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Effect of improved flight and control loads modelling on wing-box preliminary sizing

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The proposed approach in this paper aims to bring the accuracy of CFD to quick linear aeroelastic simulations for structural sizing. This is achieved by deriving reduced-order models (ROM) of the aircraft movables, gust loads and manoeuvres loads from rigid CFD analysis and to use these as substitutes for the loads in the aeroelastic simulation. The corrected loads can then be incorporated into the wing-box sizing process which relies on a gradient-based optimizer that will eventually determine the optimal stiffness and thickness distribution of the wing structure.

Keywords: aeroelasticity, structural sizing, gust loads, control surfaces, aerodynamic characterisation

1. Introduction

The quest to reduce fuel consumption has led the aircraft industry to develop new strategies to decrease aero-structures weight. In order to do so, the wing box can be made of composite materials and control surfaces used for active load alleviation. However, the actual weight saving may only be evaluated once the airframe is sized for the large number of load cases it will have to withstand during service life. The final design will also need to comply with the multiple requirements for flight performances, safety and handling qualities.

To cover all possible flow regimes, the sizing process is greatly based on loads computed at several flight points. It mostly relies on panel codes (doublet lattice, vortex lattice etc.) as they are relatively accurate and yet very fast. However, they are limited to linear flow conditions, and transonic shock or flow separation can’t be simulated with such methods. Moreover, the load alleviation and manoeuvring capabilities of control surfaces will also be inaccurate. This means that a great part of the sizing load cases for a regular passenger aircraft can’t be approximated with satisfying accuracy, leading to over-conservative load assumptions and generally heavier design. On the other hand, computational fluid dynamic with Reynolds averaged Navier-Stokes (CFD-RANS) analysis, is capable of approximating flight loads under transonic and detached flow regime with higher fidelity. The computational time required for such simulations is nevertheless too long to be efficiently included in the sizing process of the airframe and is usually restricted to validation purposes only.

The proposed approach in this paper aims to bring the accuracy of CFD to quick linear aeroelastic simulations. This is achieved by deriving reduced-order models (ROM) of the aircraft movables, gust loads and manoeuvres loads from rigid CFD analysis and to use these as substitutes for the loads in the

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aeroelastic simulation. The goal of this methodology is to remain non-intrusive, and easily compatible with commercial analysis and optimisation tool such as NASTRAN. Building a fast aerodynamic model of the control surfaces also allows for quick control optimisation, in order to evaluate their load alleviation potential which can also impact the sizing of the wing box. The corrected loads can then be incorporated into the wing-box sizing process which relies on a gradient-based optimizer that will eventually determine the optimal stiffness and thickness distribution of the wing structure. Although only one configuration is evaluated in the present work, the methodology developed here aims to facilitate the wing layout design process.

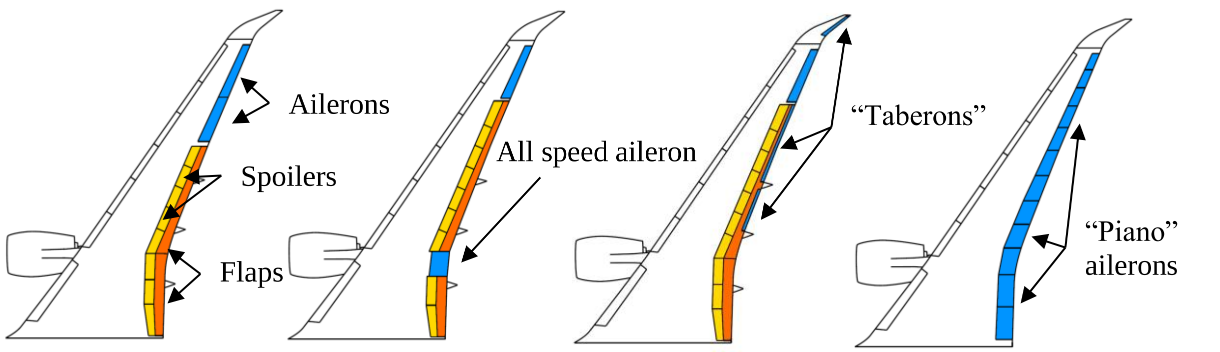

Figure 1: Various wing layouts to be considered for a new aircraft. This illustration is inspired by [1].

2. Methodology

a. Dynamic loads

Today, the wing box optimisation strategy relies on the use of gradient-based algorithms. A gradient-based optimizer has the advantage to easily handle a great number of design variables, together with several loads cases and constraints. It is ideal for large structure sizing and is usually the centre-piece of any structural optimisation chain in both industrial and academic applications [2]–[4]. Aircraft structures are sized for multiple load cases which cover different flight regime in accordance with the certification authorities [5]. Loads must be provided for steady and dynamic conditions.

Dynamic loads are usually a difficult type of load case to include in the optimisation. The sensitivities are more difficult to compute on transient responses and can be quite demanding in term of CPU time. Only a hand few of aeroelastic sizing frameworks handle dynamic loads sensitivity analysis such as *Airbus Lagrange* [6] and *TU Delft Proteus* [7]. When using NASTRAN SOL200, such capability isn't available [8]. *Stodieck et al.* [9] used finite difference approximations, to derive externally the actual response sensitivities. Another option is to decouple the response analysis from the structural sizing, and by updating the loads in a load loop. Skipping some of the sensitivities don't necessarily yield to the best optimum [10] but present the advantage to make the dynamic analysis code independent from the optimizer. The equivalent static loads (ESL) method formalised by *Kang et al.* [11] is used to bypass this issue and provides and a way to do structural optimisation with dynamic load cases. The optimisation strategy in this paper is built around this technique and its architecture shown below in Figure 2. The optimisation process mostly relies on MSC NASTRAN SOL200 for the structural optimisation and SOL146 [12] for the gust load analysis. Aerodynamic corrections are derived from rigid RANS simulations using Ansys Fluent. Matlab/SIMULINK is used to connect all the different tools and to run both gust and control surfaces aerodynamic models, as well as tuning for outer iteration the GLA controller.

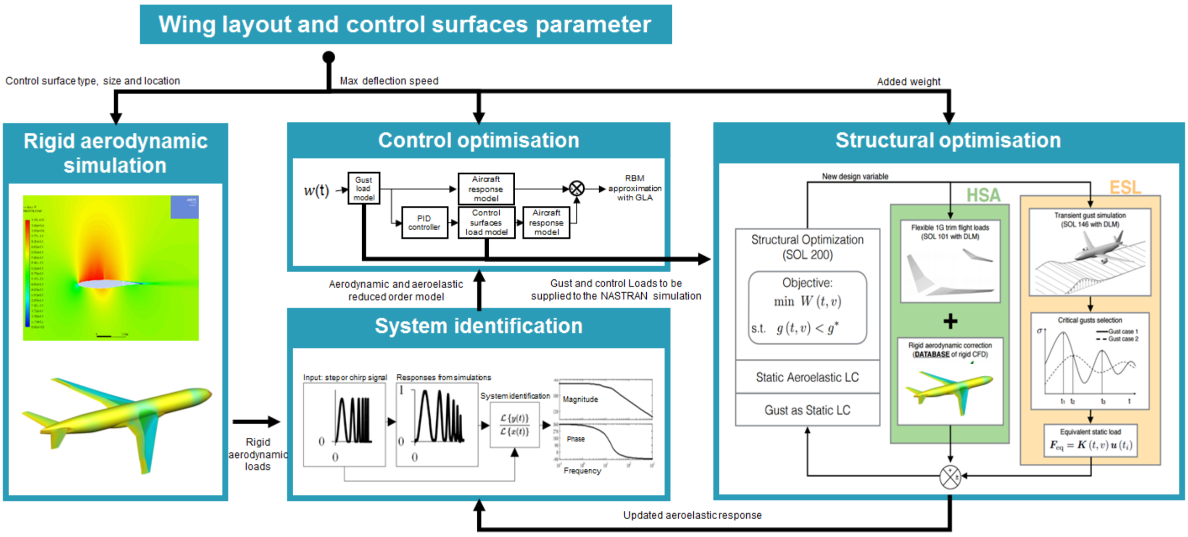

Figure 2: Schematic of the optimisation process.

b. Aerodynamic correction for loads

Another issue is the accuracy of the loads predicted by linear potential flow codes. Various approaches have been developed to perform suitable load corrections, but none are universal and usually case dependent. *Dillinger* [13] used Euler CFD simulations to improve steady manoeuvre loads normally obtained with the DLM code embedded in NASTRAN. More recently, MSC Software implemented in NASTRAN the hybrid static approach (HSA), which replaces the rigid aerodynamic contribution of the wing with higher-order CFD results and stored in a database [14]. This method simplifies the load correction process and only requires the correction to be computed once. The rigid aerodynamic databases can also be swapped for different flow conditions. Aeroelastic effects are captured using the DLM method and allow NASTRAN to retains its capability to compute steady aeroelastic sensitivities. It has been used by *Bordogna et al.* [15] to size a wing box.

$$Q = \underbrace{Q_{rigid}^{CFD}(\alpha)}_{\text{From RIGID CFD database}} + \underbrace{\Delta Q_{elastic}^{DLM}(u)}_{\text{Elastic increment}} \tag{1}$$

Equation 1 above shows how the aerodynamic loads Q are obtained from rigid CFD database and is a function of the trim angle α. The elastic load increment is a function of the wing deformation u.

Gust load corrections are also a very active topic of research. Recent studies have highlighted significant discrepancies between loads from linear panel methods and high fidelity CFD [16]–[18]. *Raveh* [19] proposed a method using reduced-order models of the unsteady aerodynamic forces from rigid high fidelity simulations. This method could be seen as a hybrid approach because it still relies on a lower order aeroelastic model to obtain aero forces due to the aircraft structural vibrations and flight mechanics. Yet it is very fast and the gust ROM only needs to be computed once for a given flight point and rigid aircraft configuration.

c. Load alleviation

Including manoeuvres and gust load alleviation in the wing box sizing has potentially the advantage to decrease the wing box weight significantly thanks to a reduction of the loads. *Bramsepie et al.* [20] sized a carbon fibre composite aircraft configuration with MLA using MSC.NASTRAN and *Bordogna et al.* [21] have shown an increase of gust criticality when aggressive MLA setting is applied. Wing box optimisation was also performed with more futuristic configurations, using ailerons spanning the entire wing and showing significant flight performance improvements [22], [23]. *Wildschek et al.* [24] included a winglet tab for gust load alleviation purpose in the sizing process of a wing box using a feedforward controller. *Handojo et al.* [25] also included the GLA function in the sizing of a composite wing box and showed the effect of control delays on the resulting wing root loads. *Bussemaker* [26] used a more integrated approach revolving around *Airbus Lagrange* allowing concurrent optimisation of both control and structural parameters. This type of optimisation architecture is considered more efficient, although fewer load cases and design variables were included. It also requires full access to the code to compute the sensitivities.

Because MLA and GLA are used for load alleviation, control effectiveness evaluation is therefore critical. This is usually estimated using panels method. A more accurate aerodynamic characterisation is usually performed when looking at aircraft handling qualities but isn't necessarily used for aircraft sizing. Because nonlinear effects can interfere with the control surfaces efficiency, it is important to use the right models. In his thesis, *Fillola* [27] showed that RANS CFD is accurate enough to achieve the aerodynamic characterisation of the ailerons and spoilers on an aircraft. *Bertrand* [28] later extended this work to a parametric model that could predict the steady aerodynamic properties of various geometry and location of control surfaces. The aerodynamic corrections used in this paper are described next section.

3. Setup

a. Model

The aircraft model used in this paper is based on the NASA Common Research Model [29], a widely popular configuration for aerodynamic and aero-structural studies. The wing is used in its undeflected shape provided by *Brooks et al.* [30]. The structural mesh has been rebuilt with fewer elements (about 1314 CQUAD4 shells) to allow quicker runtime. As shown below in Figure 3, the half aircraft is fitted with an aileron and a spoiler. On this model, ribs are modelled as rigid, using RBE2 elements. This allows a model reduction to only 264 degrees of freedom. Every shell elements on the FEM model have their thicknesses as design variables. The material used is Aluminium. The structural constraints are Von Mises stress and buckling. A simply supported plate model is directly implemented using NASTRAN DRESP2 and DEQATN cards, hence removing the need for expensive global buckling analysis. In the present work, only the maximum take-off weight mass configuration is used. A +2.5G pull-up and -1G push-down during cruise (M0.85) conditions are used as the two manoeuvre load cases. Additionally, six 1-cos gust cases (positives and negatives) with a frequency ranging from 1Hz to 10Hz are simulated.

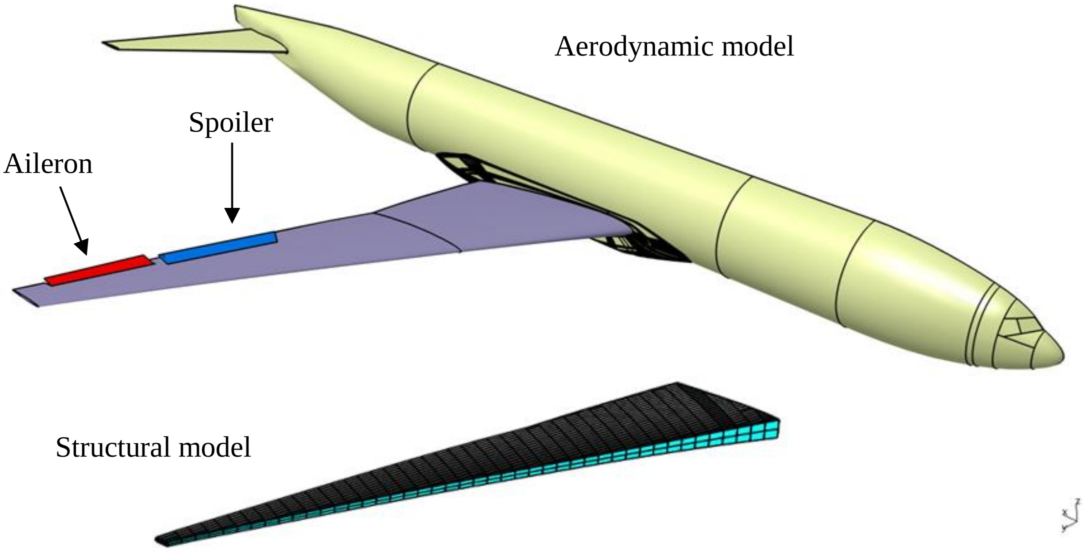

Figure 3: Undeflected aerodynamic and FEM model. The aileron is in red and spoiler in blue.

b. Steady aerodynamic characterisation of the control surfaces

While linear potential flow aerodynamic codes remain standard for aeroelastic simulations and preliminary sizing, they do not always capture all relevant effects. This is especially the case for control surfaces, which under certain flow conditions exhibit some non-linearities. RANS simulations using k-ω turbulence model were run at cruise speed (M0.85) with different aileron and spoiler deflections. The lift contribution of the movables from CFD is compared below with NASTRAN DLM in Figure 4:

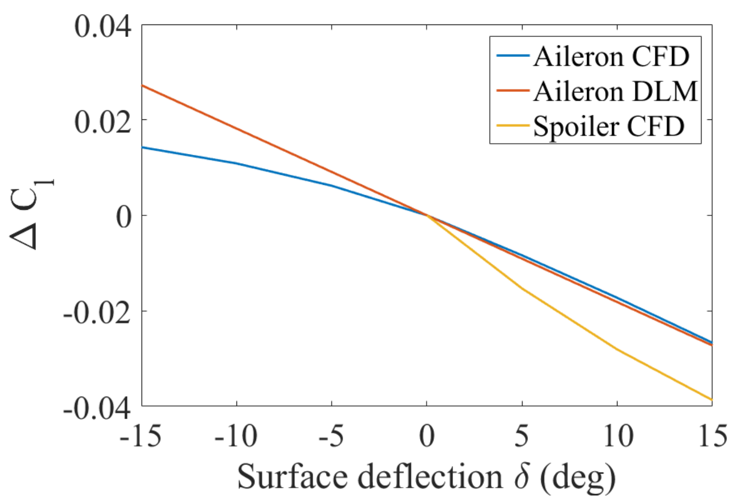

Figure 4: Rigid and flexible lift increment of the control surfaces.

It is interesting to note how DLM remains quite accurate for positive deflection (aileron up) compared to the CFD. Nonetheless, it shows quite large discrepancies at negative deflection (aileron down). This may be due to the linear code not being able to capture flow separation around the hinge of the aileron. Comparison with the spoiler aerodynamics cannot be made as it genuinely requires non-linear flow solver to be approximated. Ultimately, a wrong approximation of the moveable loads increment may lead to the unsafe sizing of the wing.

c. Unsteady aerodynamic characterisation of the control surfaces

In the previous section it is shown that control surfaces may have nonlinear behaviours, this also applies to their dynamic behaviours. It is critical to achieving a correct characterisation to obtain proper GLA performance estimation.

$$\left([\boldsymbol{M}]\boldsymbol{s}^2 + [\boldsymbol{K}]\boldsymbol{s} + \boldsymbol{q}_\infty \underbrace{[\Delta \boldsymbol{Q}_{\boldsymbol{elastic}}(\boldsymbol{s})]}_{\text{Elastic aerodynamic increment (SOL146)}}\right)\{\boldsymbol{\xi}(\boldsymbol{s})\} = -\left([\boldsymbol{M}_c]\boldsymbol{s}^2 + \boldsymbol{q}_\infty \underbrace{[\boldsymbol{\Delta Q}_c(\boldsymbol{s})]}_{\text{Movables aero transfer functions}}\right)\{\boldsymbol{\delta}_c(\boldsymbol{s})\} - (\boldsymbol{q}_\infty/\boldsymbol{V})\underbrace{[\boldsymbol{\Delta Q}_G(\boldsymbol{s})]}_{\text{Gust loads transfer functions}}\{\boldsymbol{w}_G(\boldsymbol{s})\} \qquad (2)$$

The methodology used here is to derived transfer function from transient CFD simulations in order to evaluate the unsteady lift and moment characteristic of the moveable. As the transfer functions estimated are linear, look up tables are also used to approximate the steady, non-linear, lift and moment contribution. Linear unsteady and non-linear steady loads contributions are summed up together as shown in Figure 5:

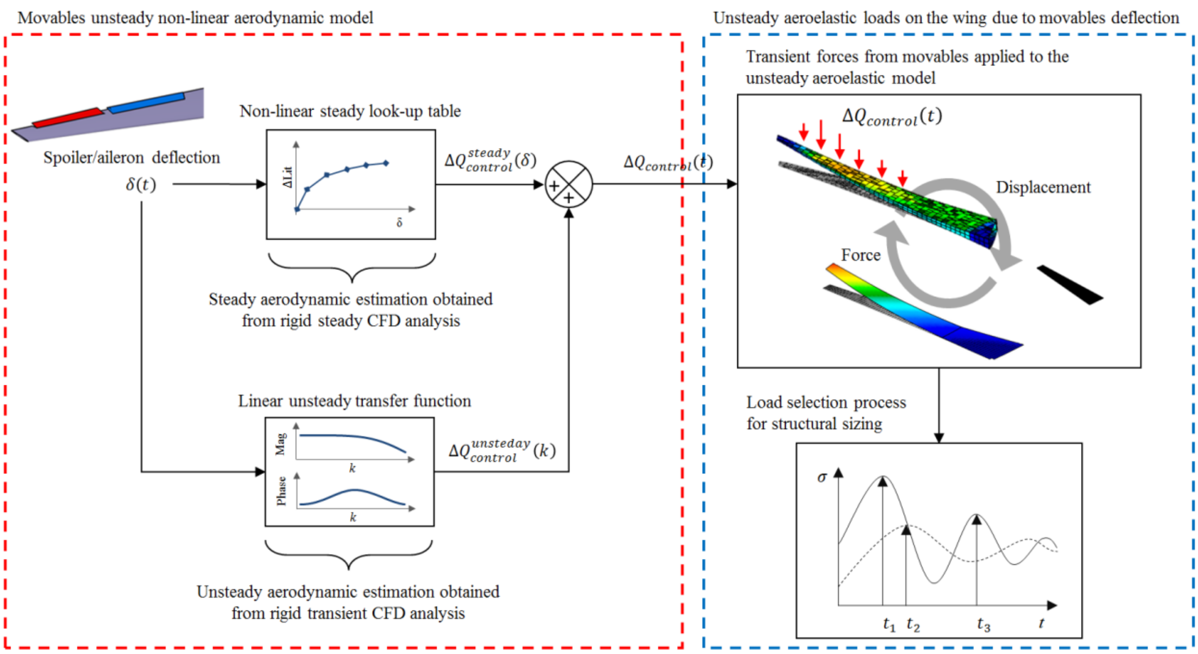

Figure 5: Schematic of the aerodynamic model.

Ailerons and spoilers unsteady loads are identified following the same process. The resulting forces and moments are then applied directly to the NASTRAN model during gust simulations, to simulate the effect of the GLA. In Figure 6 is shown the resulting total lift of a spoiler undergoing an arbitrary motion. The transient rigid CFD simulation was executed using Ansys fluent with a k-ω turbulence model. The simulation used an unstructured mesh of 19 million cells and run at Mach 0.85. The loads are identified at every degree of freedom on the wing.

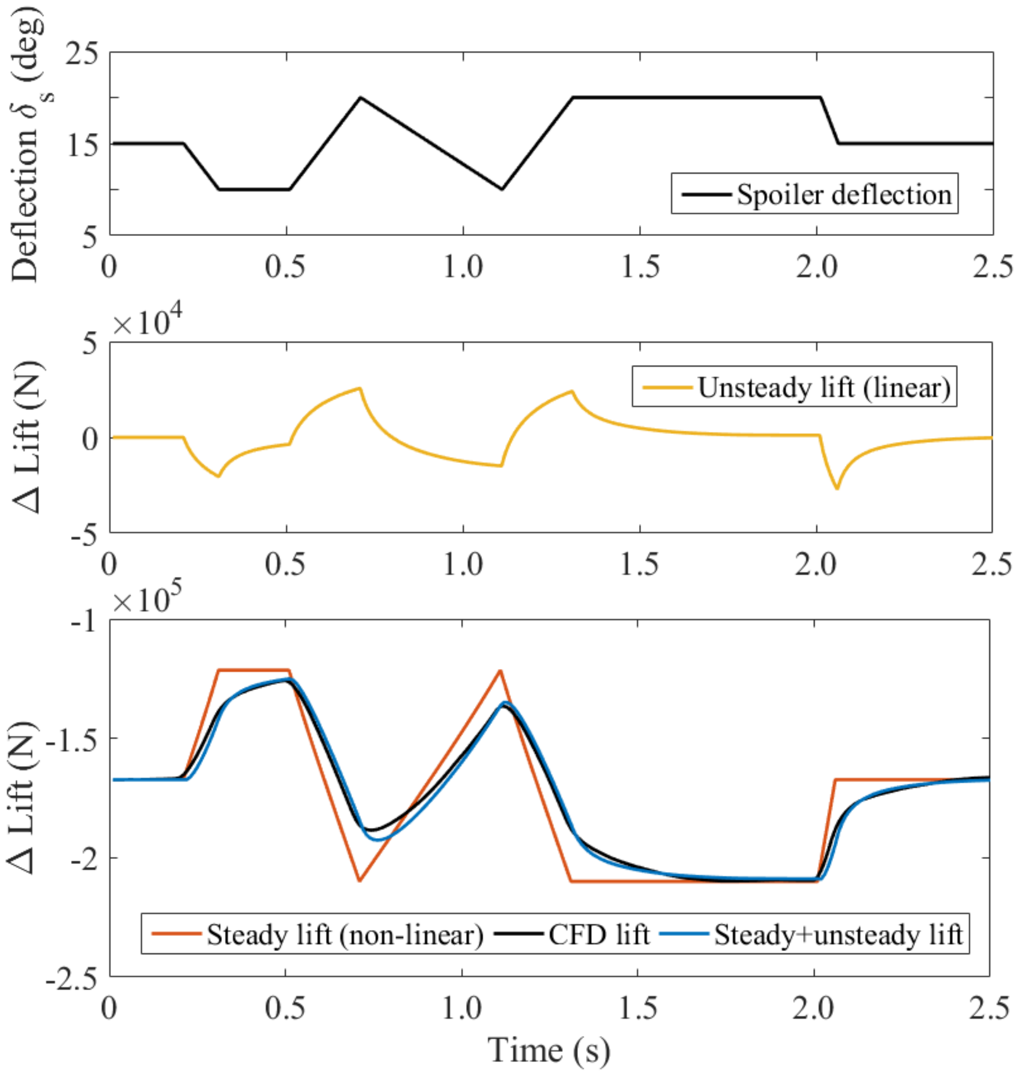

Figure 6: Comparison between the reference lift from the spoiler using CFD and its approximation using the mixture of transfer functions and lookup tables.

d. Gust load correction

Similarly to the aerodynamic correction of the control surfaces, gust corrections are also approximated with a transfer function. Using a step gust propagating through the fluid domain, lift and moments are recorded at each degree of freedom on the wing and at the centre of gravity for the rest of the aircraft in order to characterise its aerodynamic incremental loads.

The results in Figure 7 highlight decent agreement between the reference gust loads evaluated during the CFD simulations and its approximation using convolution.

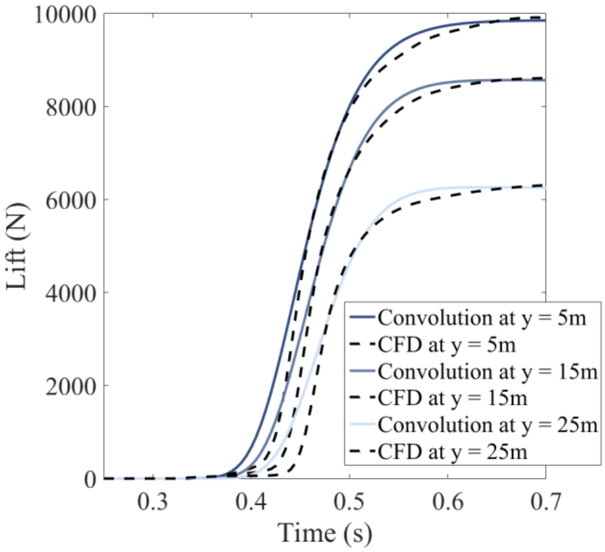

Figure 7: Lift and moment due to a gust at various locations spanwise on the aircraft.

The gust model using the approximated RANS simulations can then be compared with native DLM implementation of NASTRAN. It has to be noted that in both cases, DLM is retained for the aeroelastic behaviour of the aircraft itself. In Figure 8 is shown the comparison, where the CFD gust induces a larger response in amplitude than what is computed by NASTRAN SOL146 only. This difference tends to decrease as the frequency of the gust increases.

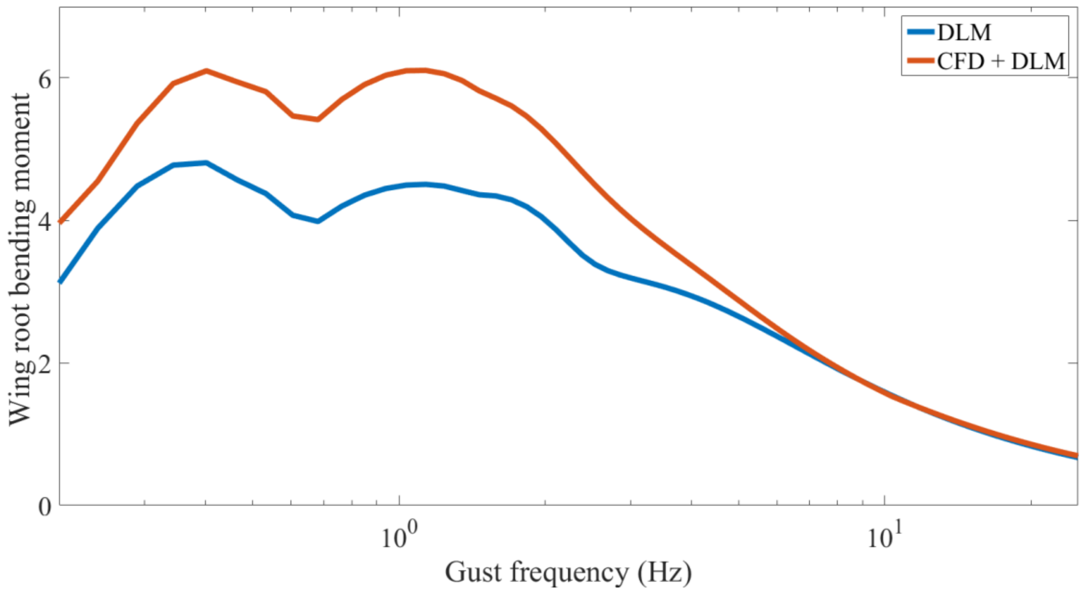

Figure 8: Root bending moment due to gusts of different frequency on a free-flying, flexible aircraft.

4. Results

The relative effect of MLA on the sizing of the wing is assessed. In that case, a 15 deg deflection of the ailerons upward is applied during pull-up, while 15 deg deflection downward is applied for push-down. Spoilers are not used to avoid excessively high trim angle. On Figure 9 is shown the wing thickness difference between two wings sized with and without MLA. The reference wing is the one sized with MLA and the negative thickness difference values indicate a higher thickness on the reference wing. It can be noted that overall, the top and lower wing skin are thinner on the MLA wing, while the front spar is notably thicker. This could be explained by the requirement for the wing to support additional torsion due to the aileron deflection.

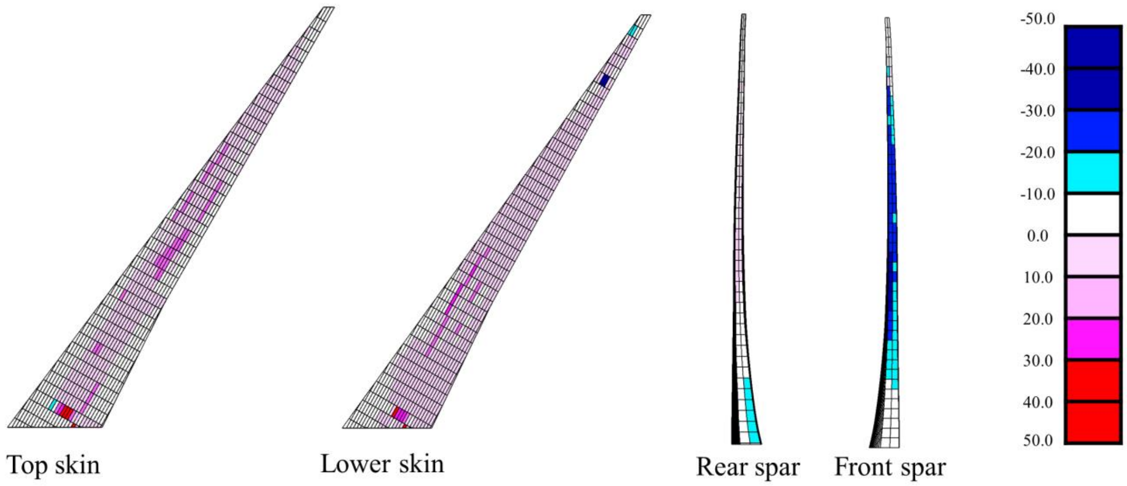

Figure 9: Thickness difference (mm) between two wings sized with and without MLA.

As shown in Figure 10, gust loads are the sizing load cases for the outer part of the wing. When MLA is used during the sizing, the wing area sized by gust cases extends further inboard.

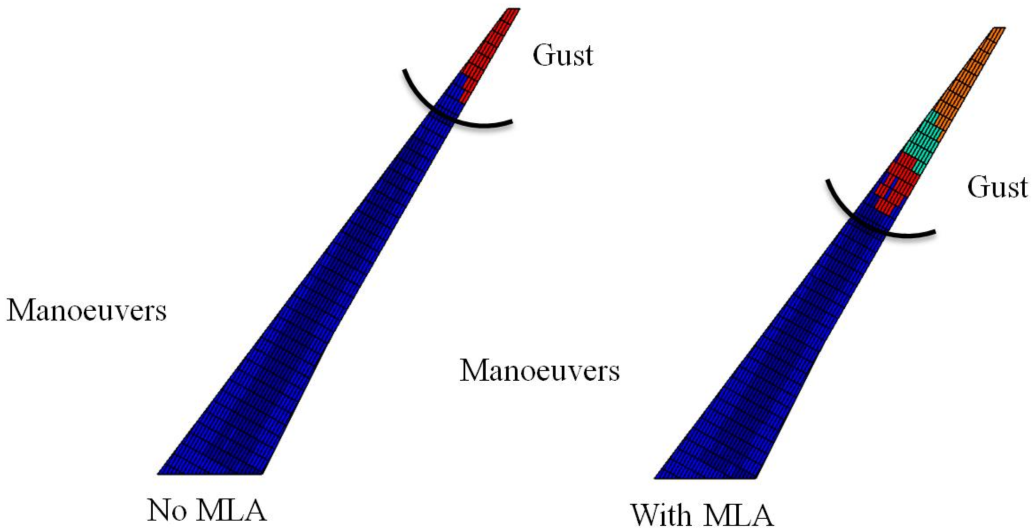

Figure 10: Sizing load cases on the top skin.

5. Conclusion

A methodology to size aircraft wing box accounting for the load alleviation functions of the control surfaces has been presented. The overall optimisation remains mostly sequential, with the dynamic loads being updated using the equivalent static load approach. Gust, manoeuvers and control surfaces loads are corrected through reduced order models and databases obtain from RANS CFD simulations. Corrected loads differ in amplitude from their panel linear potential flow counterpart. In the case of gust loads, the lift increment is much higher using the CFD gust model. For the aileron, the improved load model is able to capture some important flow non-linearity and also accurately models the spoiler unsteady aerodynamic, which would not be possible otherwise with a linear method. Ultimately the methodology provides a good and consistent level fidelity for most relevant steady and dynamic load cases used in the sizing process. Additional effects such as the aircraft incidence influence on the gust and control surfaces could also be implemented in the future. It remains however important to benchmark these correction methods against validation data from fully coupled CFD-CSM simulations or wind tunnel test. Failure scenario of one or several load alleviation systems on the aircraft may also be included in the sizing process, in order to determine a safe MLA/GLA budget when sizing the structure.

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