Computational aeroelastic analysis of a competition cargo UAV of box wing type

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Abstract. SAE aero design is a competition in which university teams design a radio-controlled cargo aircraft aiming to obtain its highest structural efficiency. Several unconventional configurations have been developed and the aeroelastic analyses during the design phase must be well established. Analytical aeroelasticity methods are difficult to implement in unconventional aircraft, given the difficulty of obtaining the structural interaction of all components. Besides, the analysis needs to have a well-defined modeling workflow to not obtain erroneous results. The main objective of this work is to contribute to the aeroelastic analysis of an unconventional box wing type aircraft and also to assist aero design competitors, through the implementation of an aeroelastic analysis workflow in a real aero design project. The work starts with the elaboration of a CAD model for the selected aircraft, followed by the construction of a finite element model for the structural model. To represent the unsteady aerodynamics, aero panels were used accordingly to the Doublet Lattice Method and then interpolated with the structural mesh, allowing a complete aeroelastic analysis. Both static and dynamic aeroelasticity analyses were conducted. The initial results showed that the aircraft would present flutter inside the flight envelope, so it was necessary to apply flutter suppression techniques by modifying the geometry and structural elements to mitigate the problem. The work presents aeroelastic information about the box wing aircraft configuration as well as techniques for solving problems related to this kind of geometry. An aeroelastic workflow for an aero design aircraft is presented aiming to assist aero design teams to carry out their aeroelastic projects.

Keywords: Aeroelasticity, Structural dynamics. Fluid-structure interaction, Aerodynamics, Structural analysis.

1 Introduction

With the advance of aviation, new aircraft concepts are developed that can attend a particular mission or a requirement. Thus, unconventional aircrafts tend to emerge, and with it, new design challenges are also observed. A growing aircraft category on rise in the market are the VANTS, thereby, new criteria and design methodologies need to be established, as they include the PART 23 [1] and PART 25 [2] standards.

The SAE aerodesign is a competition that encompasses teams from all over the world and encourages a real aeronautical project for undergraduate students in a practical way. The objective of the regular class (the most popular) is to develop a radio-controlled aircraft with the greatest structural efficiency, that is, one that can carry the greatest payload with the minimum empty weight. For this, light materials and unconventional aircraft configurations should be explored.

On structural field, the aeroelasticity workflow need to be well defined, due to the fact that light materials can increase the aircraft's flexibility. In addition to this fact, when investigating unconventional aircraft, new aeroelastic instabilities may arise. Therefore, a consistent aeroelastic methodology need to be established that well represents the aeroelastic model correctly. Also, new points of attention for unconventional configurations and how to solve possible aeroelastic instabilities need to be studied, since the unconventional configuration can bring singular aeroelastic effects.

For this study, the aircraft designed by the Harpia Aerodesign from UFABC for the SAE Aerodesign 2019 competition was used, as can be seen in figure 1.

Figure 1. Aircraft of study.

2 Methodology

Initially, for the implementation of the requirements, the design criteria were established by $1.20V_D$ (dive speed) for flutter barrier and 65% of control efficiency in V_C (cruise speed).

For the aeroelastic model (finite element and aerodynamic models), the Femap® was used following Siemens [3]. The MSC.NASTRAN® was used for the analysis, where the cards and bulk data were based on MSC [4].

2.1 Finite element model

For the elastic and dynamic models, a finite element model was conducted based on a CAD model, which was inputed the stiffness and density of materials, thus, the model contemplate the elastic and mass properties at the same time. The model was made in Femap® and were used shell elements (QUAD4 and TRIA3) and bar element (CBAR) for tubes, as seen in figure 2, due to the thicknesses of the vast majority of components are very small in relation to the full model, so, the use of volumetric mesh would make the model too complex and heavy. It is noteworthy that the bar and shell elements represent well the results in this study and guarantee a relatively light model.

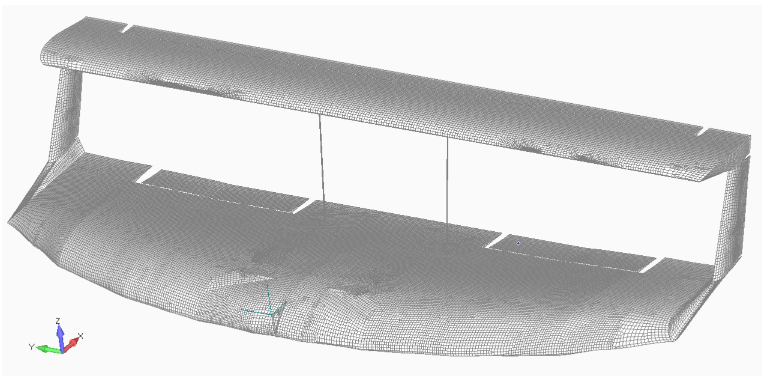

Figure 2. Finite element model of the aircraft.

2.2 Unsteady aerodynamic model

A doublet lattice method was used for the unsteady aerodynamic model. The wing, control surfaces, vertical and horizontal tail were represented by panels according with the leading and trailing edge, the span of the each section and the hinge position of control surfaces. The number of lattices were determined by Rodden and McIntosh [5] and a refinement on leading edge of all surfaces were made, due to the high pressure variation along the chord in that region. There was a concern of match the edge of each lattice with the neighbor, as well as in a structural mesh, in order to avoid numerical errors.

For the aero control surface settings, the lattices of the control surfaces were selected and a coordinate axes were created on hinge point for the orientation. The unsteady aerodynamic mesh is shown in the figure 3.

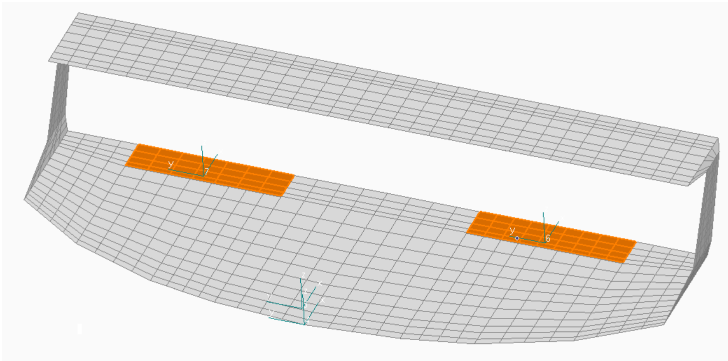

Figure 3. Unsteady aerodynamic model of the aircraft.

2.3 Interpolation of unsteady aerodynamics and finite element model

With the objective to interpolate the structural and aerodynamics models, elements SPLINE2 were used. The chosen points were of the greater stiffness in the structure, in order to abstract correctly the modal displacements of the structure (global mode shapes), which can be seen in the figure 4.

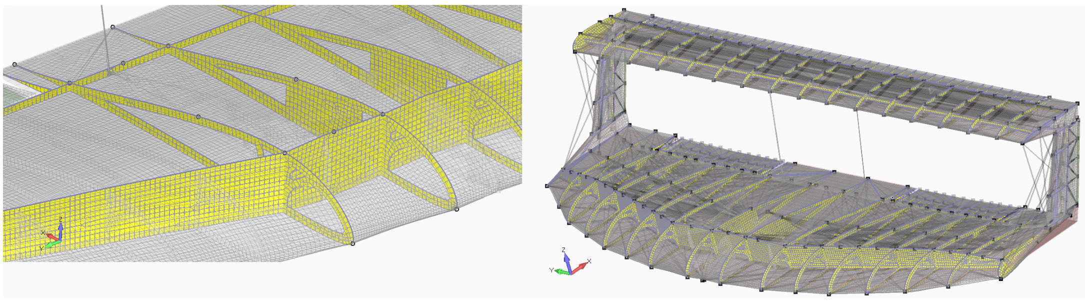

Figure 4. Spline locations.

2.4 Analysis settings

Modal analysis: For the modal analysis, the solution 103 of MSC.NASTRAN® was used with the lanczos algorithm. Modes shapes up to 50Hz were analyzed, since modes above this frequency are hardly excited and haven't any instability due to the aircraft operation speeds.

Flutter and divergence analysis: The solution 145 of MSC.NASTRAN® was used for the flutter analysis. The method PKNL was used, which the density was fixed and the speed and mach number were varied, the reduced frequencies were varied between 0.001 and 5. The flutter point is denoted by negative damping and the divergence when the frequency becomes zero with a negative damping on v-g-f (velocity, damping and frequency) diagram.

Control efficiency analysis: To determine control efficiency, the solution 144 of MSC.NASTRAN® was used. The control surfaces lattices and their hinge coordinate axes were selected and for TRIM conditions, it were considered uniform roll without acceleration (URDD4 = 0) and vertical load factor N_z = -1 (URDD3 = -1) to denote that the aircraft is on the same flight level. Finally, the deflection of the control surfaces were fixed and several cases of dynamic pressure were analyzed, obtaining the dynamic response for each speed and thus, when compared the rigid body with the elastic body response, the efficiency of controls were obtained.

3 Results and discussions

3.1 Nominal analysis

Firstly, the nominal model was analyzed without any modification, in order to observe the initial aeroelastic deficiencies. A flutter solution was made and were observed five unstable modes (negative damping), as shown in the figure 5, where the red vertical line denotes the certification speed.

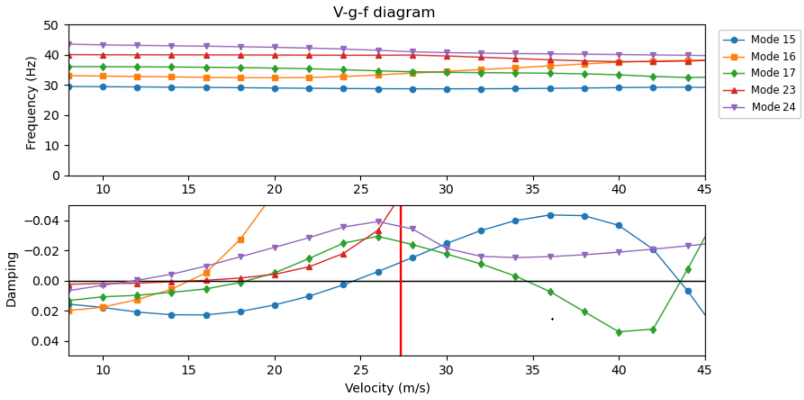

Figure 5. Unstable modes on nominal analysis.

Given this fact, it was necessary to perform a flutter suppression techniques.

3.2 Flutter supression

First correction

Initially, the most critical mode (where the instability occurs at the lowest speed) was isolated and analyzed. The unstable mode and the possible mode of coupling were verified on modal analysis at the instability speed, aiming to observe the modal displacements and find possible points to apply a correction, which can be seen in figure 6 .

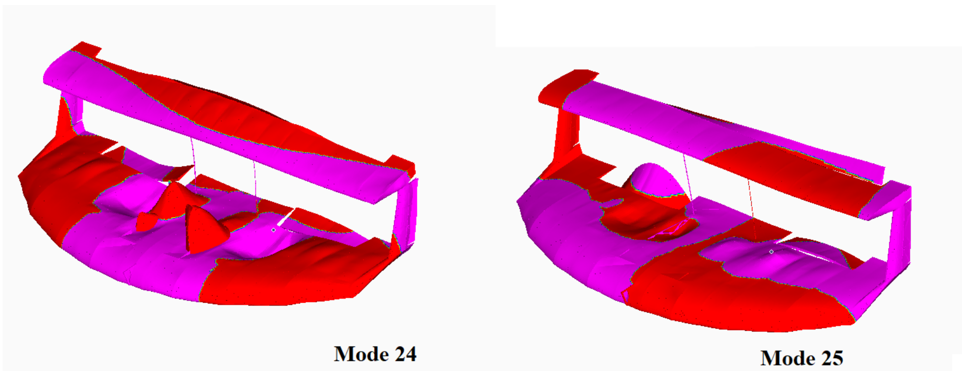

Figure 6. Possible modes coupling in flutter mechanism.

Observing the modal displacements, were seen a wing bending 2N with the horizontal tail inplane on mode 24 and wing torsion with horizontal tail bending 3N on mode 25, evidencing that there was a deficit of movement restriction between the connections of the wing and the horizontal tail with the vertical tail. Based on this, the thickness of the vertical tail stringer has been increased, but it was not effective, as it would require a very high thickness and stiffness values. So, a new tube was added in the connections, as shown in figure 7, which had a considerable positive effect.

After the correction, a new flutter analysis was conducted. The suppression of three unstable modes was seen, however, still remain two unstable modes, as shown in the figure 8, therefore, a new correction was needed.

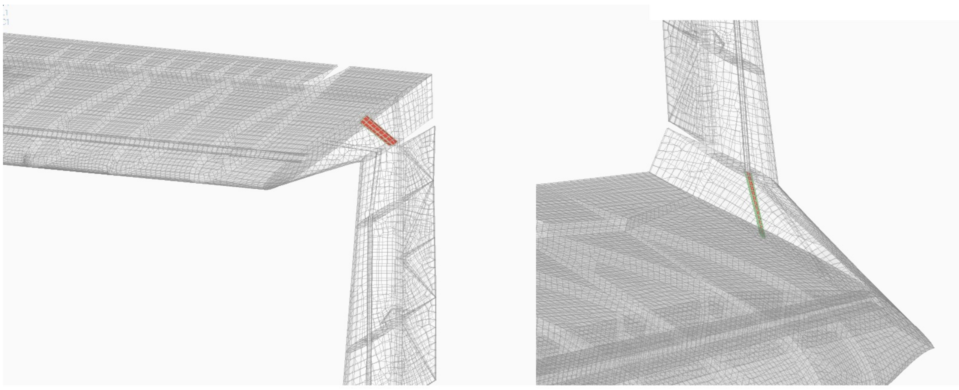

Figure 7. New added tubes.

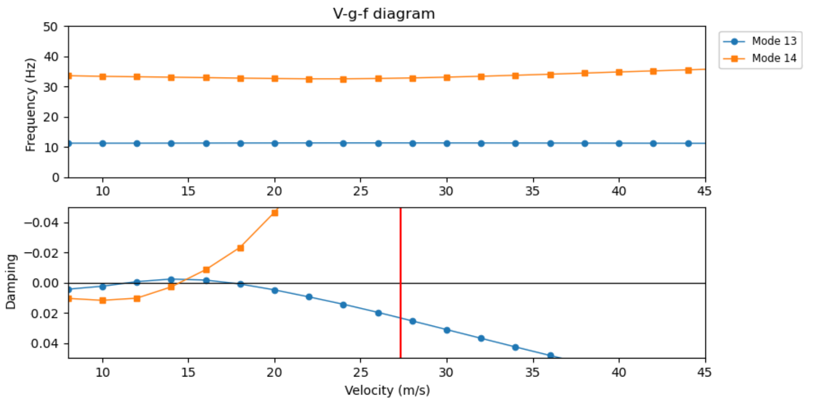

Figure 8. Remaining unstable modes.

Second correction

Analyzing the remaining unstable modes, it was observed that there were no changes in the modal evolution compared to before the first correction, indicating that the connections (new tubes added) are not influent at remaining flutter mechanisms.

Thus, analogous to the first correction, the unstable modes were analyzed on modal analysis and were seen a rotational mode shapes of aileron and drag rudder, as shown in figure 9, indicating a flutter on control surfaces. Based on this, the stiffness of the hinges were increased and parameterized in order to obtain an acceptable aeroelastic stability.

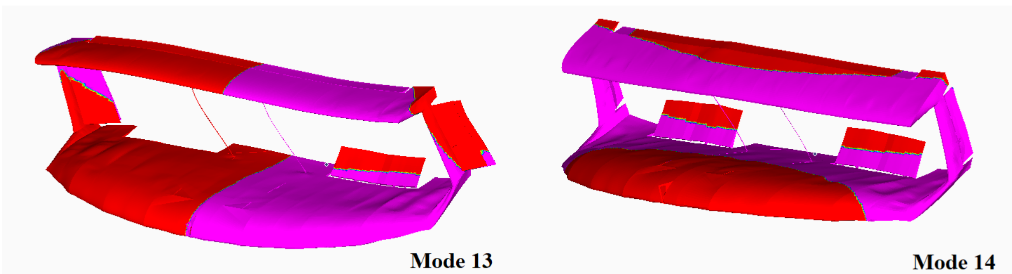

Figure 9. Unstable rotational modes shapes.

Evaluating the results, was necessary an increase of hinges stiffness by 70-80%, as shown in the figure 10.

After the correction, all modes became stable under the $1.20V_d$, as evidenced in the figure 11.

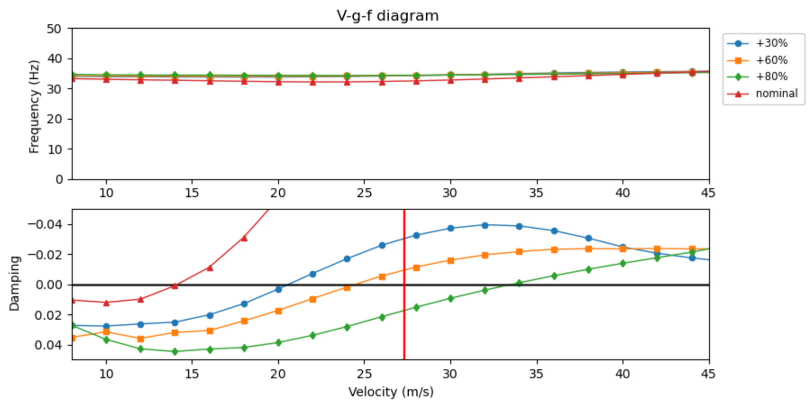

Figure 10. Parameterization of the hinge stiffness.

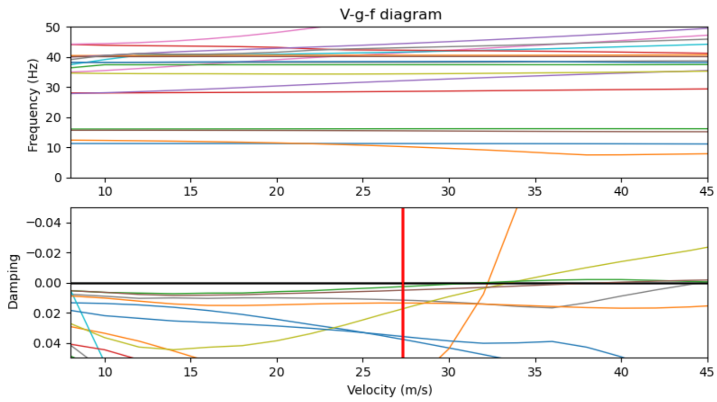

Figure 11. V-g-f diagram of all modes.

3.3 Parametric optimization

For the parametric optimization, the Solution 200 of MSC.NASTRAN® was conducted, which the variables were the thickness of the stringers of vertical and horizontal tail.The variables were simultaneously varied to find the best configuration, for this, the objective function was set by the minimization of the sum of components weights and the restriction as the certification speed for all modes, which its damping is monitored on analysis.

Then, the best solution was found at 61.3% of the horizontal tail stringer thickness and 83.2% of the vertical tail stringer thickness, which caused the lowest cost. Such values obtained were found exactly at the flutter boundary point, as seen in the figure 12.

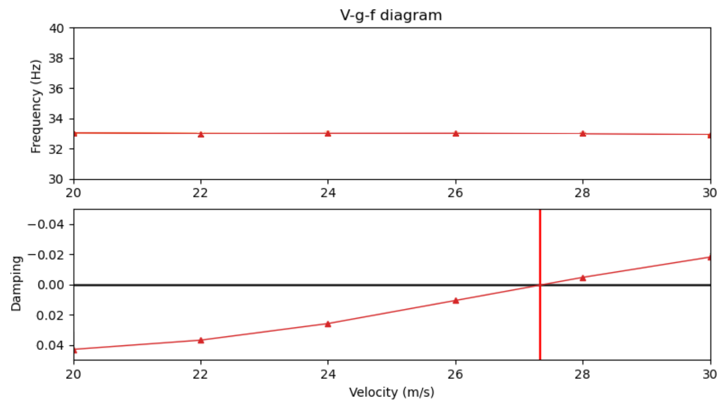

Figure 12. Optimized (and critic) mode.

Thus, it can be concluded that the aircraft is dynamically certified and optimized.

3.4 Static aeroelastic analysis

Finally, the control effectiveness analysis was performed. The results showed that the aircraft has a good efficiency inside the envelope and is within the requirement, as shown in the figure 13.

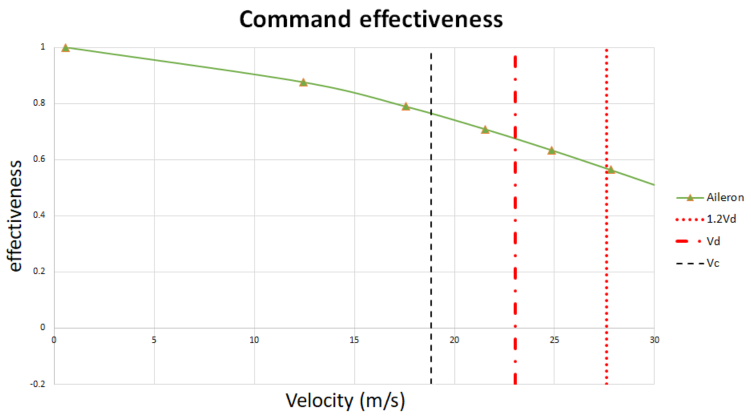

Figure 13. Control effectiveness after the optimization.

It is noteworthy that the point of divergence was not found on dynamic analysis, therefore, the aircraft is statically certified.

4 Conclusions

The results show that the aircraft of study has instabilities caused by deficit of restriction on connections of wing and horizontal tail with vertical tail, and the solution was the addition of a new tube. This fact can be seen as a point of attention for aircraft design of box wing type and the solution found can be useful to solve this singular aeroelastic problem.

Also, it was observed flutter on control surfaces, which the instability speed reduces by increasing the stiffness of the hinges. This fact shows the importance of the correctly modeling of control surfaces on the aeroelastic model and a point of attention for aerodesign aircraft designs, since most of aerodesign teams use the same type of hinges.

Therefore, the present work contributed to establish an aeroelastic workflow for aerodesign projects and how to address aeroelastic problems for the box wing configuration. Other unconventional configurations can be investigated under the same premises.

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