33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

Wing Loading Process in Knowledge-Based Aircraft Design and Optimization Framework

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Abstract

An automated wing loading process is developed to be used in a multi-fidelity knowledge-based aircraft design framework. The overall process includes the development of load cases based on flight envelope, load analysis, load distribution, load discretization, and load filtration. The developed process is capable of load analysis of novel truss-braced aircraft with novel wing configuration, where it is not possible to apply textbook methods. This process contains hundreds of load cases, investigated and processed in a very short time, and the critical cases are identified and exported for wing sizing and aircraft optimization process.

Keywords: Wing; Loading; Design Framework; Truss-Braced Wing; Aircraft Design.

1. Introduction

As aircraft technology has evolved and longer ranges are achieved with lower fuel consumption, new environmental goals have been set by the top-level organizations to be met in 2030, and more ambitious goals are targeted to be achieved in 2050. To this aim, in 2011 the Advisory Council for Aeronautics Research in Europe targeted a 75% reduction in CO2, a 90% reduction in NOx and, a 65% reduction in noise for 2050 [1].

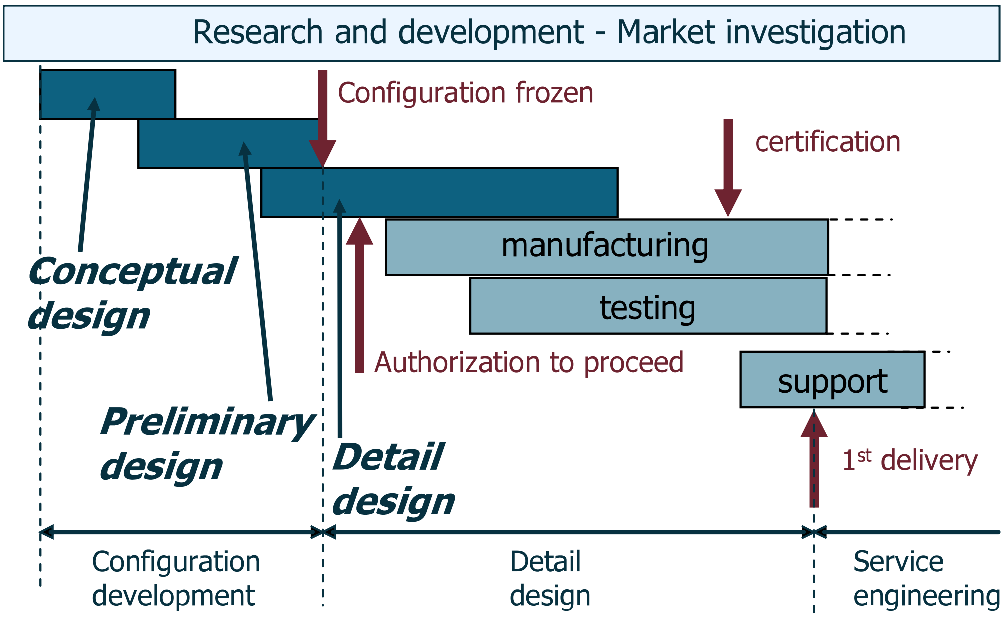


Figure 1 - Conventional design process

1.1 Background

For many decades, almost all the aircraft that succeeded in the market were designed with the "tube & wing" configuration; while equipped with under-wing or aft-fuselage mounted engines. To achieve the highest level of efficiency, this configuration has been evolved and optimized up to a point, which seems that more radical changes in the configuration are required to achieve the targeted performance goals [2]. There are many configurations that have been investigated in recent years to find the most promising one for future transport aircraft, such as Blended Wing Body [3], Boundary Layer Ingestion [4], Turbo-Electric Propulsion [5], and Truss-Braced Wings (TBW) [6].

In the conceptual design phase (Figure 1), many different aircraft configurations are investigated. In this design phase, the configuration is so fluid that even topology of the aircraft is allowed to change. For this reason, and in order to keep this agility and flexibility affordable, the fidelity of the aerodynamics and structural analysis tools are kept low. Furthermore, the details that are considered in this phase is limited [7]. But with the new requirements and considering the cost of aircraft development, it’s important to develop tool and methods which are capable of design and optimization of aircraft with high-fidelity methods, even at the conceptual design phase.

1.2 Challenge

The general workflow for the evaluation of the configurations and conducting the MDO (Multi-disciplinary Optimization) is presented in Figure 2. The process starts with the development of the configuration, weight, followed by the aircraft sizing and design of aircraft layout. In the next step, the aircraft aerodynamic characteristics and weight breakdown are estimated. The aircraft performance is analyzed, and data are fed back to the aircraft sizing step, and the process is repeated until the solution is converged. At the final step, the aircraft life-cycle cost, including the operating costs, are estimated. The weight includes structure, system, powerplant, fuel and payload weight. The structure weight estimation in novel configuration can be challenging as no previous design exists, and empirical methods can not be used.

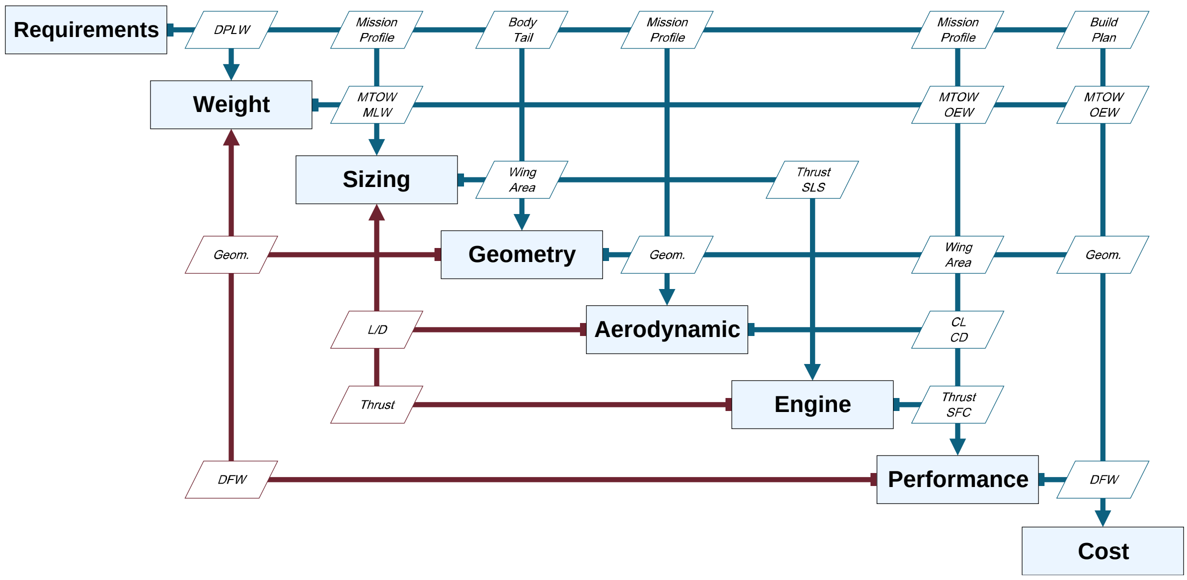


Figure 2 - General process for development and analysis of the aircraft [18]

The methods which are available for the calculation of weight can be categorized in three types [8]:

1. Empirical Methods: These methods employ available aircraft weights breakdown and link them to the aircraft layout, material, and the flight mission [9]. These equations are widely used for the design of conventional aircraft, where the database is rich.
2. Analytical Methods: In these type of methods, the structural loads are calculated by theoretical and engineering methods, and the wing structure at each station is sized for strength, stiffness, stability, and durability criteria [10].
3. Numerical Methods: A finite element model, either beam elements or shell elements, is created, and the loads from each load case are applied, and the element thicknesses and cross-sections are sized based on those requirements [11].

1.3 Approach

With current advances in the computers and computation parallelization, more researches are focused toward the application of high-fidelity methods for the calculation of weight [12]. For this reason, a module should be available in the optimization process that is able to define the load cases, calculate the loads, and distribute the loads for the Finite Element Analysis (FEA) accurately and fast enough, to make the optimization process feasible. In this process, a code dedicated to the calculations of load is developed and integrated in the design framework. This module will develop the required loads for the FEA based on user inputs and design requirements, and will pass the result to sizing module.

1.4 Literature

In many of design optimization tools, analytical methods for the loads are used to improve the speed of the design, and making the implementation possible in a spreadsheet software [10]. In these methods, the few load cases are defined, and for each of them, the aircraft trimmed using stability and controllability derivatives, and then the load is distributed using analytical methods. These methods are fast, but on the other hand, many of the design features are lost, especially for novel configurations.

High-Fidelity Computational Fluid Dynamics (CFD) analysis was used to calculate the aerodynamic loads in the estimation of wing weight [12]. This method provides accurate aerodynamic loads both chord-wise and span-wise and it can predict the compressibility effects. On the other hand, its application is limited to few load cases due to the extremely high computational time demands. For this reason, in this approach, few load cases are only investigated.

Vortex Lattice Method (VLM) and Doubled Lattice Method (DLM) are used for the calculations of load [13, 14], as they provide enough accurate results for subsonic and low-sweep wings. It is possible to develop a DLM or VLM codes, or existing codes, like Athena Vortex Lattice (AVL) [15] or Nastran [16] can be used. Furthermore, panel methods can be used instead of DLM and VLM, which provide more accurate results, but with higher computational and preparation time [17].

1.5 Contribution

As can be seen, and up the knowledge of authors all above mentioned methods use one method to estimate the loads, and there is no option to select the load method based on fidelity of the method. For this reason, it is found that there should be a tool that make use of existing tools, and develop the loads for hundreds of load cases in a short time. To this aim, an automated wing loading process is developed to be used in a multi-fidelity knowledge-based aircraft design framework. In order to make this aircraft design framework adequate enough for future unconventional configurations, high-fidelity methods should be usable alongside low-fidelity methods in the conceptual design of the aircraft.

This code is implemented in MATLAB, and interact with existing and validated tools for geometrical data and aerodynamic distribution. The application of existing tools, increase the reliability of the code, however, the interface with these tools should be developed. The developed code is capable of calculating hundreds of load cases in just few minutes with the conventional home computers.

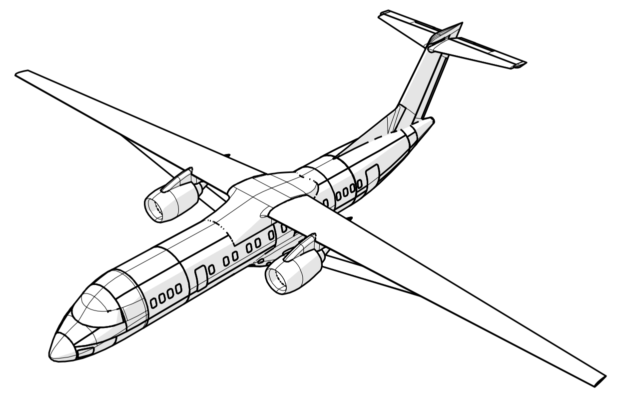
1.6 Outline

In section 2, the characteristics of the target aircraft, which the develop load process is applied to, is presented. In section 3, the load pre-processing activities such as development of load envelopes and extraction of load cases are presented. In section 4, the methodology for the calculations of aerodynamic loads is presented. In section 5, the post-processing of loads, including discretization of fuel loads, weight loads, and aerodynamic loads and preparing the loads for FEA is presented.

2. Target Aircraft

The developed method is applied to a novel turbofan-powered truss-braced wing regional aircraft. The aircraft under-investigation has a capacity of 72 passengers and has a range of 2300 km. The cruise altitude is 20000 ft, and the cruise speed is 570 km/h (True Air Speed). Aircraft is partly a conventional tube-and-wing aircraft, with a 4-abreast tube-shaped fuselage, high-mounted very high aspect ratio wings braced with struts, T-tails, and two under-wing mounted turbofan engines. The overall view of the aircraft is presented in Table 1. The design specification and features of this aircraft is presented in [18].

Table 1 - General specifications of the aircraft

Parameter	Unit	Value	Layout
Maximum Take-Off Weight	kg	28740	
Operational Empty Weight	kg	17410	
Number of Passengers	-	72	
Design Payload Weight	kg	6480	
Maximum Payload Weight	kg	7000	
Design Fuel Weight	kg	4850	
Range	Km	2300	
Wing Area	m^2	69.3	
Aspect Ratio	-	20.0	
Thrust at Take-Off Sea-Level	lbf	2 x 12020	
SFC at Cruise	lb/hr/lbf	0.546	
Airfoil Thickness Ratio	%	15%	
Airfoil Camber Ratio	-	2.8	

3. Load Pre-Processing

At the beginning, and based on overall design requirements, a comprehensive list of load cases is generated. To this aim, maneuver and gust loads are developed with the aid of load and gust envelopes. In addition, other type of load cases, such as roll, landing, and taxi loads are considered. To this aim, the variation of weight, center of gravity, altitudes, Mach numbers, and throttle values are considered.

To find the critical load cases, the load envelopes are generated, and the corner points will be passed for the analysis. The load envelopes are created based on Part 25 requirements [19]. To this aim, three types of envelopes are created: clean configuration, flap configuration, and gust envelope.

3.1 Clean Envelope

The user provides with the V_C and M_C , and the V_D and M_D are calculated based on the minimum requirements, see equation (1). It's possible to define the dive velocities explicitly to be more than the requirement.

$$\begin{gathered} V_D \geq V_C / 0.8 \\ M_D \geq M_D / 0.8 \end{gathered} \tag{1}$$

Based on the aircraft maximum take-off weight (W_{TO}), the maximum positive load factor is computed:

$$2.5 \leq 2.1 + \frac{24,000}{W_{TO}[lb] + 10,000} \leq n \leq 3.8 \tag{2}$$

A typical result of the clean envelope is presented in Figure 3A.

3.2 Flap Envelope

For each flap configuration (landing and take-off), the maximum speed and maximum load factor is different from the clean configuration. The maximum load factor for all flap configuration is constant:

$$n = 2.0 \tag{3}$$

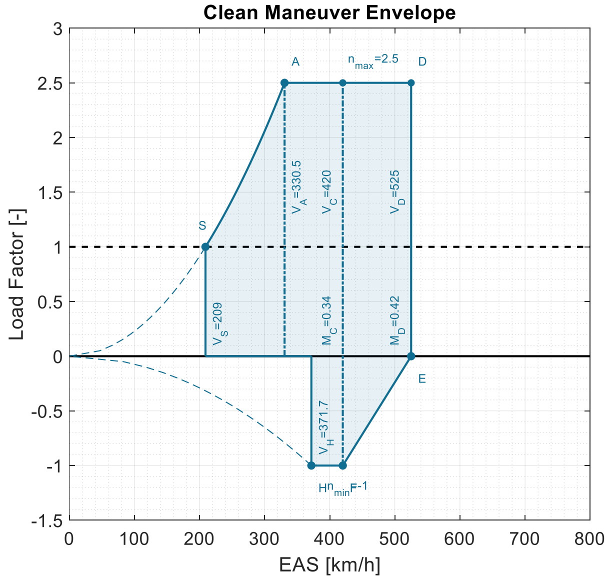
The maximum speed for take-off configuration is calculated from:

$$V_F\big|_{Take-Off} = 1.6\ V_{S1} \tag{4}$$

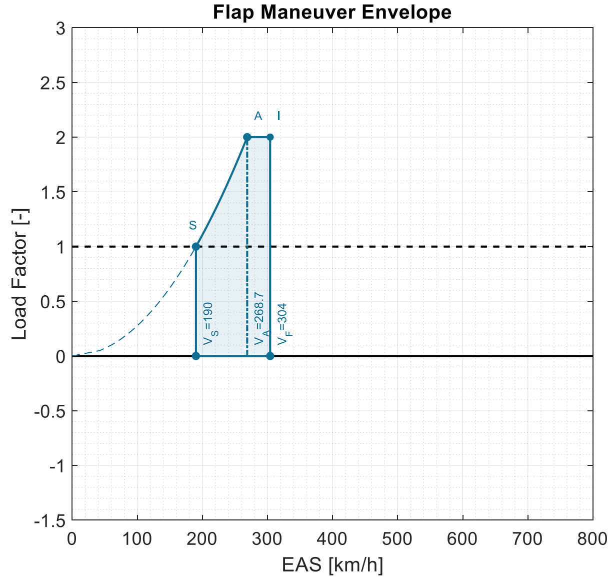
In which, V_{S1} is the stall speed at the maximum take-off weight and configuration. For landing configuration is calculated from:

$$V_F\big|_{Landing} = 1.8\ V_{S0} \tag{5}$$

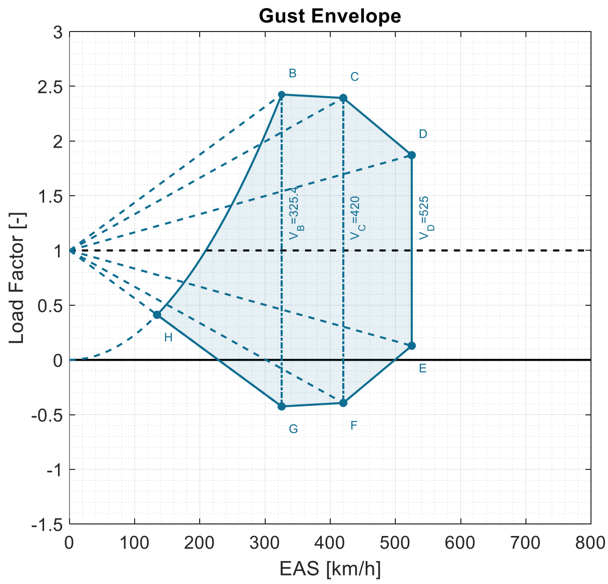
In which, V_{S0} is the stall speed at maximum landing weight and configuration. A typical result of the flap envelope is presented in Figure 3B.



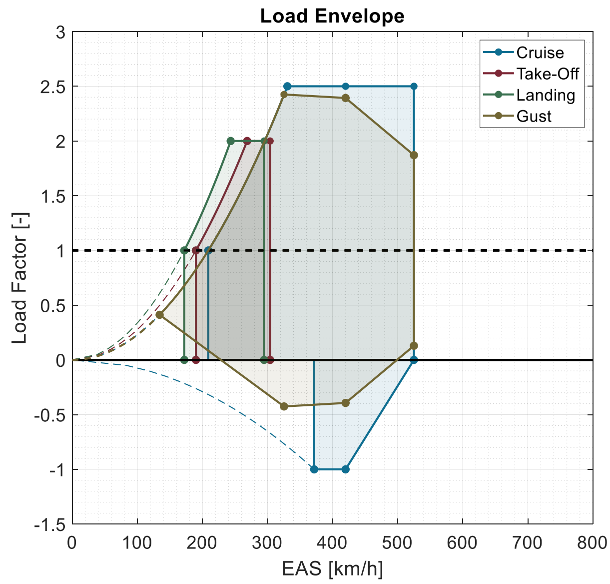
A) Clean configuration



B) Flap configuration



C) Gust loads



D) Combined load envelopes

Figure 3 – Load envelopes

3.3 Gust Envelop

For the calculation of gust loads, the load factor can be calculated from:

$$n = 1 \pm \frac{K_g U_{de} V C_{L_\alpha}}{498 W/S} \tag{6}$$

In which alleviation factor K_g is calculated from:

$$K_g = \frac{0.88\mu}{5.3+\mu} \tag{7}$$

Where:

$$\mu = \frac{2W/S}{g\bar{c}\rho C_{L_\alpha}} \tag{8}$$

The above load factors are calculated at each of V_B, V_C, and V_D. The calculated flight envelope is presented in Figure 3C.

3.4 Combined Envelope

To find the critical points, all flight envelopes are plotted in single plots, and the critical points can be found. The resultant is presented in Figure 3D.

3.5 Effect of Weight

The value of gust load factors is dependent to the weight under consideration. For this reason, it's important to consider the aircraft weight from empty operating weight (OEW) to maximum take-off weight (MTOW), Figure 4 left. In addition to this, for each load case the most forward and rearward center of gravity (CG) locations are considered. The CG limitations at each weight is extract from the CG limit plot, which is presented in Figure 4 right.

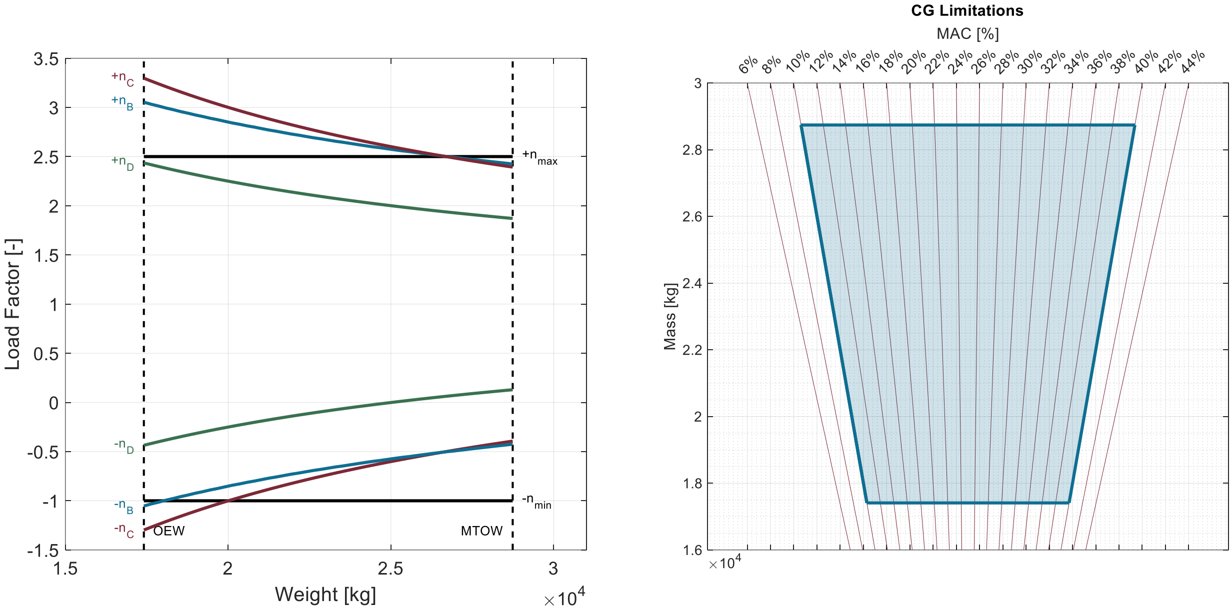


Figure 4 – Effect of weight on load factor and CG limitations

3.6 Effect of Altitude

As the altitude increases, the limiting velocity may become the Mach number instead of the Equivalent Air Speed (EAS). For this reason, the effect of altitude on the load factors are investigated, and the corner points are extracted, see Figure 5 left.

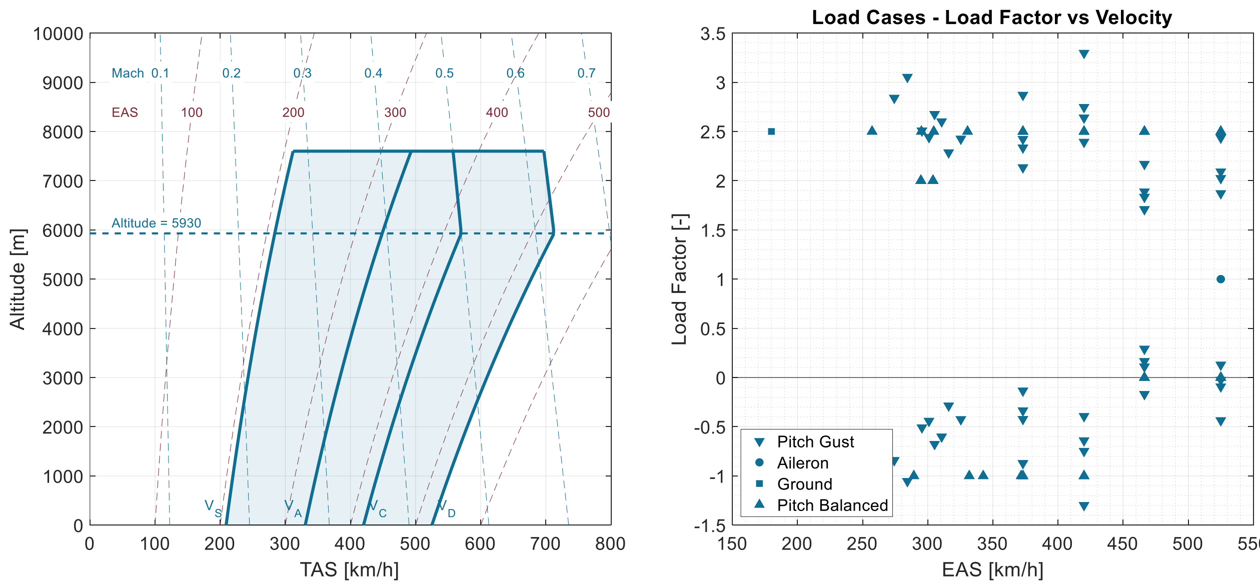


Figure 5 - Variation of load factor due to altitude and total load cases

3.7 Ground Loads

For the ground load, a single load case with positive load factor is assumed to represent the loads applied to aircraft during landing.

3.8 Aileron Loads

Two load cases representing the aileron load cases are considered. One for full upward deflection and the other for full downward deflection.

3.9 Load Cases

Based on above-mentioned, the total number of load cases will be as following:

1. Weight: 4 values at MTOW, Maximum Zero-Fuel Weight (MZFW), Maximum Zero-Payload Weight (MZPW), and Operating Empty Weight (OEW),
2. Altitude: 3 values at sea-level, break altitude, and maximum altitude,
3. In total 12 flight envelopes will be generated. It may be mentioned the reason that clean and gust load cases are considered separately, is that the elevator deflections in gust load factors are zero, while for the clean should be computed from trim analysis. Each flight envelope will have following load cases, which in total will be 14:
    a. Clean: 6 load cases at positive and negative loads at stall, cruise, and dive speed,
    b. Flap: each configuration 1 load case, at maximum load factor at the maximum speed. Since there are two flap configurations, the total cases will be 2.
    c. Gust: 6 load cases at positive and negative loads at stall, cruise, and dive speed,
4. Center of gravity: at each generated load case, 2 values at most forward and most aft CG location,
5. Throttle: 2 values, maximum and idle,
6. The total envelope load cases will be $12 \times 14 \times 2 \times 2 = 672$,
7. Two load cases for aileron and one load case for ground loads are added, and it will become: 675 load cases.

The load factor and EAS of all considered load cases are presented in Figure 5 right.

4. Load Processing

For each load cases, the aircraft states and required condition for trimming the aircraft is computed using AVL [20]. This tool, provide the capability of running a larger number load cases within short time. The loads are calculated at Load Reference Line (LRA), and later, the loads will be applied to points on this hypothetical line, and these points will be connected using interpolation elements to the wing structure.

5. Load Post-Processing

5.1 Load Extraction

The aerodynamic force and moments distribution are imported from the AVL results into MATLAB, and after transformation to the appropriate coordinate system, the aerodynamic force at each structural segment is computed. This has been achieved by developing a package in MATLAB, which is able to process AVL input model, and computed results. At each chord-wise strip, the lift and moment coefficient are extracted from the result file. These data are raw data and should be processed before application for wing sizing.

5.2 Load Discretization

The calculated loads from AVL are calculated at span-wise sections that essentially are not the same as structural section. It was possible to have the AVL sections exactly at the same locations as the structure model, but it was decided to make them independent, as there are different requirements for defining AVL and structure sections. For this reason, the data calculated from AVL should be converted to points which match the structural section.

The structural segments geometry is extracted from an automated CAD model in CATIA. The CAD model provide the required geometrical data for each wing segment, i.e., chord, area, center of volume, and fuel volume. Wing segments are developed based on the ribs and spar arrangement, and by changing the wing planform, the structure architecture is updated accordingly. Component Object Model (COM) connection is used to establish a two-way communication with CATIA, and in this process, the data for each segment can be extracted.

Based on the weight configuration, the fuel weight in each is computed and is added to the weight discretized model. In addition to that, the wing empty weight, which consists of structural and systems weight, are discretized along the sections. It should be mentioned that these distributions are the result of optimization process, and the results of the load-carrying structures sizing combined with empirical method (to calculate the weight of secondary structures) are used to calculate the weight at each station.

The empty weight consists of two types of weights: distributed weight (in terms kg/m), and discrete weight (kg). Their loads are treated separately. The discrete loads are applied to the nearest inboard rib section. The most important item of this category is the engine weight. The structural weights and fuels weight are of distributed type. The distributed and discretized loads for a single case are presented in Figure 6.

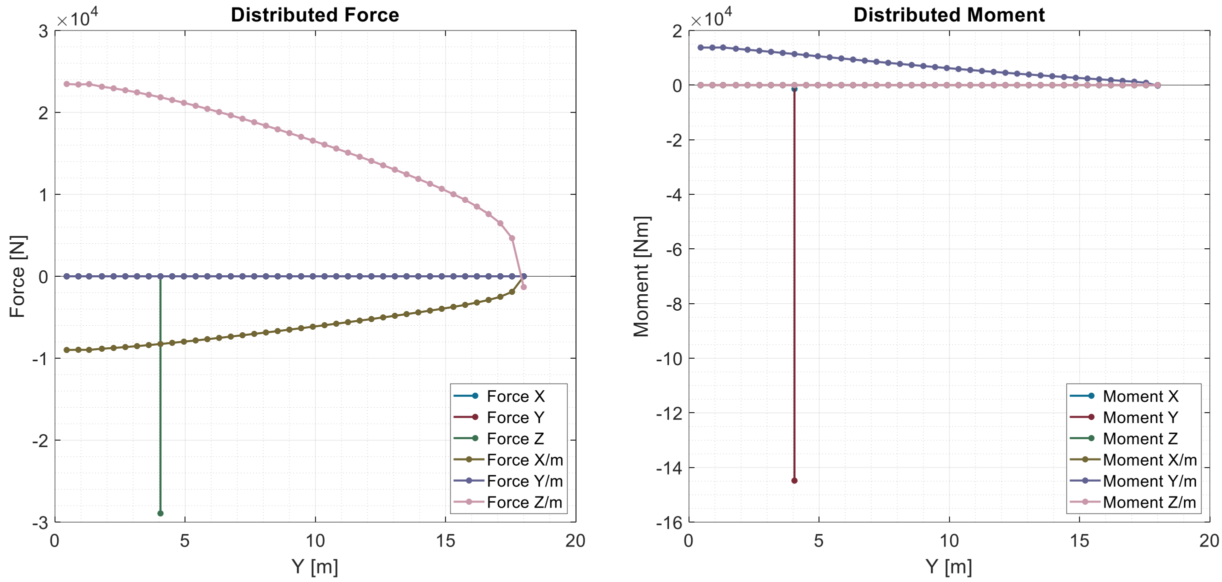


Figure 6 - Distributed loads, discrete loads are presented by vertical lines

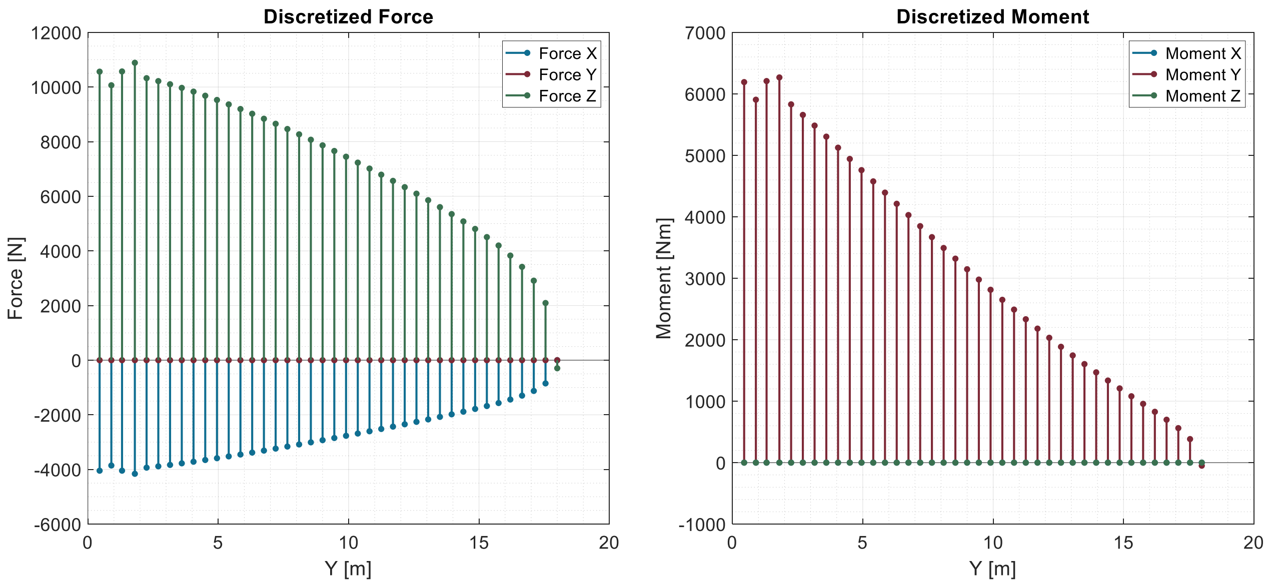


Figure 7 - Point loads at single load case

The discrete and distributed weights are added to fuel weight and aerodynamic loads, and based on the extracted geometry, the point loads that should be applied to each point is calculated. These point loads then will be applied to the FEA model for sizing purpose. These points loads are expressed in 6 directions: F_X, F_Y, F_Z, M_X, M_Y, and M_Z. The point loads for single load case are presented in Figure 7.

Because of the configuration in the truss-braced wing is not in the form of cantilever one, it is not accurate to use the accumulated loads for sizing of each wing section, as presented in classical textbooks [21]. This is due to the effect of truss and its connection point to the wing.

5.3 Load Filtration

Since the calculated loads will be used in a wing sizing and optimization process, it's important to consider only those load cases that are critical for the wing sizing.

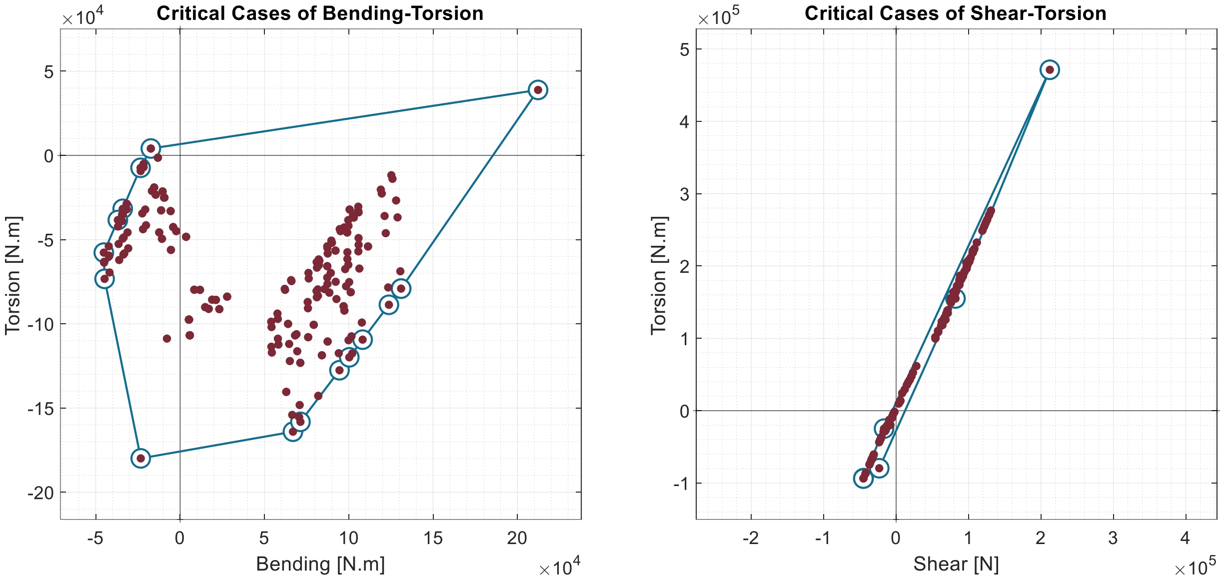


Figure 8 – Critical load cases

There are two ways to accomplish this aim:

1. 1-D approach: In this approach at each point, and at each load case, if one of the load components are maximum or minimum, that case would be assumed critical.
2. 2-D approach: In this approach, at each section, the combination of load components ($F_Z - M_Y$, $F_Z - M_X$, and $M_X - M_Y$) are plotted in 2-D plot, and a convex hull is created surrounding these points, and all points on the boundary of this hull, will be assumed critical.

The 2-D approach is more accurate, as it is possible there are load cases that none of single components are maximum, but the combination of its components makes it critical. For this reason, the second approach was used for this research.

To this aim, the critical load cases for each wing section is extracted by using two-dimensional load envelopes at that section. The critical points (points on the boundary of the hull) are added to the list of sizing load cases. The critical load cases are presented in Figure 8.

At the end of this process, the points load for each critical load case is exported to files, so the FEA modeler can read them, and prepares the sizing cases.

6. Summary

A method for the calculation of novel configurations loading during preliminary design and optimization phase based on high-fidelity CAD and mid-fidelity aerodynamics is presented. This method is capable of generating the combination of load cases considering variations in weight, altitude, throttle, and center of gravity. In addition, aileron and ground load cases, which are critical for truss-braced wings are included. The weight and fuel load distribution are extracted from the CAD model with an automation interface, and aerodynamic load distribution are calculated using a VLM tool. The distributed load is discretized over loading points of the model, and components of load are calculated. The critical load cases are filtered using 2-D envelope of loads at each section, and are exported for the sizing process. This method, which has the flexibility to be applied to novel and conventional configurations, was able to extract the loads for a regional truss-braced aircraft within few minutes, which make it a suitable tool for the application in MDO.

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8. Copyright Statement

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