning of the optimization process, the design variables of the wing, in terms of ply thickness and spar location, are defined in MATLAB. A Variation Asymptotic Beam Sectional (VABS) analysis is used for a 2D linear beam cross-section investigation of the composite wing. VABS is a FEM-based analysis tool through which the sectional stiffness, the inertia matrices of the beam and the actuation force/moment vectors of the active materials are computed.

By performing a VABS run, we can also determine the chordwise locations of the center of gravity, the elastic axis and the centroid. At this stage, also wing airfoil shape, material properties of composites and layup configuration are passed into a MATLAB mesh generator to generate the finite element mesh of the outer walls and webs of the wing. The sectional properties, in terms of stiffness and inertia, obtained by means VABS are transferred in input to DYMORE, a FEM-based code for the Analysis of Nonlinear Flexible Multibody Systems, used here for the multibody modeling of the SUAV TRS4 and to investigate the flutter and whirl flutter stability.

The aeroelastic stability study is performed under the worst loading conditions that consists of the sectional wing loads for the flapwise bending and torsion moments from the load analysis by ARGON. The lifting line theory with a finite-state dynamic inflow model is adopted for the aerodynamic loads on the rotor blade.

Finally, the previous load analysis results are used along with the results provided by VABS to recover the local strain components at all points on the wing. The maximum strain criterion is applied for each component in the resulting strain and it is compared with the allowable values for the material. At the same time, a MATLAB-based 3D stress/strain analysis module is applied to consider the structural integrity of the wing. This element computes the internal local 3D strain and stress fields under the worst-case loading condition.

When the cross-sectional analysis, whirl flutter stability analysis, and 3D strain analysis are completed, design constraints such as the locations of the center of gravity and the elastic axis, wing beam mode damping, and the maximum value of 3D strain are obtained. The global process will be continued until the convergence is achieved. The process convergence occurs when the maximum iteration number or the values of the tolerances fixed for the design variables are reached. Finally, the MATLAB optimizer finds the minimum wing section weight while satisfying the design constraints and an aeroelastic analysis is conducted at each design iteration step to predict the air loads and structural loads on the wing precisely for various flight conditions.

It is noteworthy that, for the design optimization study of a composite wing box for the civil tiltrotor transport aircraft, the choice of the constraints can fall into one or more areas such as the structural architecture of the wing box, the structural dynamical behavior or the aeroelastic one. Some alternative constraints could be based on primary natural frequencies and overall buckling strength.

Another interesting composite wing structural optimization framework proposes a two-level approach where the maximization of the flutter speed was selected as scope for the optimization procedure. The XV-15 Tiltrotor was used as an object of the analysis, by changing the structural properties of its wing [4]. In the first level of this optimization process, the response surface methodology (RSM) plays a fundamental role. RSM is a statistical method and through its application, the response of the surface is obtained as polynomials, the orders of which are identical to the number of design variables or inputs used. The advantage of using this empirical method is that the efforts in the aeroelastic and cost calculations are smaller than with the other optimization algorithms. The second-level optimization concerns the determination of the cross-sectional parameters of the composite wing (ply orientation angles and thickness and web positions) to verify the structural integrity of the wing. Also in this case, the estimation is performed by means VABS software and the MATLAB-based 3D stress/strain recovery analysis module [5], whereas the internal forces and moments are predicted by CAMRAD II under the maximum cruise flight speed increased by 10% (330 kts, 612 km/h), to provide a more conservative prediction. Finally, a KARI in-house aeroelastic analysis was carried out to predict flutter stability. Even for this case, for the entire optimization process, a genetic algorithm included in MATLAB Optimization Toolbox is adopted. As final output of the process, a realistic composite wing configuration, compatible with the optimized wing structural properties, was obtained.

In the present work, the preliminary design of the tilt rotor composite wing was performed through a multi-objective evolutionary algorithm (of the genetic type) in which the objectives were the wing structural weight, the strength and buckling margins of safety of the structure and the first elastic frequency. Following the optimization phase, flutter analysis on selected wing configurations on the Pareto front have been executed to verify the aeroelastic stability of the vehicle. The first phase was implemented in Matlab environment using as core code an in-house software (named MultiCella) developed to tackling the preliminary design of fixed wing structures according to design standards used in aeronautics. The in-house code outputs in terms of stiffness, elastic axis and mass distribution fed a FE stick-beam model of the wing which was assembled to the rest of the aircraft model to carry out flutter analysis with Finite element NASTRAN solver.

The huge number of variables affecting the objectives drove the use of an evolutionary approach: use of gradient-based methods is unfeasible (very strong only for local optimizations). To speed up the optimization process and evaluate different design choices, the equivalent laminate theory was applied. The reduction in computational costs using this theory allows to multiply: the load conditions (up to 100 load conditions have been taken into account); the laminates in the material database (up to 17 laminates in the database have been included); the geometrical parameters that can be processed (in terms of thicknesses, cap area and wing sections).

With respect to the previous works, the composite model of the wing was made simpler to set up a more demanding multi-objective evolutionary optimization, to explore extensively the design space.

Whirl flutter stability goes beyond the present work, and it is assessed by the Leader once a model compliant with strength buckling, first elastic frequency and flutter free was provided.

The present work represents the very preliminary step of the wing sizing, further and more refined optimization models (e.g., 2D FEM to be optimized inside OPTISTRUCT) will be part of the subsequent work.

3 Requirements

Being the tiltrotor able to operate as both a helicopter and an aircraft, the airworthiness specifications are both taken from CS-25 and CS-29 Airworthiness Requirements, and in some cases, a tailoring is necessary, with generation of brand-new requirements, specifically for tiltrotors.

The wing-box architecture and rib spacing of the NGCTR-TD comes out mainly from the fuel tanks configuration and fuel capacity requirement. The available internal space is maximized to host fuel bladders, hydraulics, electrical and avionics equipment, the control surface actuators and an interconnect driveshaft which connects together both gearboxes of the tilting mechanism, which runs tip to tip. The outboard end of the main wing box provides the attachments for the proprotor gearbox, engines and nacelle structure. Once the qualification phase will be achieved, the wing will be installed and connected to the fuselage implying flight mechanics requirements to be satisfied.

Dynamic requirements are given as well, like, for example, limitations on the natural frequencies of the wing to grant no coupling between wing modes and FCS and with rotors modes [6–10].

In addition, given the architecture, the wing structural design, in terms of skin and spar web thicknesses and stringers and spar caps areas, has to cope with strength, buckling and stiffness requirements, the latter mainly dictated by aeroelastic requirements, which play a key role in the preliminary design of a tiltrotor, with the lowest possible weight.

Once preliminary sizing has been achieved, higher fidelity models (finite elements models—FEM and digital mock up—DMU) can be set up to verify compliance with all the remaining requirements, such as wing preliminary loads, accessibility, inspectability, assembly and integration and to assess manufacturability.

4 Design Strategy

Based on the above-mentioned requirements, the first design loop is performed by targeting an optimal composite wing structure able to withstand preliminary design loads, and simultaneously with stiffness and inertia distributions leading to a configuration free from flutter within the flight envelope. The outcome from the first design loop is then used to refine the model and compute more reliable flight loads and repeat aeroelastic analysis, returning further requirements to be fulfilled in terms of wing stiffness and inertia distributions. The process is iterated till the fulfilment of all the project requirements.

The structural design, aimed at finding a set of feasible thickness and caps areas compliant with the strength and structural dynamics requirements, with the lowest possible mass, is achieved with a multi-objective optimization, by means of Matlab in-house codes based on classical shear flow formulas in closed thin-walled sections and panel buckling formulas. The advantage of not using finite elements analysis

(FEA) at this stage allows performing optimisation runs in a very short time with an acceptable degree of fidelity.

The multi-objective optimization results in terms of mass and stiffness distributions along span-wise direction are input for the aeroelastic model aimed at assessing flutter stability.

In Fig. 4, the flowchart of the preliminary design strategy is shown.

5 Methodology

5.1 Genetic Algorithm Multi-Objective Optimization Approach

A Multi-Objective Genetic Algorithm optimization was used to optimize the wing-box structure [11]. A flowchart representing an optimization based on genetic algorithms is represented in Fig. 5.

This approach allows the identification of non-dominated optimal solutions that identify a Pareto front [11, 12]. A non-dominated solution set (the Pareto front) is a set of all the solutions that are non-dominated by any member of the solution set. A solution x1 dominates another solution x2, if solution x1 is no worse than x2 in all optimization objectives and solution x1 is strictly better than x2 in at least one optimization objective. On the Pareto front, it is possible to choose a solution that best fit the requirements of the design (performing a posteriori trade-off between non-dominated solutions).

As optimization variables, the thicknesses and areas of the different structural parts (panels and stringers) of the wing box were chosen. Optimization objectives were the wing mass (to be minimized), and the strength and buckling Margin of Safety (MS) (to be maximized). In addition, also the torsional stiffness and the wing stiffness (in terms of the frequency of the first bending normal mode that has to be greater than a certain specified value f1) were calculated to restrict feasible solutions. The optimizer is based on Genetic Algorithm due to its capabilities to explore a huge space constituted by a lot of variables with numerous local maxima and minima.

The optimization objectives together with the stress and stiffness properties of the wing were calculated through an in-house code, written in Matlab language. This code is able to calculate, for a multiple-cell wing-box section, both in metallic and composite material, the following quantities:

- Internal normal and shear stresses.
- Buckling margins of safety: through the comparison between the compression and shear loads acting on the plate elements constituting the wing thin-walled structure and the critical buckling limits. Critical buckling limits were preliminary calculated (to be used inside the optimization process as look-up tables) for the different thicknesses and planar dimensions making use of the first-order shear deformation theory (FSDT) for composites and the Rayleigh–Ritz method to obtain an analytical and approximated solution of the buckling problem.
- Torsional and flexural stiffness (referred to the elastic axis).
- Mass estimation of the modeled structural items (skin, spar, stringer, webs).

  The methodology is implemented according to bending and shear stress analysis of wing from literature [13], and it consists of modeling the wing box by means of concentrated area elements for spar caps and stringers and of skin portions.

  The following input data are needed by the program:

- Semi-wing plan form in terms of leading edge and trailing edge coordinates in a suitable reference frame.
- Aerofoil shape (points) by means of chord-normalized (*x*, *z*) coordinates in a local reference system with the origin in the leading edge and x axis directed along the local chord.
- Connectivity and id of the concentrated elements in the wing-box section.
- Loads characteristics (Shear, Bending and Torque) at each representative B.L. of the semi-wing.
- Wing stations at which the output has to be calculated.
- Material data (density, Elastic and Shear moduli) of each element in the section (caps and panels modeling webs and skins) and at each wing station.
- Panels thickness and caps areas.

As regards material data, if the material is orthotropic (e.g., Carbon Fiber-Reinforced Plastics—CFRP laminate), the properties are inputted as laminate equivalent engineering properties (preliminarily calculated by means of the classical lamination theory—once properties at lamina level and lamination sequences are known).

The output stresses are used to calculate strength and buckling MS: a solution is considered feasible if all strength and buckling MS (both for normal and shear stress) are ≥ 0.

The flowchart of the wing preliminary design optimization process is shown in Fig. 6.

5.2 Aeroelastic Model

The aeroelastic model developed to assess the aeroelastic stability of the model, a mandatory requirement for the preliminary design of wing and movable surfaces, is shown in Fig. 7.

The structural part of the model consists of different components: wing, movable surfaces, fuselage, nacelles, tail and wing to fuselage junction. Furthermore, the structural model is a hybrid model: in fact, wing and movable surfaces are represented by a stick-beam model; while all the other components (e.g., fuselage, t-shape tail will be updated, nacelles),

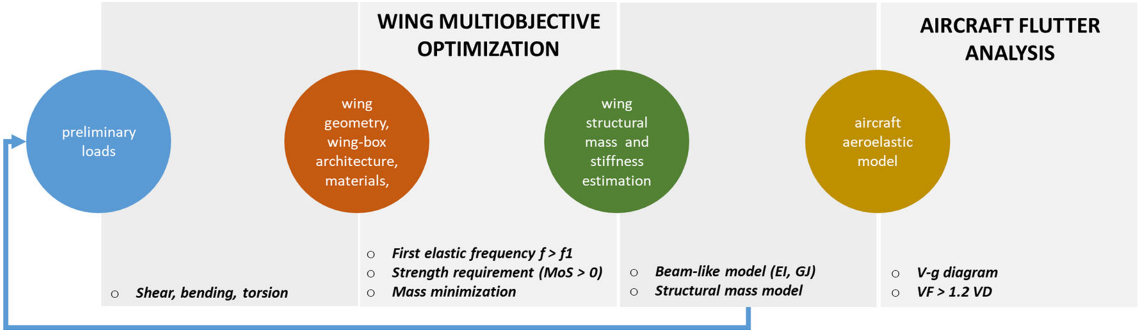


Fig. 4 NGCTR-TD wing preliminary design flowchart

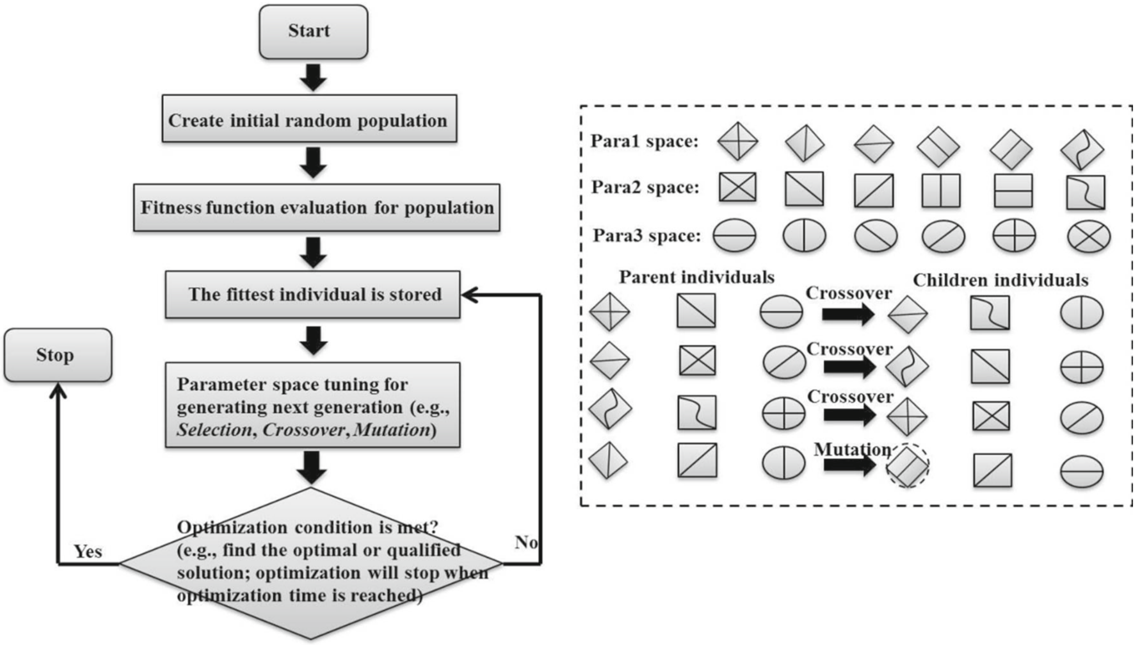


Fig. 5 Genetic algorithm optimization flowchart [13]

whose development is not in the scope of the project, are represented by Nastran super-elements and provided by the WAL.

As aforementioned, the wing is setup with beam elements for main wing and movable surfaces, which are connected to the fixed part of the airframe by means of suitable stiffness connections (concentrated springs). The beam stiffness properties are output of the structural design optimization process.

The wing mass model encompasses concentrated masses which are distributed along the wing span-wise direction and represent the following components:

- Wing structure mass (which is an output of the structural design optimization process).
- Fuel mass.
- Systems mass, like:
  - Fuel systems.
  - Interconnect driveshaft.
  - Hydraulics.
  - Cables.
  - Actuators.

The aerodynamic model is based on the Doublet Lattice Method (DLM) [14, 15]. The aerodynamic mesh is spread over the wing and the tail surfaces, represented by flat panels. Fuselage and nacelles are modeled with slender bodies and interference elements.

The matching between dynamic model and aerodynamic model has been implemented by the use of Infinite Plate Splines (IPS) [16, 17].

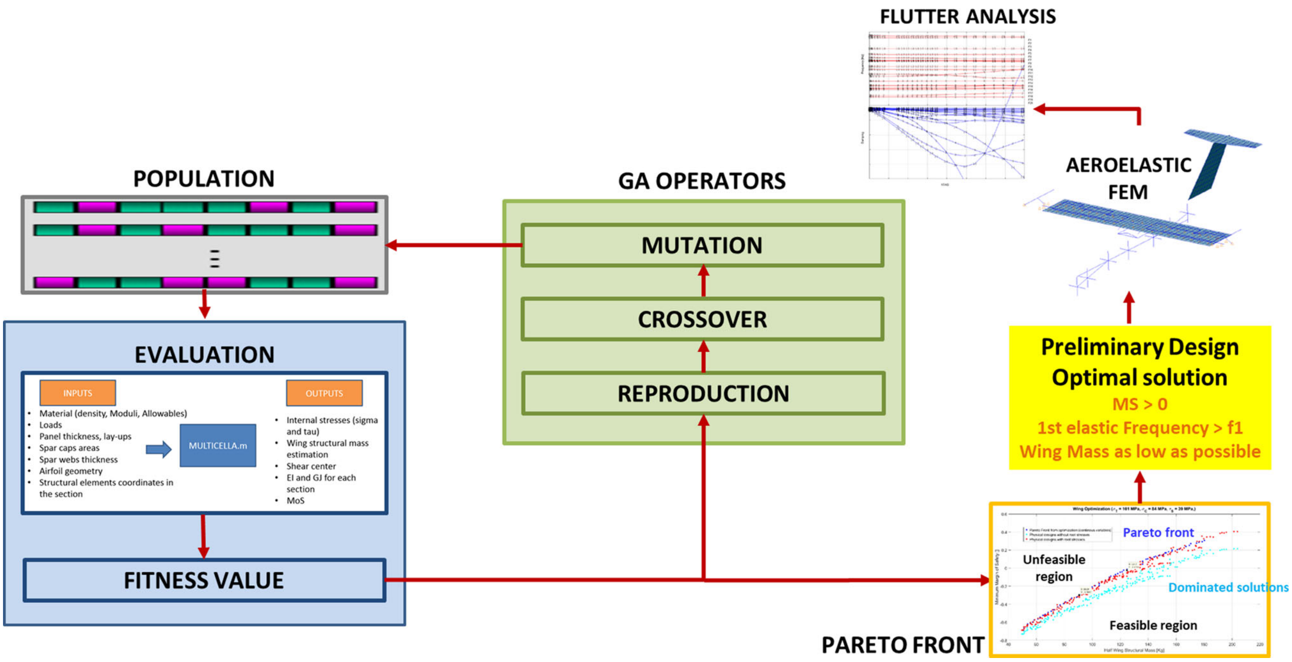


Fig. 6 NGCTR-TD wing preliminary design optimization flowchart

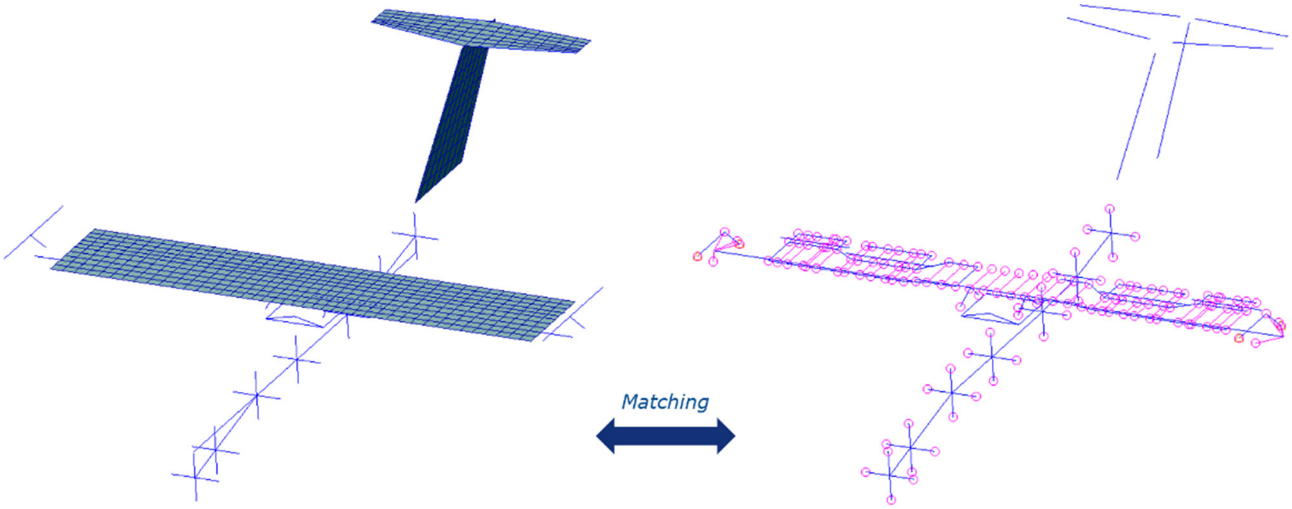


Fig. 7 Aeroelastic model

6 Results of the Optimization Process

As mentioned in Sect. 5.1, the output of the multi-objective optimization is the Pareto front. Some of these Pareto front (calculated for different input load sets) are shown in Fig. 8 together with their near points, to have the possibility to explore also similar solutions that can be better from a manufacturing point of view.

Each point of the plot represents a possible wing box, with its structural mass and MS.

Figure 9 highlights the performances of the multi-objective optimization, showning the ratio between a feasible solution on the Pareto front with MS near or equal to 0 from the beginning to the end of the optimization process: a mass enhancement of about 30% is produced by the algorithm.

The wing was subdivided in different zones whose thicknesses can be varied by the algorithm. The ensemble of the different thickness values builds up a wing configuration: these values evolve during the optimization progression toward the best solution. Figure 10 shows how the optimization variables (represented as the ratio between the current thickness and the maximum possible thickness for all the wing zones) evolve during this optimization process.

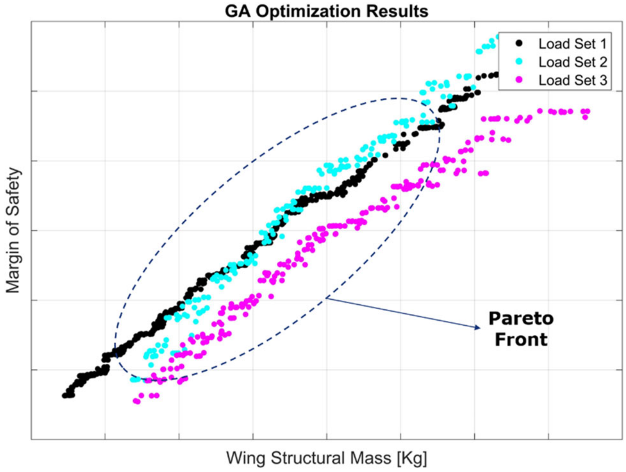


Fig. 8 Pareto front

As represented in Fig. 11, one of these optimal solutions is chosen to be further analyzed. More refined techniques, like Finite Element Modeling, are then used to refine the wing box and for further weight improvement of the structure.

7 Results of Flutter Analyses

After the FEM refinement aimed to a weight improvement of the structure, the optimal wing-box solution mentioned in the previous paragraph is implemented in the full aeroelastic model to assess the aeroelastic stability of the selected configuration [18–21].

As shown in Figs. 12 and 13, the V–g diagrams, output of the aeroelastic analysis performed for both the mass cases considered in this phase of the design (Full Fuel and Zero Fuel), demonstrate that the identified solution is free from flutter inside the envelope (1.15 times the Dive Speed, VD).

From the above-mentioned diagrams, it is possible to appreciate different flutter mechanisms, all of them involving mainly the tail-related modes, and not at dangerous speeds.

Thus, being verified the aeroelastic stability of the wing (moveable surfaces NOT modeled in this phase of the project), the analyzed configuration is considered as a valid and acceptable configuration, allowing to proceed to the following loops of the design.

8 Conclusions

In this paper, the main steps followed to achieve the composite wing preliminary sizing of the NGCTR-TD tiltrotor are presented. Being tiltrotor a peculiar vehicle, able to operate as both a helicopter and an aircraft, the airworthiness specifications are taken from CS-25 and CS-29 Airworthiness Requirements, and in some cases, a tailoring is necessary, with generation of brand-new requirements, specifically for tiltrotors.

The wing-box architecture and rib spacing of the NGCTR-TD come out mainly from the fuel tanks configuration and from the requirement to host an interconnect driveshaft (tip to tip) which connects together both gearboxes of the tilting mechanism. Dynamic requirements (for example, limitations on the natural frequencies of the wing) and aeroelastic requirements are also taken into account from the very preliminary stage of design.

The paper has shown the results obtained within the first design loop, which was aimed at targeting an optimal wing structure able to withstand preliminary design loads, and simultaneously with stiffness and inertia distributions lead-

Fig. 9 Enhancement of optimization goals during the optimization algorithm iterations

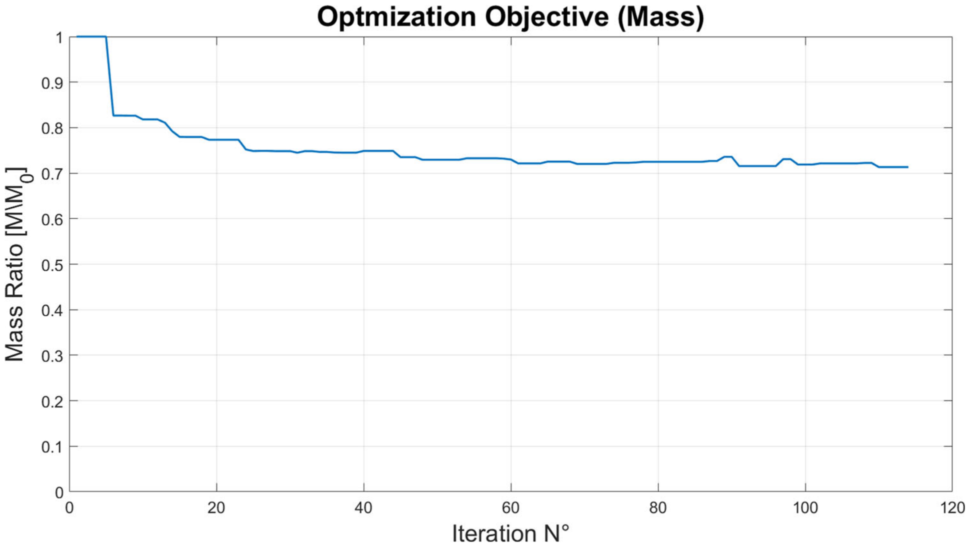
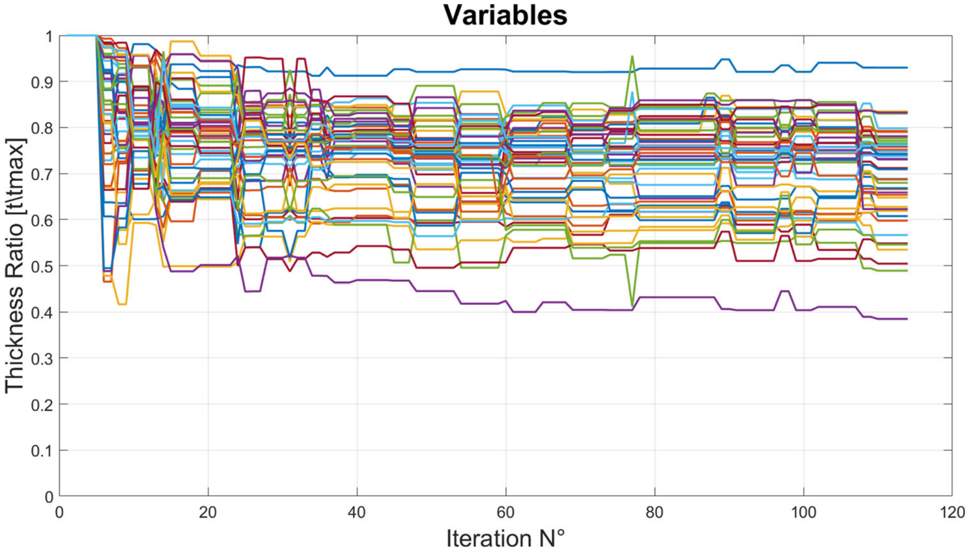


Fig. 10 Evolution of optimization variables during the optimization algorithm iterations



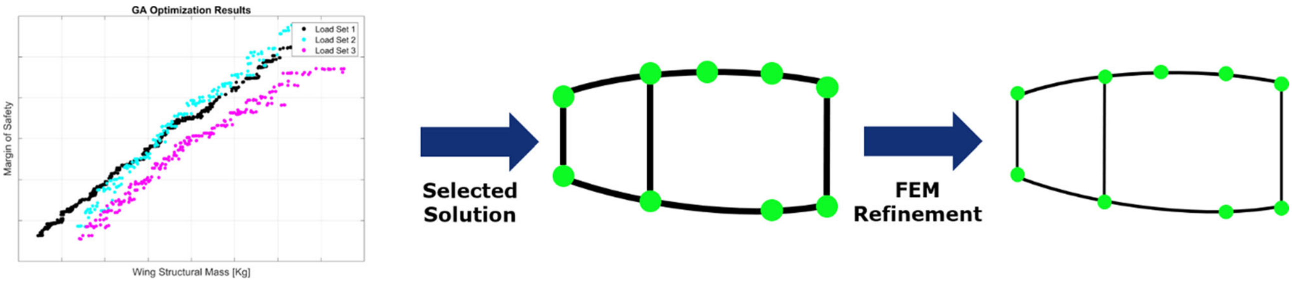
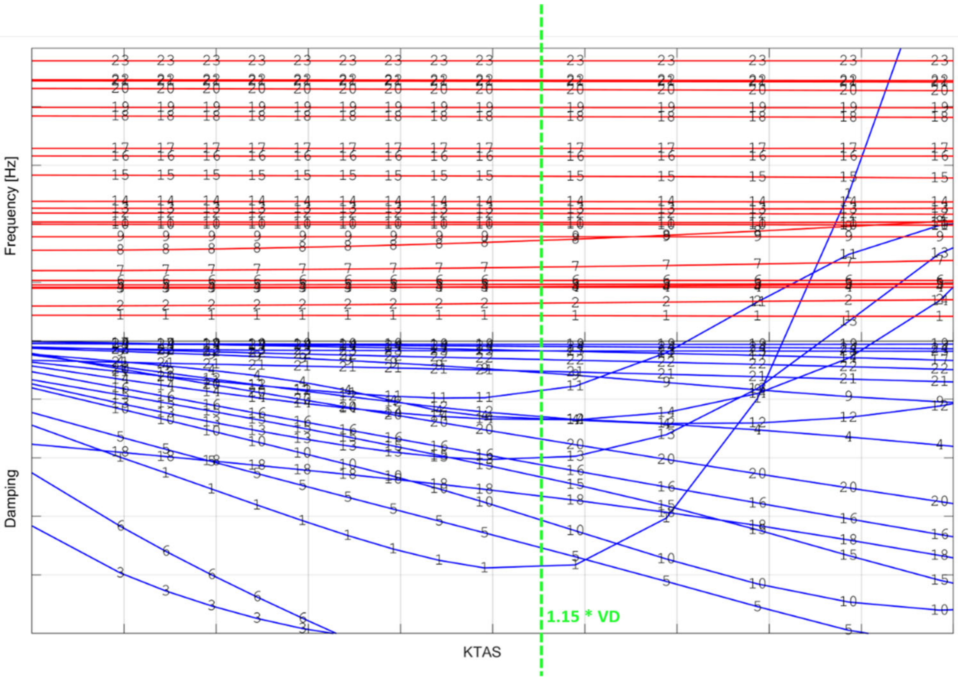


Fig. 11 Optimal solution identification work-flow

Fig. 12 V–g diagram: full-fuel case



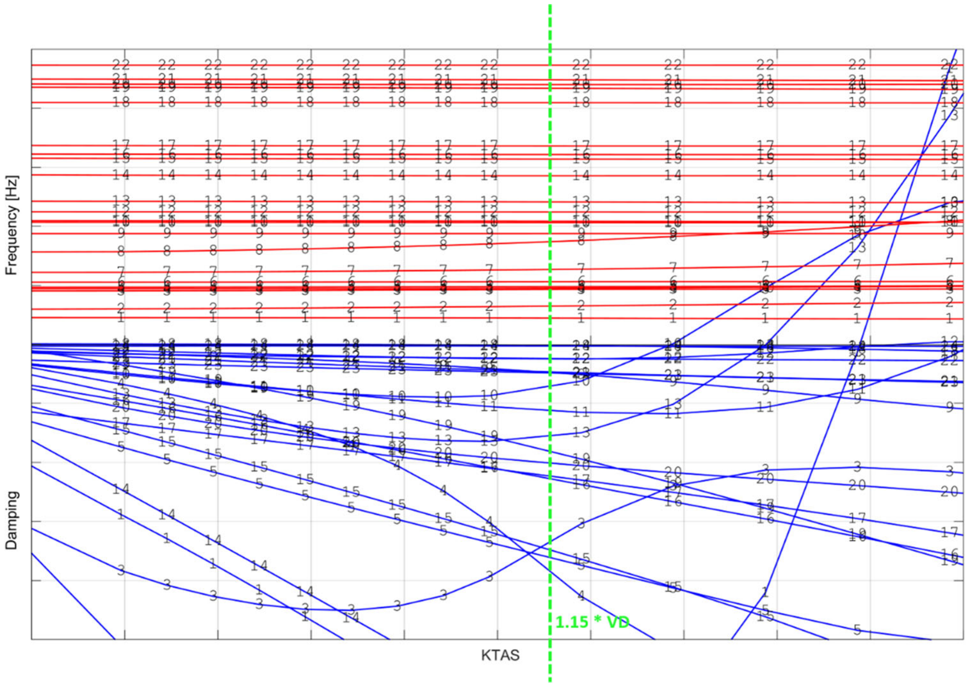


Fig. 13 V–g diagram: zero-fuel case

ing to a configuration free from flutter within the flight envelope.

A Multi-Objective Genetic Algorithm optimization was set up by means of in-house codes, written in Matlab, to find the optimal solution (wing-box skin/ web thicknesses and spar caps areas) which minimizes the mass and maximize the MS at strength and buckling, by also taking into account frequency boundary requirements. The optimal solution was then analyzed from flutter point of view.

It was shown that, provided the wing architecture is given due to functional requirements, a wing-box solution at minimum mass which is also flutter free in the flight envelope was found.

The next steps will be aimed at assessing whirl flutter stability and at refining the model and computing more reliable flight loads and repeat aeroelastic analysis, returning further requirements to be fulfilled in terms of wing stiffness and inertia distributions. The process will be iterated till the fulfilment of all the project requirements. After iterations will be complete, all the results in terms of wing-box sizing will be transferred into higher fidelity models (FEM and DMU) to verify compliance with all the remaining requirements, such as wing preliminary loads, accessibility, inspect ability, assembly and integration and to assess manufacturability.

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