Aeroelastic assessment of distributed electric propulsion wings

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Abstract. During recent years, aircraft manufacturers focused on environmentally friendly and aerodynamically efficient aircraft concepts that could allow a radical reduction of emissions. The use of a hybrid-electric powertrain is one of the most effective ways to design near-zero-emission aircraft. These aircraft are highly performing and sophisticated so the design process must be extremely accurate. Among the various innovative aspects, the use of distributed engines to improve aerodynamic performance poses new challenges from a structural perspective due to the tip-mounted propeller demanding a complicated design due to reduced flutter performance. This results in higher stiffness requirements and consequently increased mass. Both the weight penalty needed to prevent dynamic instability, and the wing aeroelastic tailoring, crucial to minimize such an additional weight, is of utmost importance. Because of setting up a preliminary approach to estimate the static and dynamic effects of such a non-conventional wing architecture, the present paper shows a comprehensive structural analysis of a wing opportuneely designed according to certification specification and equipped with a variable position powertrain. Several different engines are then moved along the wingspan to estimate how it affects the dynamic response using a simplified beam-stick finite element model. The results show that the engine position strongly affects the flutter velocity with a particular band bell curve over the wingspan with the maximum in between 60-70% wingspan. In addition, it is worth noting how the tip propeller may cause a reduction of flutter velocity with respect to the conventional configuration with the turbine mounted in between 30-40% wing-span.

1. Introduction

Energy transition demands electric propulsion to achieve more sustainable aviation. In this context, distributed electric propulsion (DEP) is barely a new concept and has captured the attention of major players in the aviation landscape to increase propulsion system efficiency along with better aerodynamic flow [1]. However, all-electric technologies require updated airframe configuration to be effectively introduced in commercial aviation. One of the major concerns is to establish updated and enhanced preliminary design approaches, useful to estimate the potential outcomes after the implementation of such an innovative concept on a selected aircraft configuration.

The use of distributed engines to improve aerodynamic performances poses new challenges from a structural perspective. Despite the static relief, generally introduced thanks to the load
alleviation induced by the outboard mass of the engines, the dynamic response of the wing gives rise to concern. It is indeed expected that outboard mass, and especially tip-mounted propeller, may require a complicated design due to reduced flutter performance. This results in higher stiffness requirements and consequently increased mass. Both the weight penalty needed to prevent dynamic instability and the wing aeroelastic tailoring, crucial to minimize such an additional weight, are of utmost importance and should be addressed long before the certification stage, whose flight tests may reveal undesirable dynamic response and claim for a new wing design increasing manufacturing cost of the aircraft. Hence, a dedicated design model is needed to establish the mass and stiffness of the wing.

Generally, different methods are available in the literature to estimate the mass of the airframe as well as the overall aircraft weight. It is possible to broadly divide those methods according the approach adopted in: (i) empirical and semi-empirical methods [2, 3], (ii) analytical and quasi-analytical based methods [4, 5], and (iii) finite element-based methods [6]. Empirical methods consist mostly of statistical evaluation based on existing aircraft. Although great and valuable results have been obtained, the implementation and accuracy level of statistical-based methods in predicting aircraft mass depends primarily on the amount and quality of the data available for existing aircraft and, as such, of limited practical use for DEP equipped aircraft. A similar discussion can be done for semi-empirical methods, used when a simplified geometrical layout of the aircraft configuration becomes available. However, it is still difficult to capture the layout peculiarities of a specific configuration. Analytical and semi-analytical approaches require the use of a simplified structure model to estimate the mass and performance of the structure. As such, they are well suited to perform parametric studies. However, they still require holistic approaches able to account for aerodynamic effects and aeroelasticity. To overcome these limits, specific effects of static and dynamic aeroelasticity need to be accounted for using high fidelity models, such as those relying on Finite Element Methods (FEM) [7].

Although the major advantage of numerical simulation is the possibility to introduce as many details as needed in the model, including non-linear behaviors, they may increase the computational costs, or may not be available at the preliminary design stages [8]. This is the reason why a high fidelity approach is a build-up in this work to look into dynamic effects of DEP with the general aim to define specific trends useful to update semi-empirical or semi-/analytical methods. In particular, those approaches require advancements in setting formulas for aeroelastic compensation while dealing with high aspect ratio aircraft and distributed propeller wings. The use of a high aspect ratio paves the way to the application of really flexible wings, which may undergo very high deformation due to the low twisting resistance of the outer wing box. In addition, the presence of tip propeller mounting may generate dynamic instability reducing strongly the flutter velocity. While the high aspect ratio can be compensated by introducing a strut[9], actually the engine mounting over the wingspan may be a big issue due to the lower flutter speed expected when moving the engine outboard [10]. However, they also showed that engine placement at a certain location has also the potential to increase the flutter speed, which can be used to compensate for the negative effect of the tip mounted engine. Nonetheless, the study is strongly related to a specific analytical model, demanding for such a parametric investigation using high-fidelity approaches, whose first attempt is established in the present paper.

2. Materials and Methods
This section introduces the statement of the problem along with the high-fidelity model set up to look into the effect of distributed mass on the dynamic response of the wing.
The idea behind DEP is to get advantage of local propeller blowing to get to more efficient wing. With many propellers blowing air over it at high speed, the wing behaves as though it is traveling faster than it actually is, providing greater lift. During takeoff and landing, air can be blown over the wing at higher speeds, providing additional lift without sacrificing cruise performance. However, sizing and weight estimation becomes complicated because of the non standard load ratio, \( W_s \). A typical configuration under investigation for different platforms ranging from general aviation to regional aircraft is reported in Figure 1. It displays how the engines are typically distributed over the wingspan. Namely a gas turbine can be either tip- or inner-mounted and connected to the electrical motor (EM) cluster through an electric generator (EG) mounted just behind. The number of electrical engines is then depending upon many aspects which are not addressed in this paper but are dealt with in [11]. Also, a hybrid configuration can be conceived where a battery pack is used to feed power to the electric engines to optimize power consumption.

In this context, statistical/Semi-empirical, Analytical/Semi-analytical, and High-fidelity models are then necessary to be implemented in such a combination to look into different aspects which affect airframe design. In particular, the idea behind this investigation is to exploit the high-fidelity model to study the aeroelastic effect of DEP, whose findings can improve Analytical/Semi-analytical approaches or moved back to Statistical/Semi-empirical formulation to account for the specificity of DEP configuration from preliminary design.

2.2. High-fidelity modeling

The Aeroelastic Analysis is related to issues that arise in the framework of aircraft design concerning aeroelastic requirements: the adequate control effectiveness of control surfaces and prevention of flutter and divergence speeds in the required flight envelope.

In general, the numerical aeroelastic investigation of a wing or an entire aircraft involves different areas depending on the design phase in which it is performed starting from the conceptual stage to the detailed design one. For instance, during the design concepts stage the number and/or the position of spars, ribs, and stringer, the wing geometry, or the sizing of components can change in the wing box. It is possible to allocate this work in a hypothetical aircraft concept step, where the aeroelastic effect of the position of the engines on the wing is investigated. Hence, mass and structural models are required to represent the stiffness and structural dynamical properties for flutter analysis.

This section shows the modeling setup to investigate the dynamics of the wing equipped with distributed propulsion. The structural model used in aeroelastic modeling of the wing can be generally classified as a 1D beam model since the \( CBEAM \) elements, in which one of the dimensions is significantly larger than the other two, are used. The beam axis is defined along the largest dimension and it is considered that a cross-section perpendicular to this axis varies along the beam span and characterized the wing with its local structural properties. In other
In a stick model, the wing is represented by beams capable of bending, shear, torsional and axial deformations. Each beam is divided into several elements with a flexural stiffness $EI$ and torsional stiffness $GJ$ estimated from the member section properties by classical structural analysis methods.

To represent the mass distribution, the wing is divided into several strips, centered on the nodes of the beam-like model. For each section, the mass is lumped at the reference positions and attached to the beam axis node by a rigid link element which allows the lumped mass to be represented by section mass, a moment of inertia, and mass moments. In the specific, a wing with 19.28m semi-span, 2672kg mass, 6.56m root chord, and 24% taper ratio is modeled. Figure 2(a) shows the flexural and Torsional stiffnesses distribution along the wing while Figure 2(b) provides information on the distribution of the masses of the model used (without engine).

Based on the calculated mode shapes of the wing stick-beam model, the Doublet Lattice Method (DLM) is applied since the subsonic flow. To better fit the aerodynamic model with the structural model, the wing is divided into two macro panels: the inboard wing is from the wing root to the break station while the outboard wing is from the break station to the tip section. Each panel is modeled with a $CAERO1$ element. Two beam splines are created by connecting the aerodynamic panels of the wing to the structural model using the input command $SPLINE5$ (1D beam spline). The spline function transforms the aerodynamic loads into the structural model and structural deformations into the aerodynamic model.

Nastran solution SOL 145 is implemented and the problem is studied with the PK-Method. The analysis includes 10 vibration modes. The structural damping is not included to have more conservative results. Input for flutter solutions is dynamic characteristics that are represented by reduced frequencies and flight conditions (density, velocity). The Flutter analysis is performed for speeds ranging between 50-700 m/s.

3. Results
This section reports the results obtained by the high-fidelity model conceived. A first preliminary analysis is carried out to evaluate the effect of engine mass on the natural response of the structure. Afterward, a comprehensive flutter analysis is implemented to establish the effect of distributed mass on the dynamic response of the wing.

3.1. Preliminary sensitivity analysis
The purpose of the study is to evaluate the effects of engine position on the dynamic and aeroelastic behavior of the wing, with frozen distributions of structural stiffnesses and masses. Before proceeding to the aeroelastic analysis, a sensitivity study is performed to establish the
effect of the engine mass on wing behavior. In particular, Figure 3 shows the natural frequency of the first ten modes of the wing in four different configurations: (i) isolated wing and wing with engine mounted at (ii) $\eta_1 = 0.37$, (iii) $\eta_2 = 0.68$, and (iv) $\eta_3 = 1$. In addition three different masses are considered: (a) $m_1 = 1500\, \text{kg}$, (b) $m_2 = 2000\, \text{kg}$, and (c) $m_3 = 3000\, \text{kg}$. From the graphs, it can be seen that:

- as the mass of the engine moves from root to tip, the natural frequencies of the mounted engine wing differ more than those of the isolated wing;
- the position of the engine influences the dynamic behavior of the wing much more than the value of the mass itself;
- when the engine is mounted at $\eta_1$ and $\eta_2$, the mass variation has an influence above all on structural elastic modes 2, 5, 8, and 9. Instead, when the engine is placed in position $\eta_3$, the elastic modes 4 and 7 have frequency differs more as a function of the mass of the engine.

Due to the slight effect of the mass value, the following analysis is carried out using $m_2$ as reference engine mass.

### 3.2. Flutter investigation

Figure 4 shows the typical solution of the aeroelastic investigation distributing $m_2$ (total) in two different locations. In detail, the damping of mode 5 approaches zero around 580 m/s. At that velocity coalescence of Mode 4 (Torsional-like) and mode 5 (Flexural-like) is present and enables flutter.

Similarly, the analysis is carried out fixing the position of one engine ($E_F$) and moving the other one ($E_M$) along the wingspan, and changing both the relative mass and the total mass concerning the reference $m_2$ value. Figure 5(a) shows the results when $E_F$ is at 40% wingspan (inner mounted gas-turbine). Hence, when the movable engine ($E_M$) is located at the same position, the reference flutter velocity of such a conventional wing with $m_2$ engine is obtained.
Figure 4: Flutter analysis results. Wing with mass $m_2$ split into two masses of 1000 kg each placed in $\eta_1$ and $\eta_2$

Instead, Figure 5(b) shows the results when $E_F$ is at the tip, simulating the configuration with tip-mounted gas-turbine.

In both cases, it is possible to identify one best configuration in terms of safety for the flutter condition. In the first case (Figure 5(a)), the fixed engine is positioned at 40% of the wingspan while the second engine will be positioned at 60% of the wingspan. On the other side, if the fixed engine is placed at the tip, the safest solution is achieved by positioning the second motor at 80% of the wingspan as shown in Figure 5(b). This is even better than having one engine located at the conventional position. However, tip-mounted engine configuration usually returns lower flutter velocity. Having a better look at Figure 5(a), a strong variability of flutter velocity against
Figure 6: 1 fixed engine at 40% wingspan and 2 movable engines configuration (a). 1 fixed engine at 100% wingspan and 2 movable engines configuration (b).

engine position is generally found. It is also worth noting that the flutter velocity variability increases with the mass ratio between $E_M$ and $E_F$ (see orange curve). That is to say, the greater the mass of the engine moved to the tip, the lower the flutter velocity results. In addition, the curve shifts upper when increasing the overall mass (see yellow curve). Namely, increasing mass helps in accommodating flutter velocity reduction (weight penalty). Finally, better looking at the Figure 5(b), not much difference is found when $E_M$ is much smaller than $E_F$.

The analysis is repeated having distributed propulsion with 3 engines, whose results are shown in figure Figure 6. For the masses assigned in the various cases, it is noted that the best solution concerning the wing free from flutter is the configuration with 2 mobile engines of equal mass (500 kg each) positioned respectively at 50% and 60% while the fixed engine (1000 kg) is located at 40% (figure Figure 6(a)). If the fixed engine is placed at the tip instead, the safest solution is achieved by positioning the 2 mobile engines at 70% and 80% of the wingspan (figure Figure 6(b)).

As to the flutter variability, Figure 6(a) shows again that it depends upon mass ratio between $E_M$ and $E_F$ (see orange curve). Instead, Figure 6(b) shows that it is also a matter of total mass, in favour of highest values (weight penalty).

4. Concluding remarks

This paper presented a wing dynamics analysis accounting for the possible presence of distributed propulsion on a commercial aircraft wing. Several different engines are moved along the wingspan to estimate how it affects the dynamic response using a simplified beam-stick finite element model solved by Nastran. The results show that the engine position strongly affects the flutter velocity with a particular band bell curve over the wingspan with the maximum in between 60-70% wingspan. In addition, it is worth noting how the tip propeller may cause a reduction of flutter velocity with respect to the conventional configuration with the turbine mounted in between 30-40% wing-span.

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