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Wing structural Changes of Hybrid-Electric Aircraft: A case of Study

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Abstract. Decarbonization and sustainability are emerging global goals as solutions to mitigate these temperature changes. The search for alternative fuels that reduce or eliminate gas emissions has become one of the most researched topics. In this context, electric energy has re-emerged as a source with the potential to revolutionize humanity, both for powering cars and airplanes. The attempt to use electric energy to power aircraft is nothing new. Pioneers tried to use it, but in the late nineteenth and early twentieth centuries, the weight-to-power ratio made this possibility unfeasible. Currently, with lighter engines and batteries with greater energy storage capacity, in addition to the use of renewable sources such as wind and photovoltaic energy, this possibility has begun to become a reality. Electric aircraft have begun to appear using photovoltaic panels on the wings and fuselage, demonstrating the viability of this energy alternative. Another option found was to electrify existing aircraft. This option does not simply involve removing the piston engine and turbine and replacing them with electric motors. From a structural perspective, the designer will have to deal with, at the very least, a fixed Center of Gravity (CG) instead of the CG movement that exists in aircraft as a result of the distribution of fuel between the wing and fuselage tanks. If he chooses to replace the propeller in the nose of the aircraft with several smaller propellers on the wings, he will have to deal with changes in loads and moments and it may be necessary to increase the number of ribs on the wings to increase their resistance. This work studies the transformation of an aircraft to electric propulsion and the effects of these modifications on the wing structures and their attachment to the fuselage. The structural analysis is performed in a typical flight scenario at sea level, with a fixed standard atmosphere temperature, maximum cruise speed and a specific angle of attack. It was necessary to determine a power-plant configuration to run a Vortex Lattice Method Simulation to obtain aerodynamics loads. Once the wing loads and the power-plant were defined, it was possible to obtain the modified wing loads, and, in addition to the geometry model, it was possible to run structural simulation. Despite the challenges related to added weight and reduced useful loads, the developed study indicated that the proposed modification is viable from a structural viewpoint.

Keywords: distributed propulsion, aircraft electrification, hybrid-electric aircraft

1 Introduction

The aviation industry has established future goals to guide the development of new technologies, such as the improvement of flight efficiency to reduce: the carbon emissions, the vulnerability to any aviation fuel price volatility, the noise levels and increase passenger comfort during flights. In an effort to achieve these goals, discrete improvements in aircraft designs developed in the past several decades were introduced. Some examples are the use of aerodynamic devices such as winglets, the use of modern high-pressure ratio engines, the introduction of larger fan diameters, and the use of engine digital control systems [3]. These improvements were able to reduce the fuel consumption per available seat kilometer of an average airliner by about 30% over the last years [1]. However, the efficiency limit of these solutions seems near. In this scenario, distributed propulsion systems appear as a new concept change that promises to increase overall efficiency even more for new aircraft

and to reduce the noise levels produced [8].

This system of propulsion introduces new technical challenges that need to be solved in the fields of aerodynamics and structural analysis. One of the many subjects to be studied is the structural impact of incorporating a significant number of propulsion elements in an aircraft wing. This introduces multiple trust application points and modifies the lift and drag distribution on the wing. Furthermore, the dynamic loads imposed by the propulsive system assume a new form, with a tendency to decrease the natural frequencies of the structure due to the installation of engines near the wingtips [13]. However, the structural aspect of this new concept, like many others, still suffers from a lack of studies and represents an opportunity for new developments, especially when considering the need to understand the impacts of distributed propulsion in current aircraft structures. It is important to recall that, for new projects, it is common practice in the aviation industry to reuse previous structural design developments.

The purpose of this paper is to study the effects of changing the propulsion system on the aircraft's main structure, the wing. To analyze this effect, we begin with a wing from a known aircraft, the CESSNA 208B, and modify the propulsion system by removing the fuselage propeller, which is driven directly by its engine, and replacing it with a set of smaller propellers on the wings driven by electric motors. This paper is divided into a section addressing the research methodology, a section addressing the finite element mesh analysis and the results obtained at key points on the wings, and finally, a brief conclusion.

2 Methodology

The first step of this research was to incorporate the distributed propulsion concept into the aircraft design and to estimate the additional weight resulting from its application. To maintain the focus of this work in the structural analysis, a hybrid-electric distributed propulsion concept will be chosen. In accordance with the objectives of this work, the concept to be used will be based on the Serial Powertrain design presented and analyzed by Vries, Brown and Vos [19]. This concept makes use of an engine that is connected to an electric generator and to an electric power management unit. From there, the electrical power is sent to a series of engines distributed along the wings. The aircraft used as a reference for this work, the Cessna Caravan 208B chosen, has a PT6A-140 with 867 SHP. Considering that, and with the proposal of achieving a power value between the power options available for the original aircraft, the power plant selected is a configuration with six Emrax 348. According to its data sheet [6], at 2500 rpm, this 39 kg motor produces 87.5 kW of continuous power. The six-motor configuration will be able to provide 525 kW (714 SHP) continuously.

For simplicity, a constant-speed propeller will be used directly connected to the engines running at 2500 rpm. The selected model is the electrically controlled MT Propeller MTV-7. According to its type certificate, this 3-blade model has a maximum power of 101 kW at 2500 rpm and a weight of 14.5 kg with a diameter of 140 cm. The generator to be used will be Honeywell's 1 MW peak generator unit. According to information available on Honeywell's website [10,11], this unit is capable of providing 900 kW continuously with a total weight of just 154 kg (generator + control system + DC rectifier bridge). Since Honeywell's generator operates at a similar rotating speed of the engine before the propeller reduction, the original gearbox can be removed. In addition, the propeller and its governors would also be removed that reduces about 130 kg in weight.

Using Amprius SIMAXX^{TM} 450 Wh/kg 4C continuous discharge rate batteries [2], it is possible to obtain a required weight of 166 kg. Adding a margin for the power management unit, the weight of 200 kg will be used. With this configuration, the added weight is estimated to be 675 kg. This means that this aircraft would have a new empty weight of 2742 kg and using 80% of fuel capacity, a useful load of about 437 kg. Figure 1 shows the approximate position of the selected components.

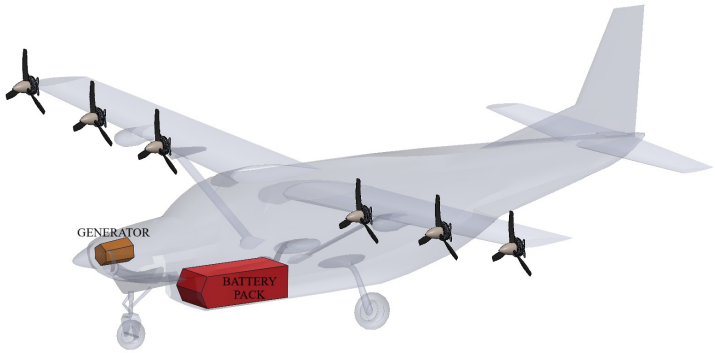
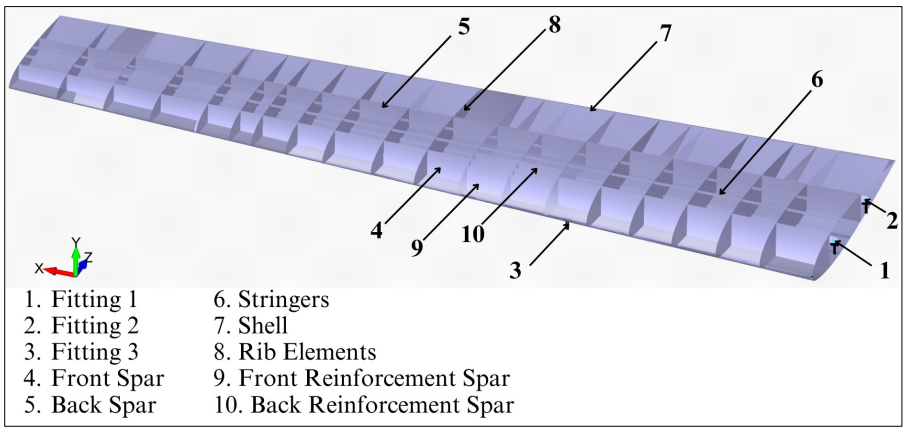


Figure 1. Components Positioning

The motors are located with existing ribs, while keeping the distance of about 90 inches (2.286 m) from one to another.

With the distributed propulsion concept defined and detailed, a three-dimensional model of the structure of the aircraft was created in a CAD software. It was constructed based on data available in the manufacturer's technical documentation and in real measurements taken from an aircraft of the same model.As shown in Figure 2, the geometry model incorporates all the major details of the wing structure.



1. Fitting 1
2. Fitting 2
3. Fitting 3
4. Front Spar
5. Back Spar
6. Stringers
7. Shell
8. Rib Elements
9. Front Reinforcement Spar
10. Back Reinforcement Spar

Figure 2. Geometry Model

The aircraft wing is attached to the fuselage structure by three pinned points: fitting 1 attaches the front spar to the upper portion of the fuselage, fitting 2 attaches the back spar to the upper portion of the fuselage, and fitting 3 attaches the front spar to a strut. Figure 2 better shows these connection points.

Since the objective is to obtain a preliminary study, the modeled geometry includes some simplifications of the real wing. The real wing mainly uses rivets as the connection elements, for this work, it was considered an ideal connection, and a "Glued" interface type was used. In this condition, Nastran interprets that the components that were defined as glued are perfectly connected to each other, and the mesh displacements are transferred between the meshes continuously over the connection region.

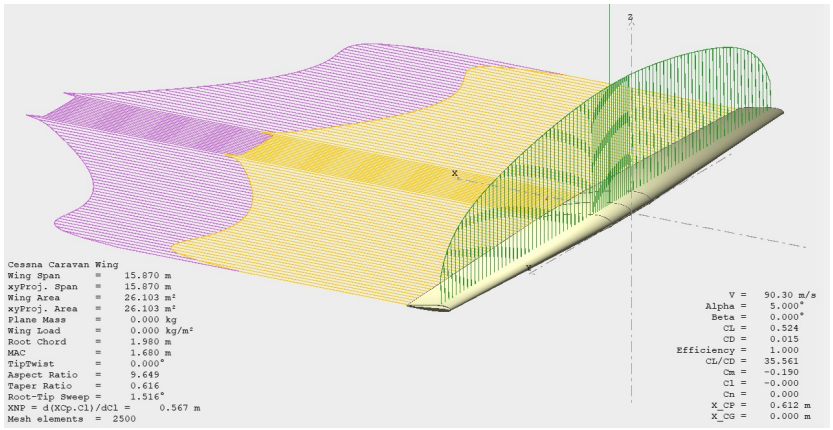


Figure 3. Vortex Lattice Method

Based on the information available in aircraft technical publications, a Vortex Lattice Method simulation (VLM) setup was constructed on XFLR5 [5] by modeling the basic wing geometry and inputting the flight condition. The simulation (and all subsequent required calculations) was developed considering a flight with the maximum operating speed (175 knots) at sea level, considering ISA+10 and a typical angle of attack of 5 degrees. The Figure 3 shows the VLM model and the lift and total drag (purple) distribution over the wing.

Having the lift and drag distribution from the simulation output, a total lifting force of 54785.6 N and a total drag of 1537.4 N were obtained for both semi-wings. Subsequently, the semi-wing was divided into 6 areas

(Figure 4) matching the location of the motors and the modified aerodynamic loads of the wing-propeller interaction were estimated using the correction factors obtained from Veldhuis [18] and Fischer [7].

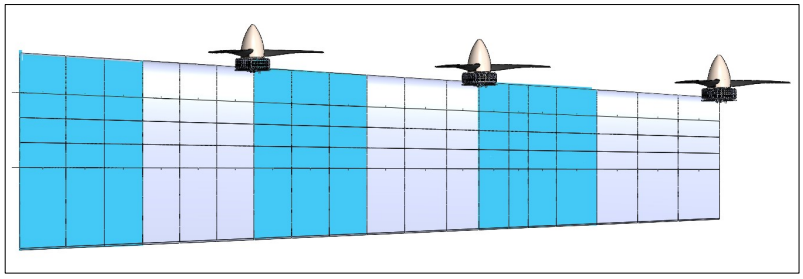


Figure 4. Engines Mounting Positions and Areas Division

In the Femap model, the aerodynamic loads were applied at the 25% chord length for each region. These loads were applied to the model using a rigid element that interpolates them to each mesh element on the upper side of the wing of each correspondent region.

The effective thrust (Te) produced by each propeller can be approximated and obtained using the experimental results presented by Hartman and Biermann [9]. It was possible to determine that each propeller could produce a thrust of 220.4 lbs (980.4 N) and it would operate with an overall efficiency of 80%.

Finally, using FEMAP software [16], a finite element structural analysis was developed to accomplish the objectives of this work. The loads obtained from the considerations above were applied to the model by using RBE3 elements. This allowed for the application of the load to the exact desired regions. In addition, the wings were constrained by the fittings 1, 2 and 3 considering a pinned fixation to the fuselage (fixed translation). Using the base geometry, a simulation mesh was created and refined using CQUAD4 plate elements.

The Figure 5 shows the loads applied to the unmodified wing model and Figure 6 shows the loads for the modified model. Basically, the difference between the loads is the magnitude of the lift and drag forces and the application of the motor and propeller thrust and weight (modified wing model only). It is important to say that the software calculated the resultant force between lift and drag, so the forces shown in Figures 5 and 6 are in accordance with this.

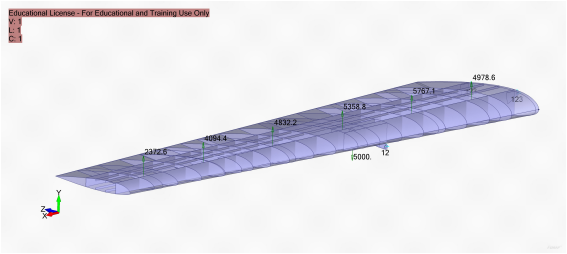


Figure 5: Loads in original wing

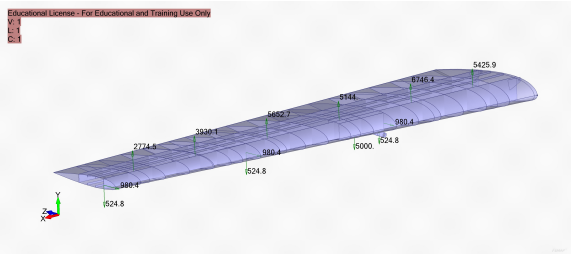


Figure 6: Loads in modified wing

3 Results and Discussion

This section presents the results obtained by the author regarding the structural analysis run. Each finite element model passed through a mesh convergence test separately, so the results could be verified.

The convergence was tested to the original wing and the modified wing. The convergence analysis was performed with a focus on verifying the variation of the Maximum Von Mises Stress (MVMS) in the shell, the stringer and the fitting 1 as the number of elements increases. The Figure 7 and 8 shows the convergence analysis to the original wing. It is possible to see that the model satisfies the convergence criteria (error ≤ 3%) for all three selected structural elements when 282,010 elements is used, indicating that this mesh is adequate for the intended analysis.

With the objective of complementing the mesh analysis presented above, a mesh quality test was plotted using as a reference the same criterion as used by Ruas [15].

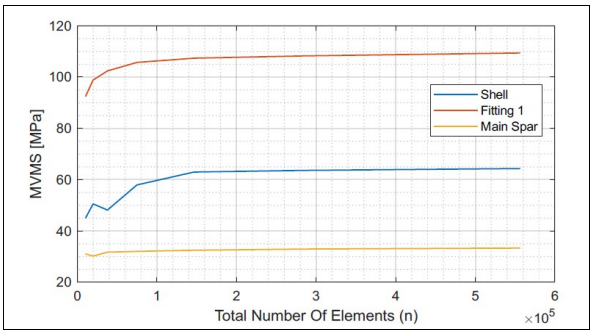


Figure 7 . Convergence Test Original Wing

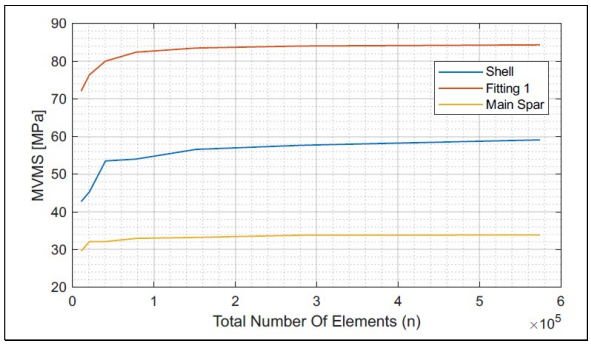


Figure 8 . Convergence Test Modified Wing

In accordance with the purpose of the study, the aim is to compare the results obtained for each model, so it is possible to understand the structural impacts of the introduction of a distributed propulsion concept on a typical aircraft wing. Table 2 presents the Maximum von Mises Stress (MVMS) for each of the structural components of the models.

Table 2. Comparison of MVMS between Unmodified and Modified Wings

Component	Original Wing MVMS [Mpa]	Mod. Wing MVMS [Mpa]	Diff (%)
Fitting 1	84	108.2	28.8
Fitting 2	23.6	17.6	-25.7
Fitting 3	72.3	66.3	-8.3
Front Spar	33.8	32.9	-2.5
Back Spar	19.9	18.4	-7.6
Stringers	26.3	26.1	-0.8
Shell	57.7	63.6	10.3
Reinf. Spars	39	38.1	-2.4

It can be seen that the application of the motor loads (modified aerodynamic loads, thrust, and weight) creates significant impacts on the MVMS of the structural components. As a cut-off criterion, the elements in which the absolute difference in stress is greater than 10% as shown in Table 2 are presented in figures.

As can be seen, after the incorporation of the motor loads, Fitting 1 experienced an increase in MVMS of approximately 28.8% (Table 2) as shown in Figures 9 and 10. Therefore, by adding thrust loads to the wing, the drag momentum is reduced, and the compressive stresses on this element increase. According to the technical publications, this component is constructed of 7075-T73 aluminum, which has a yield strength of at least 360 MPa [12]. Even applying a conservative project factor of 2, the MVMS of Fitting 1 after the modification corresponds to a minimum safety factor of about 1.66. This indicates that even with an increase of about 28.8% in the stress, the modification does not implies in critical change.

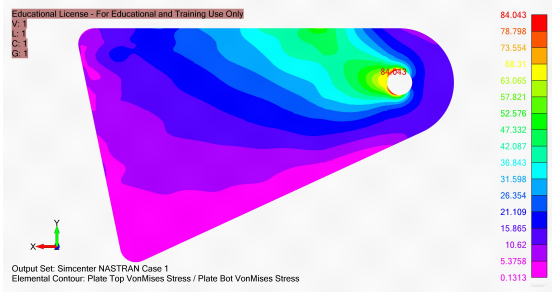


Figure 9. Fitting 1 in original wing

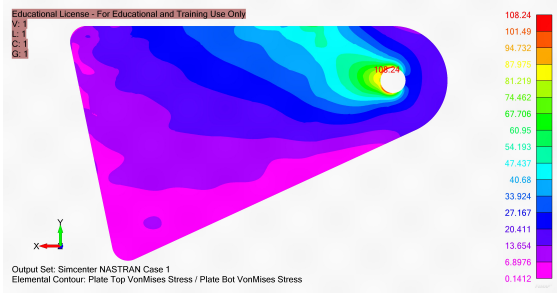


Figure 10. Fitting 1 in modified wing

Regarding fitting number 2, Figures 11 and 12 show the result of MVMS in this component for the unmodified and modified wings. As a first hypothesis for this work, it was believed that by adding the thrust loads, the main structural impact would be an increase in stress on Fitting number 2. The hypothesis was based

on the fact that the wing was not originally designed to support positive loads in the flight direction, and therefore the thrust loads would increase the stress on the root fittings.

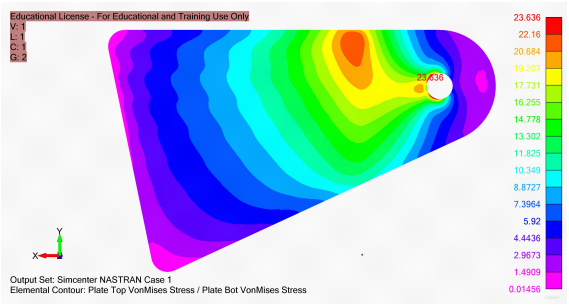


Figure 11. Fitting 2 in original wing

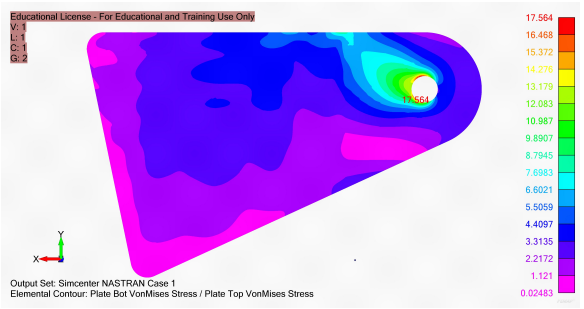


Figure 12. Fitting 2 in modified wing

However, as can be seen in Table 2 and in Figures 11 and 12, the MVMS for Fitting 2 decreased by about 25.7%, showing the exact opposite of what was believed. Analyzing the physics of the problem to understand the reason behind this behavior, it is possible to see that Fitting 2 is originally under compression as a result of the lift and drag moments.

As presented in Table 2, the shell of the wing experienced an increase in MVMS of about 10.3% after wing modification. Figures 13 and 14 show the MVMS distribution for this component. For this component, the manufacturing material is 2024-T3 ALCLAD aluminum with a yield strength of approximately 300 MPa [14]. Again, statically, the addition of the motors to the wing does not implicates in critical change.

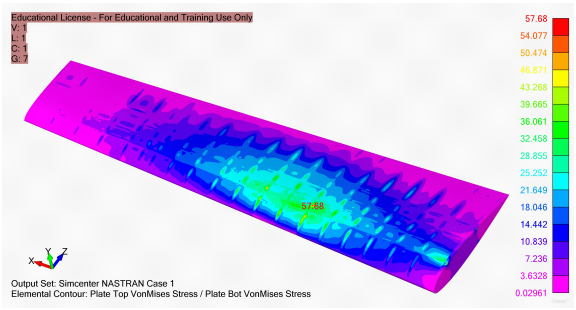


Figure 13. Shell in original wing

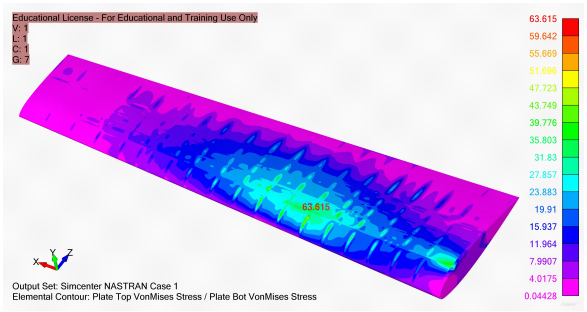


Figure 14. Shell in modified wing

By plotting the shell displacement for both models (Figures 15 and 16), it can be seen that the total translation for the unmodified wing is greater.

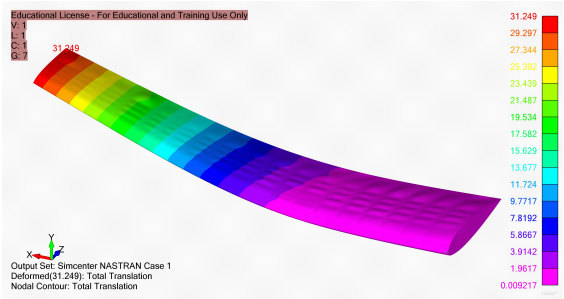


Figure 15. Shell Total displacement [mm] in original wing

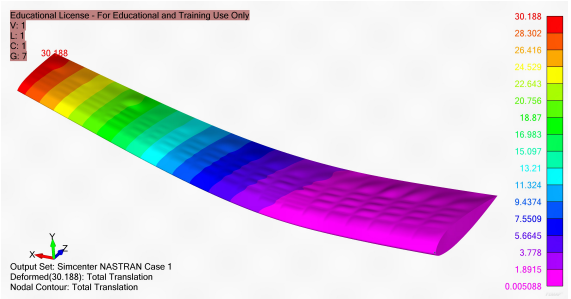


Figure 16. Shell Total displacement [mm] in modified wing

4 Conclusions

From the results and the discussions presented above, it is possible to conclude that, at first analysis, the introduction of a distributed propulsion concept to a typical aircraft wing can lead to significant changes in the Maximum Von Mises Stress (MVMS) experienced by the wing components.

It was observed an increase of about 10.3% to the MVMS on the shell of the wing and an increase of 80.5% in the displacement in the flight direction for this component. This result could be questioned by the connection method between the components of the simulation and other simplifications applied to the geometry. However, it gives a good idea of the impacts of the modifications applied and is a guide to improving the model.

There are still many challenges related to the implementation of hybrid electric distributed propulsion concepts. The propulsion components selected for this work (motors, propellers, battery, generator, and wiring) meant an increase of about 32.7% of the original empty weight of the aircraft. Even if the focus of this work was not the optimization of this criterion, it is a symptom of the related challenges.

Finally, the developed study indicates that the proposed modification is viable from a structural point of view. The changes in MVMS presented are significant but do not exceed the yield strength of the materials (minimum safety factor equals 1.7). However, it is important to say that this work only analyzed a typical flight configuration with the maximum cruise speed and that other critical scenarios should be studied in order to confirm this statement.

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