Aeroelastic Analysis and Optimization of a Highly Flexible Aircraft and Application at X-HALE-BR

(Bibliography report)

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***Abstract*—This work addresses the formulation on a mathematical model based in unsteady aerodynamics with strip theory and a nonlinear beam model to analyze the aeroelastic properties of highly flexible aircrafts. This formulation will be used to optimize its characteristics, aiming at its improvement.**

I. Context

Aeroelasticity is the subject that describes the interaction of aerodynamic, inertia and elastic forces in a flexible structure and the phenomena that it can result in. Since some aeroelastic phenomena (as flutter and divergence) can cause structural failure, it has been influencing the design of airplanes, bridges, wind turbines, helicopters, etc. The first recorded flutter problem to be modeled and solved was the Handley-Page O/400 bomber in 1916 [8].

The studies about aeroelasticity have greatly evolved since 1916 and today it is possible to analyze and design very light, and highly flexible flying wing configurations, which is of interest for the development of the next generation of high-altitude, long endurance (HALE) unmanned aerial vehicles. The flexibility of such aircraft leads to large deformation, what makes linear theories not relevant for their analysis. The deformed shape is significantly different from the undeformed shape [4].

One example of this highly flexible HALEs is the X-HALE-BR aircraft. This specific aircraft will be of great importance for the following work and the object for its application. It is a unmanned aerial vehicle that was born in the ITA (Instituto Tecnológico de Aeronautica/ Technological Institute of Aeronautics), a Brazilian Institute.

Combined with recent studies, it is possible to combine the aeroelastic studies in highly flexible aircraft and aeroelastic optimization to improve its aeroelastic characteristics, as the flutter speed [3]. This may be done using computational tools as the python's package *openMDAO* [2].

II. Past works

Nowadays there are some recent modelings for the aeroelastic model of highly flexible aircrafts.

In [6], Su makes a complete analysis of flexible aircrafts based in a reduced-order, nonlinear, strain-based finite element framework combined with finite-state unsteady subsonic aerodynamics to compute airloads along the lifting surfaces. An important characteristic of his work is that all members of the vehicle are considered flexible. In the joints of the structure the Lagrange Multiplier Method is applied to model the nodal displacement constraints. The model is then applied in real fully flexible aircrafts for validation.

In [1] and [5], Ribeiro et al makes a mathematical formulation to model highly flexible airplanes along with a self-made computational tool, a MatLab's Toolbox, called AeroFLex. A nonlinear beam model for large displacements was applied to represent the structural dynamics combined with the strip theory for the aerodynamics including three bidimensional modeling approaches: a quasi-steady, a quasi-steady with apparent mass and a full unsteady. A large aspect ratio flying wing was considered as a test case.

In [7], van Schoor et al. makes an aeroelastic model for airplanes with very flexible wings in which the structural dynamics of the airplane were obtained from its finite element model. In an assumed mode approach, a sub-set of the natural mode shapes were used to calculate the quasi-steady generalized modal forces using a two-dimensional strip model, which included unsteady drag and leading edge suction forces.

In [3] Guo et al. investigated the optimization to maximize the flutter speed through different optimization methods and considering parameters like the orientations of the fiber of a composite wing box structure.

For the aeroelastic analysis, the model that was chosen for the following work was the one from Ribeiro et al., because of the following:

- Originally made for the same aircraft in study;
- Come with a Matlab's Toolbox;
- Recent and updated work;
- It has very precise results in comparison with other works and experimental data;
- It is possible to take out some functionalities of the toolbox to simplify the study.

For the optimization, the analysis of Guo et al. were used to chosen the optimization methods and what parameters could be optimized.

III. Problem statement

To create the aeroelastic model, the model from [1] was used with some simplifications: the toolbox has some functionalities that are not essential for this work, as rigid body dynamics and stress and the possibility to choose between different aerodynamic models. Only the flexible body and unsteady aerodynamics will be used. This is justified by the fact that the work is preferable to start more simple and non-essential functionalities may consume computational power and increase the time of the optimization.

The equations that describe the aeroelastic model of the airplane, result of the mathematical model, may be seen in (1), in which M is the flexible structure mass matrix, $\tilde{\epsilon}$ is the vector of deformations and $\tilde{X} = \dot{\tilde{\epsilon}}$, $\tilde{\lambda}$ the lag states from the unsteady aerodynamic model and $\tilde{k}$ is the vector of kinematics variables shown in (2), with ϕ being angle of bank, θ being angle of pitch, ψ being angle of heading and H being the vertical velocity of the aircraft. $\tilde{\delta}_{u,i}$ is the flap deflection and $\tilde{\pi}_{u,i}$ is the engine throttle.

$$M \begin{bmatrix} \dot{\tilde{X}} \\ \dot{\tilde{\epsilon}} \\ \dot{\lambda} \\ \dot{\tilde{k}} \end{bmatrix} = A \begin{bmatrix} \tilde{X} \\ \tilde{\epsilon} \\ \lambda \\ \tilde{k} \end{bmatrix} + B \begin{bmatrix} \tilde{\delta}_{u,i} & \tilde{\pi}_i \end{bmatrix} \tag{1}$$

$$\vec{k} = \begin{bmatrix} \phi & \theta & \psi & H \end{bmatrix} \tag{2}$$

It is possible to see that the equation is in the space state format. In the progress of the modeling it is possible to verify that the system is nonlinear and coupled. To solve the equations, first of all the system is numerically linearized, which gives the equation (1). By analyzing the eingenvalues of $M^{-1}A$ it is possible to verify if the system is stable.To determine the instability speed (flutter, divergence or other), the following procedure is applied: the airplane speed is increased; for each speed, a new equilibrium condition is obtained; the system is linearized; the largest real part of the eigenvalues of $M^{-1}A$ is taken. Once one of the eigenvalues has a positive real part, the system is unstable. The imaginary part of this eigenvalue gives the frequency associated with the unstable aeroelastic mode.

Once one can calculate the instability speed for the aircraft, it is possible to change parameters trying to increase this speed to improve the airplane's resilience to the aeroelastic phenomena. The strategy to optimize the aircraft is to change its general parameters and optimize the composite layers properties as direction and material of the layers using the openMDAO package [2]. One important constraint of the optimization is not to remove the flexible characteristics of the aircraft, to not heavily increase its mass.

IV. First results and future work

The diagram of the phases of the project may be seen in Fig. 1.

To start the modeling, the python classes of the nodes, elements and structures of the airplane were made, following the Fig. 2. With the mesh, the other elements of the aircraft as engines and fuselage need to be modeled, following the AeroFlex model. Then, it is possible to calculate the matrix

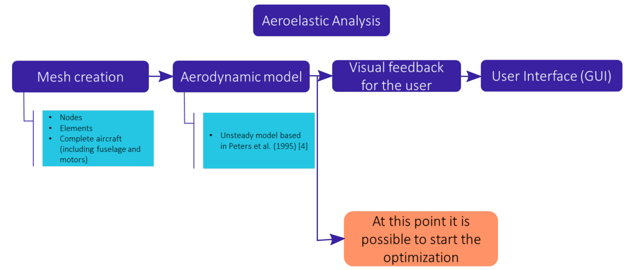

Fig. 1. Project phases diagram

of the model and calculate the critic speed for the further optimization.

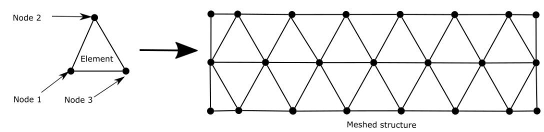

Fig. 2. Project phases diagram

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