Design and Mechanical Evaluation of a Smart Droop Nose Device Regarding the Applicability of the AZ31B-F Mg Alloy Under Multiaxial Loading Conditions

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December 2016

Abstract

The future generation of high lift devices must reduce aircraft noise and drag; Given the absence of gaps, seams and steps, smart droop nose has been identified as one of the future devices to accomplish this objectives. Moreover, in aircraft design there is an incompatibility: for cruise flight a little cambered wing provides better efficiency, but for take-off, landing and loiter a cambered wing is the best option. The smart droop nose is a leading edge device which increases the curvature of the camber and not only produces additional lift, but also (and mainly) increases the stall angle, $\alpha_s$. On the other side, given the interesting properties of magnesium alloys, the lowest density of all metallic constructional materials and high specific strength to weight ratio, have been identified as a material with great potential for future applications in aerospace industry. However, they experience a unique mechanical behavior which is still under research. This work presents a description of the design’s methodology of a smart droop nose using a compliant-mechanism made of AZ31B-F magnesium alloy. A structural optimization and an aerodynamic assessment of the capabilities of the smart droop nose are present. The final result provides improvements related with the stall angle, stall velocity, loiter time and overall weight when compared with aluminum alloys. In regards to the mechanical behavior of the AZ31B-F magnesium alloy when subjected to multiaxial loadings, a comparative study between the theoretical models of critical plane orientation and the experimental results were performed; Some theoretical models provided acceptable results when compared with the experimental fractographic analysis.

Keywords: Smart Droop Nose, Structural Optimization, Compliant Mechanism, Multiaxial Fatigue, AZ31B-F Magnesium Alloy

1. Introduction

In aeronautics, morphing is commonly referred as ‘a set of technologies that increase a vehicles performance by manipulating certain characteristics to better match the vehicle state to the environment and task at hand’, [4]. However, there is no consensus about the exact definition of morphing, since some authors associate technologies as flaps, slats, etc. to morphing devices, while other allocate it in fixed wing technologies. Due to the lack of agreement about the type or the extent of the geometrical changes necessary to be qualified as shape morphing, its definition is not established. Nevertheless the capabilities that it enables are identified: ‘increases the adaptability of the vehicle to enable optimized performance at more than one point in the flight’, and increases conventional mission capability or enables new mission capabilities that are not possible without the shape change, through an expanding of the flight envelope, [8]. In future morphing will be used to: 1. improve aircraft performance to expand its flight envelope; 2. replace conventional control surfaces for flight control to improve performance and stealth; 3. reduce drag to improve range; 4. reduce vibration or control flutter, [13]. There are several types of morphing: wing, fuselage/tail and engine morphing. Within wing, the concepts can be separated in 3 groups, figure 1. This work focus on the smart droop nose device (aileron morphing). [3, 6].

Trailing edge flaps increase the lift but, in fact, decrease the stall angle due to the changes in the location of the stagnation line and local pressure gradient near the leading edge, which leads to a leading edge flow separation. To overcome this problem a common solution is to increase the leading edge radius through leading edge device. Smart droop nose
is a seamless and gapless leading edge device commonly associated to new morphing technologies and seen as a mandatory enabler for future wings to increase aerodynamic efficiency and reduce acoustic emission. Its actuation is usually performed by a mechanism designed to have some mobility by elastic deformation in one or more elements, instead the traditional mobility by movable joints. This type of mechanism are called compliant.

Recently, magnesium alloys have kept the attention of automotive and aerospace industry, and have been used in several high-end applications such as Formula-1 and Boeing aircraft models. Magnesium is the lightest structural metal available, with a density lower than aluminum’s about a third; it constitutes about 2% of the earth’s crust, and it is the third most abundant element dissolved in sea water, averaging a concentration of 0.3%, i.e., approximately 1.1 kg per cubic meter of water which indicates that magnesium is a resource hardly inexhaustible. In fact, magnesium is the eighth most common element and the sixth most plentiful metal on earth. However, in order to be suitable for mechanical application it must be alloyed to improve the mechanical properties which are greatly appreciated due to their high strength to weight ratio, stiffness and low density. The extensive use of magnesium alloys would have a beneficial impact on the environment since they present good recyclic properties and promote the reduction of CO$_2$ emissions through a reduction of fuel consumption: This reduction would be achieved with structural weight reduction substituting aluminum alloys for magnesium alloys. In fact, this is the main reason to justify the great interest on this type of alloys. However, the hexagonal close-packed (HCP) crystal structure provides a peculiar mechanical behavior under multi-axial loadings, thus it is essential to study and research this type of alloys.

Considering the benefits that morphing structures and devices may provide to an aircraft, seamless and gapless high lift devices are easily identified as a new trend on the aeronautical design. Having that the magnesium alloys are considered materials with great potential for future applications on automotive and aeronautical industries and are commonly seen as a good alternative to aluminum alloys, this work aims to design a smart droop nose device with AZ31B magnesium alloy, this way a concept and a material often related to future trends are assigned. Since it is crucial to assess accurately the fatigue crack propagation lives and final fracture modes, this issue have kept the scientific attention. There are a lot of studies regarding this problem on steels but just a few on magnesium alloys. Plus, the state of the art on the research of smart droop nose devices neglects fatigue and material behavior under cyclic loading of the components. Generally complex shapes and multi-axial loading conditions lead to the initiation and propagation of fatigue cracks, causing structural failure. Thus, this work also aims to provide a study on the critical plane orientation of the AZ31B magnesium alloy when subjected to multi-axial loading, [2].

2. Smart Droop Nose Background

The objective of this work is to design a smart droop nose device using a magnesium alloy in the compliant mechanism. The starting point to the research and design of the smart droop nose is the work developed by Radestock et al. in DLR, where it is considered an UAV with 4m of span. It consisted on a skin optimization with the main objective to realise a skin layup and a load introduction point, to match the target shape. Later, a topology optimization was performed to realise a compliant mechanism to be placed inside the leading edge. After this step, the mechanism was manufactured and tested in a experimental investigation to clarify the divergence between the simulation and the manufactured kinematic, [10].

The final result consisted on a compliant mechanism attached to the skin through a omega stringer, actuated by a servo-mechanism. This device has a particular feature: it provides a positive droop nose, deforming the leading edge to a upper position, in contrast to the majority of the smart droop nose investigations that deform the leading edge to a lower position. In figure 2 are shown some details of the device, [10].

![Figure 2: Assembled device, [9]](image)

Figure 2: Assembled device, [9]

1. Skin: some holes for countersunk bolts can be observed;
2. Stringer: its function is to attach the compliant mechanism and the skin; it is located in the upper surface of the skin and presents some reinforcement plates contacting with the actuation mechanism. However, no information was provided in regard to the connection of this part with the skin, nor between this part and the compliant mechanism;

3. Compliant Mechanism: applies the actuation motion from the servo-mechanism into the skin; It is connected to the front spar through a fixing part: pins, bolts or similar; The upper part is completely constrained but the lower one allows the actuation of the servo-mechanism. This concept is based on the flexure hinge, since it bends and allows rotation of other parts.

4. Servo-mechanism: provides the necessary actuation to the desired droop nose;

5. Front Spar: where the servo-mechanism and the skin are fixed;

3. Magnesium Alloy Background

Structural materials present different properties according to the cyclic and monotonic regimes that they are exposed. Magnesium alloys tend to have a cyclic hardening behavior highly dependent on the grain refinement, purity, lattice intrinsic behavior like twinning or foundry transformation processes. The mechanical properties of the AZ31B-F magnesium alloy are presented in table 1, [2].

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus [GPa]</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>Density [Kg/m³]</td>
</tr>
<tr>
<td>Hardness [HV]</td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
</tr>
<tr>
<td>Yield strength [MPa]</td>
</tr>
<tr>
<td>Elongation [%]</td>
</tr>
<tr>
<td>σₖ Fatigue strength coefficient</td>
</tr>
<tr>
<td>b Fatigue strength coefficient</td>
</tr>
<tr>
<td>εₖ Fatigue ductility coefficient</td>
</tr>
<tr>
<td>c Fatigue ductility exponent</td>
</tr>
</tbody>
</table>

Table 1: Mechanical properties of AZ31B-F magnesium alloy

There are several models to estimate the critical plane orientation and multiaxial fatigue life, projecting the stress tensor in several planes to determine the one which maximizes the inherent damage parameter.

3.1. Fatemi and Socie Criterion

The Fatemi and Socie model suggests that the critical plane orientation θ is the one that maximizes the F-S damage parameter:

\[ max_\theta \left[ \frac{\Delta \gamma}{2} \left( 1 + k \frac{\sigma_{n,max}}{\sigma_y} \right) \right] \] (1)

where \( \Delta \gamma \) is the shear strain range, \( \sigma_y \) is the material’s yield tensile strength, \( \sigma_{n,max} \) is the maximum normal stress on the plane of maximum shear strain and \( k \) is a material constant, [7].

3.2. Smith, Watson and Topper Criterion

This model is a critical plane model based on principal strain range plane and maximum stress on that plane, and can be expressed by the following equation:

\[ max_\theta \left( \frac{\sigma_{n,max} \Delta \varepsilon_1}{2} \right) \] (2)

where \( \sigma_n \) is the normal stress on a plane \( \theta \) and \( \Delta \varepsilon_1 \) is the principal strain range on that plane, [2]

3.3. Liu Criterion

Liu’s model to estimate the fatigue life is based on the virtual strain energy. For multiaxial loading, this model considers two parameters associated with two different modes of fatigue crack: Mode I (tensile failure) and Mode II (shear failure), and the virtual strain energy is given by the sum of elastic and plastic work components. Failure is expected to occur on the plane in the material with the maximum virtual strain energy quantity.

\[ \Delta W_I = (\Delta \sigma_n \Delta \varepsilon_n)_{max} + (\Delta \tau \Delta \gamma) \] (3)

\[ \Delta W_{II} = (\Delta \sigma_n \Delta \varepsilon_n) + (\Delta \tau \Delta \gamma)_{max} \] (4)

Where \( \tau \) and \( \gamma \) are the shear stress range and shear strain range, respectively, \( \Delta \sigma_n \) and \( \Delta \varepsilon_n \) are the normal stress range and normal strain range, respectively, [2].

4. Smart Droop Nose Design Strategy

The initial specifications to design the smart droop nose are: wing span of 4 meters, chord of 0.6 meters, leading edge morphing of 30% of the chord, NACA 2510, servo-mechanism to transfer loads from the compliant mechanism to the skin through an omega stringer which is capable of transmitting both forces and moments, flexible fiber glass composite for skin of 42 GPa of Young’s modulus and 0.26 of Poisson’s ratio.
4.1. Design Framework

It is necessary to guarantee that the smart droop nose will provide aerodynamic improvements, that it will match the target shape and the mechanism can withstand the loads within its yield strength. Thus, a design process was established, as represented in figure 3.

![Design framework](image)

Figure 3: Design framework

To perform the aerodynamic assessment was used the software Javafoil® which provides traditional methods and several tools to study airfoils; The backbone of the program uses the potential flow analysis done with a higher order panel method (linear varying vorticity distribution). The analysis were performed using Reynolds numbers of 450,000, 650,000, 830,000 and 1,000,000.

The structural optimization was performed using a routine of Ansys® APDL and an algorithm with the function fmincon of the Matlab® Optimization Toolbox; This function uses finite differences to calculate the objective function and, verifying the applied constraints, finds a local minimum. This process required as input the finite element model and used as variables the skin and compliant mechanism thickness distribution, the stringer thickness and the actuation performed by the servomechanism to fit the target shape. As the objective of the design is to match the target shape, the objective function is the minimization of the maximum error that occurs between the deformed shape of the structure and the target shape. Thus, is necessary to build carefully a post-processing model able to deliver the error of the deformed shape. The base line of the post-processing algorithm is the comparison of the displacements of the skin nodes with the target shape; For this, it is essential to compute the local, maximum and mean errors.

5. Material, Equipment and Methods

The objective of this work is to add value and information to the investigation done by Anes et al., testing the alloy under different cyclic conditions: 0°, 30°, 45°, 60°, 90° proportional and 45° non proportional loading, see figure 4, and with this trying to cover the broadest selection of loading conditions.

![Loading paths](image)

Figure 4: Loading paths

The experimental tests were performed in the Instrons biaxial servo-hydraulic machine, model 8874 on the laboratory of mechanical engineering department of Instituto Superior Técnico. The geometry of the specimens used are represented in the figure bellow.

![Specimen geometry](image)

Figure 5: Specimen geometry [mm]

To analyze the fracture surface was used the Veios USB digital microscope also present in the laboratory.

6. Structural Optimization Results

After the optimization of the skin thickness distribution, compliant mechanism thickness distribution and actuation of the servomechanism, the final deformed structure is represented on figures 6,7 and 8.

![Deformed structure](image)

Figure 6: Deformed structure at white and target shape at blue

4
The Mean and Maximum error of the final deformed structure to the second target shape are the following:

- \textit{Mean Error} = 0.175\%
- \textit{Maximum Error} = 0.424\%

The actuation done by the servo-mechanism is approximately \(16^\circ\).

The results of the skin thickness optimization are represented in tables 2, 3, 4 and 5.

To facilitate the comprehension of results of the compliant mechanism optimization, first is necessary to divide it in 3 different parts, illustrated in figure 9, for which the thickness distribution will be present in tables 6, 7 and 8.
Tables 7 and 8 show the thickness distribution of parts B and C of the compliant mechanism.

Table 7: Results of the optimization of part B of compliant mechanism

<table>
<thead>
<tr>
<th>Location [cm]</th>
<th>3.330</th>
<th>7.998</th>
<th>8.272</th>
<th>12.336</th>
<th>15.300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness [mm]</td>
<td>3.778</td>
<td>2.995</td>
<td>2.352</td>
<td>4.816</td>
<td>5.832</td>
</tr>
</tbody>
</table>

Table 8: Results of the optimization of part C of compliant mechanism

<table>
<thead>
<tr>
<th>Location [cm]</th>
<th>4.800</th>
<th>7.998</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness [mm]</td>
<td>2.467</td>
<td>3.682</td>
</tr>
</tbody>
</table>

Figure 10 shows the CAD model of the compliant mechanism. Fillets were added; this may have a positive impact on reducing the stresses on the magnesium alloy, although it might increase the mechanism weight.

6.1. Aerodynamic Assessment

Tables 9 and 10 show the variation in stall angle and lift coefficient respectively. It can be noticed that for discretization with 100 or more points the results do not vary significantly, therefore can be considered converged.

Table 9: Stall angle of the normal and the deformed airfoil for different Reynolds numbers, calculated in Javafoil varying the number of airfoil points

<table>
<thead>
<tr>
<th>N Points</th>
<th>450,000</th>
<th>650,000</th>
<th>830,000</th>
<th>1,000,000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Def</td>
<td>Normal</td>
<td>Def</td>
</tr>
<tr>
<td>51</td>
<td>10°</td>
<td>12°</td>
<td>11°</td>
<td>12°</td>
</tr>
<tr>
<td>101</td>
<td>10°</td>
<td>12°</td>
<td>10°</td>
<td>12°</td>
</tr>
<tr>
<td>149</td>
<td>10°</td>
<td>12°</td>
<td>10°</td>
<td>12°</td>
</tr>
</tbody>
</table>

Table 10: Lift coefficient, $C_l$, of the normal and deformed airfoil for different Reynolds numbers, calculated in Javafoil varying the number of airfoil points

6.2. Remarks

Structural Optimization

Analyzing the previous results of the structural optimization is possible to take the following insights:

- From figure 6, it is possible to observe that the final deformed shape of the droop nose is quite similar to the first target shape; when comparing it with the second target shape, having a Mean Error of $0.175\%$ and a Maximum Error of $0.424\%$, it is easy to understand that the errors are quite small; for instance, the maximum error is equivalent to $0.76\, \text{mm}$.

- Another important result taken out from the structural optimization is the actuation performed by the servo-mechanism: $16^\circ$, which is absolutely possible to perform.

- The skin thickness distribution (having a maximum of $2.55\, \text{mm}$), when compared to the work of Radestock et al. with a constant thickness of $2\, \text{mm}$, is acceptable.

- The maximum von Mises stress in the compliant mechanism is $200\, \text{MPa}$ which is below the yield strength of the AZ31B-F magnesium alloy, verifying the constraints of the model.

This result demonstrates that the structural optimization was useful, since the final result provides a very good deformed shape, acceptable results and all the constraints were verified.

Aerodynamic Optimization

Regarding the aerodynamic assessment of the droop nose, tables 9 and 10 are clear: the deformed configuration of the droop nose provide aerodynamic improvements for a broad range of Reynolds number. This improvements vary with the number of discretization points of the airfoil, but as referred in section 4 this happens due to the panel method used in Javafoil$.^{\text{®}}$ From Table 9, where it is synthesized the variation of the stall angle, $\alpha_s$, it is possible to observe that for higher Reynolds ($830,000$
and 1,000,000), the stall angle increases 1°, but for lower Reynolds (450,000 and 650,000), when the $\alpha_s$ plays an important role, in general the droop nose configuration provides an increase of 2°.

Regarding the table 10 some conclusions can be drawn. For instance, considering the coefficient of lift:

$$C_l = \frac{L}{\frac{1}{2}\rho v^2 c}$$  \hspace{1cm} (5)

where $L$ is the Lift, $\rho$ is the density of air, $v$ is the velocity and $c$ is the airfoil chord, is possible to build a relation between the stall speed of the normal and the deformed airfoil:

$$\Delta v_{stall} = 1 - \sqrt{\frac{C_{l,\text{normal}}}{C_{l,\text{deformed}}}}$$  \hspace{1cm} (6)

where the subscript normal and deformed stands for the normal and deformed configuration. Thus, we can calculate the variation of the stall speed for the two configurations:

<table>
<thead>
<tr>
<th>$\Delta v_{stall}$ [%]</th>
<th>Reynolds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>450,000</td>
</tr>
<tr>
<td>149</td>
<td>5.55</td>
</tr>
</tbody>
</table>

Table 11: Relation [%] of stall velocities computed with equation 6

From the table 11 is possible to observe that in average the stall speed was reduced 5% which is an improvement.

Another important insight that is possible to quantify is related to loiter flight condition. Having that the loiter flight condition requires a high $C_L$ value and that the flight endurance is given by, [5]:

$$E = \frac{1}{C} \frac{L}{D} \ln \left(\frac{W_i}{W_f} \right)$$  \hspace{1cm} (7)

where $E$ is the endurance, $C$ is the thrust-specific fuel consumption (depends on the engine), $D$ is the drag and $W_i$ and $W_f$ are the initial and final weight of the aircraft during the loiter time, respectively. Considering a loiter condition for the same velocity and having that the thrust-specific fuel consumption remains constant and for the same amount of fuel, the droop nose configuration provides a higher $L/D$, which leads to an increase in loiter time.

7. AZ31B-F Results

The experimental life results concerning the nominal equivalent von Mises stress are presented in figure 11.

7.1. Critical Plane Analysis

The figures below show the critical plane results for the loading paths studied.

Figure 11: Experimental life concerning the nominal equivalent von Mises stress

Figure 12: Fatemi model: Fatigue damage parameter and plane orientation

Figure 13: SWT model: Fatigue damage parameter and plane orientation
Concerning the figure 11 is possible to observe that basically all the proportional loadings have the same trending line, leading to conclude that the von Mises equivalent stress is a good candidate to perform fatigue life correlations. Additionally, in the non proportional case, the strain energy involved is higher than the other loading cases on same fatigue life region, which indicated the activation of twinning mechanisms leading to a different mechanical behavior, [2].

Analyzing the table 13 and all the figures above, is possible to take the following insights:

- Regarding the case I, the models SWT and Liu I provided the best results which somehow is expected since both models predict that crack growth will happen on planes of maximum tensile stress or strain. However, having this stated case II presents interesting results because the loading is purely shear and both models predict the critical plane correctly.
- In regards to the case III, the non-proportional loading, non of the studied models provide acceptable results.
- For case IV, non of the models make correct prediction, but is fair to mention that all provide acceptable results.

8. Conclusions

The main purpose of this work was to design a smart droop nose device using the magnesium alloy AZ31B-F and evaluate the applicability of this type of materials as structural element in the aeronautical industry. Given that the behavior of this material under multiaxial loading condition is still under research, experimental tests were performed in order to have the broadest spectrum of loading conditions which might help the engineers during the design process since all the theoretical cases of design were covered.

Regarding to the design of the smart droop nose, the main achievements were:

- A methodology to design a smart droop nose was developed and implemented; It involved the development of Matlab® scripts to create target shapes, a structural optimization to guarantee that the targeted droop nose is structurally feasible and an aerodynamic assessment to ensure that the deformed shape provides aerodynamic improvements.
- It is possible to conclude that this methodology was useful since the final result provides a very good deformed shape, acceptable results and all the constraints were verified.
Regarding the aerodynamic assessment, the improvement provided by the smart droop nose can be synthesized as: increase on the \( \alpha_s \), increase on the \( C_l \), reduction of about 5% of the stall velocities and increase in the loiter time.

Using the AZ31B-F magnesium alloys in specific structural elements can represent weight savings of about 36% comparing with the 2024 aluminum alloys broadly used in aeronautical industry.

Regarding to the experimental test in the magnesium alloy, the main achievements were:

- The 6 cases studied cover all the theoretical design cases.
- Just some of the plane models studied provided acceptable results for the crack initiation angles; Some insight can be inferred:
  1. For pure axial loadings, SWT and Liu I provided excellent results. The same can be said for pure shear loading, even though it was not expected since this models make predictions based on the planes with maximum tensile stress or strain.
  2. For non-proportional loading case, non of the studied models provided acceptable results.
  3. For cases of proportional biaxial loading of 30\(^\circ\), 45\(^\circ\) and 60\(^\circ\) Liu II provide good results, and FS also deserves to be mentioned since it provided fair estimations.
  4. Additional experimental tests should be performed in order to obtain more data and consolidate these conclusions.

8.1. Future Work

- Other skin material should be researched and implemented in order to compare the results and evaluate which one provides better structural integrity.
- Additional optimizations might be performed. For instance, an aerodynamic optimization to define the best profiles and target shapes for the droop nose. This step can be added to the framework already developed.
- Since there is no computational models available to study the elastic-plastic behavior of the AZ31B-F, it is fundamental develop a routine on a finite element software to simulate its unique behavior. Some research have been done about this topic and can be found in [12, 11, 1].
- Having the previous topic completed, a numerical study regarding the fatigue assessment of the compliant-mechanism can be performed; A comparison between the fatigue lives of magnesium and aluminum alloy should be done. Additional results will be added in regards to the evaluation of the applicability of magnesium alloys in the aeronautical industry as structural component.
- Research and design other aircraft/morphing structures likely to have magnesium alloys as structural component.
- Perform more experimental tests to have additional results and to be possible to make more plausible conclusions.

References


