Abstract

In a search to increase the airplanes life cycles, the maintenance companies attempted to develop methods and solutions capable of guarantee a perfect performance, keeping the high levels of security.

This prolongation of the airplanes life is only possible thanks to the incessant investigation work of the engineers, predicting, simulating and solving any kind of possible problems. Considering these circumstances, the present work consists in the development of a finite element model of a wing, more precisely, the Locked C-103H side wing, for a computerized simulation of loads and identification of structure critical zones.

For a better comprehension of the load types existing in the airplane wing, a study of aerodynamic parameters is performed with the help of PSW (Personal Simulation Works) program, based on the panel method theory.

The finite elements model is created in Ansys Program and the stress calculations are based on deformations method.

Different types of load were studied, trying to recreate the stresses produced on the airplane structure, in similar conditions encountered on the aircraft flight envelope.

Given the results, regarding aerodynamic parameters and also structural analysis, we identified some critical areas of the wing, where the values of stress are very high, and therefore requiring special attention during inspection. Since this is a structure that operates for more than 30 year, this study confirmed its operation limits.

Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>FS</td>
<td>Safety Factor</td>
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<tr>
<td>n</td>
<td>Load factor</td>
</tr>
<tr>
<td>a</td>
<td>Acceleration</td>
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<tr>
<td>L</td>
<td>Lift</td>
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<tr>
<td>T</td>
<td>Thrust</td>
</tr>
<tr>
<td>D</td>
<td>Drag</td>
</tr>
<tr>
<td>W</td>
<td>Weight</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration of gravity</td>
</tr>
<tr>
<td>α</td>
<td>Angle of attack</td>
</tr>
<tr>
<td>C_l</td>
<td>Lift coefficient</td>
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<tr>
<td>C_d</td>
<td>Drag coefficient</td>
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<tr>
<td>C_m</td>
<td>Pitching moment coefficient</td>
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<tr>
<td>c</td>
<td>Airfoil chord</td>
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<tr>
<td>R_e</td>
<td>Reynolds number</td>
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1. Introduction

This project, called "Structural Analysis for C-130H wing", arose from a proposal made by "OGMA - Indústria Aeronáutica de Portugal, SA ". This study is based on the needs this company, as a solution to the lack of information and of a detailed study on the aircraft structure.

One of the important programs of this company is the maintenance of aircraft of the Lockheed C-130 type, hence the need for a project of this type. OGMA industry provided a direct contact with the structure and resources necessary for its implementation.

The company “OGMA - Indústria Aeronáutica de Portugal, SA” is a company of aeronautical activity, founded in 1918 and to this date is dedicated to the manufacture and maintenance of aircraft. The company now belongs mostly to EMBRAER and EADS, which in recent years have been improving and increasing the turnover of the company.

This company compete in the civil and military aviation market, with the certification FAR 145 and EASA 145 Repair Station, AQAP 2110 and ISO 9001-2000 Quality Management, and is authorized under maintenance for products of different manufacturers (OEM's), as are the Lockheed Martin, Embraer, Rolls-Royce, Turbomeca and others. Provide services such as maintenance, servicing and modernization of aircraft, engines and components, manufacturing and assembly of structures.

This study aims at the analysis the wing structure of aircraft Lockheed C-130. According to the needs of the company for service provided for
aircraft of this type, we set the following main objectives of the project:
- Determination of aerodynamic forces applied to the structure, within its flight envelope;
- Building a numerical model of the structure, this may be used in different programs;
- Establish and conduct a joint analysis of the structure;
- Identify the critical points of the structure and the margins of safety;

As such, the project was developed having as objectives the increase of knowledge in various areas such as computational mechanics, aerospace structures, aerodynamics, vibration and noise, among others.

The project used commercial programs: MATLAB, for data processing, ANSYS to perform the analysis of the structure, PSW to study the aerodynamic and Solid Works for creating 3D models.

2. Lockheed C-130

This aircraft has over 40 models that operate in more than 50 nations and a record of more than 50 years of service, demonstrating reliability and durability. It is still used in several military missions, civilians and even humanitarian aid. O C 130 Hercules was one of the most successful aircraft built in the history of aviation, unsurpassed in its versatility, performance and efficiency of missions.

The base configuration is a turbo-propeller (four engines) with a high wing. Hundreds of changes were made for different configurations to meet a constantly changing environment and requirements of new missions. Its first versions C-130A, B, D were removed from service, but new versions continue to be operated with great success.

The C-130H is the third generation, version equipped with engines T56-A-15, with 4910 hp. The latest generation of the C-130, is known as the "J". Then we can see a photo of the prototype C-130J.

![Figure 1 - C130H](image)

The quality and reputation of this aircraft, does not prevent the occurrence of a disaster due structural failure. In an attempt to increase the life cycle of the aircraft and trying to ensure a low risk of structural failure, maintenance engineers increase the tests inspection and limit the operation of the aircraft. The problem is that sometimes these tests and inspections are not sufficient to prevent problems hitherto unknown.

One of these problems occurred due the failure of structural fatigue in the central wing of the C-130A aircraft that caused the disaster of some aircraft. A disaster occurred in 1994 with the type of aircraft C-130A near Walker, Calif. An inquiry into what happened was conducted and concluded in 1997 that was due to structural failure caused by fatigue leading to a straight line fracture in station 53 of the wing right side (WS53R). WS mean "Wing Station" is the length along the wing and the fuselage is intercepted by the WS61. Left wing fractured at the same location WS53L. The fatigue tests have shown the great importance of the choice of materials.

Between 1995-2000 the Service Life Analysis (SLA) studied the occurrence of collapse due to fatigue in the wings of the C-130E / H and the estimation of the time life of this structure, but in 2001-2004 inspections in the aircraft C-130E / H showed that 123 aircraft were affected with fractures by fatigue in the central wing and that its occurrence was before the time specified by the SLA. This was one of the main problems of the family of C-130 aircraft.

3. Aging Aircraft

In every sector of aviation, aircraft fleets are being operated up to and beyond their designed service lives. The advanced age of these aircraft brings about new challenges for operators, maintainers and logisticians as they attempt to maintain the system’s capabilities well beyond the original designer’s specifications.

The strategy of retaining aircraft beyond their initial service life estimate reduces the costs of recurring procurement. This strategy is often employed as an effort to control costs in a restrictive budget environment. However, it also results in higher support costs as the aircraft age. The Figure presents the historical data on the KC-135, 727, 737, DC-9, and DC-10 heavy maintenance workload. It shows a workload increase from five to nine times over a 40 year period when compared to the first heavy maintenance inspection. While increasing costs cannot be completely avoided, a thorough understanding of aging aircraft concerns will make it possible to at least minimize the growth of these costs, (Pyles, 1999):

![Figure 2 - Heavy-Maintenance Workload (Pyles, 1999)](image)
Establishing a method of management of aging aircraft is the biggest challenge for the operators. Through this management it should be possible to increase the aircraft time life and the costs involved before these become uncontrollable.

There are several ways to evaluate these costs, one is the assessment of total cost, since the acquisition, operation and support. "... Experience has shown that a large segment of the cost of the life cycle of a system is assigned to the operation and support activities (e.g., a maximum of 75% of total costs)" (Blanchard, 1998), as it can observed, this kind of cost cannot be ignored.

Figure 3 - Life Cycle Cost distribution for a 30 year system

4. Aerodynamics results - Wing C-130

The study of the aerodynamic of the wing has as main objective the characterization of the distribution of some parameters as the pressure coefficient, lift and drag forces. These parameters are of great importance for understanding the loads on the structure. Through them we can obtain the resulting forces for a given flight condition and then apply it to structure.

The software simulation used was Personal Simulation Works "PSW", which has already been proved as a very efficient program, with very consistent results and very advantageous calculation times. The method used by the program is the method of three-dimensional panels, this method is characterized as a useful and economic tool for airfoils design and analysis.

His first successful implementation was achieved in 1966 by John Hess and A.M.O. Smith, employees of Douglas Aircraft, McDonnell Douglas Corporation.

This method uses a constant distribution of sources and dipoles over the body "wing", and their intensities calculated to satisfy the conditions of impermeability of the body. The intensity of dipoles is determined for the condition of equal pressure in the lower surface and upper surface the trailing edge (Kutta condition) of the body with lift. A detailed description of the panel method can be read in reference (Bortolus, 2002).

Illustrated in the figure below is the aircraft designed in the 3D-CAD program SolidWorks, which we can see the different wing sections.

<table>
<thead>
<tr>
<th>Central Wing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airfoil</td>
</tr>
<tr>
<td>Chord</td>
</tr>
<tr>
<td>Incidence</td>
</tr>
<tr>
<td>Span</td>
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</table>

Table 1 - Characteristics central wing

<table>
<thead>
<tr>
<th>Lateral wing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evolutive airfoil</td>
</tr>
<tr>
<td>NACA 64A-318</td>
</tr>
<tr>
<td>Incidence</td>
</tr>
<tr>
<td>Taper ratio</td>
</tr>
<tr>
<td>Span</td>
</tr>
<tr>
<td>Dihedral</td>
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</tbody>
</table>

Table 2 - Characteristics lateral wing

Pressure coefficient $C_p$

The pressure coefficient is studied examining the behavior of this parameter for different angles of attack and a Reynolds number of fixed $Re = 3 \times 10^6$.

In the following figures we can observe the evolution of the pressure coefficient $C_p$ vs $\alpha$ angle of attack along the chord on the wing root.

The analysis of these distributions identifies two important areas: the leading edge
where there is usually a stagnation point, i.e., velocity of flow at that point is zero and the area where the pressure coefficient is maximum in modulus, this corresponds to a area of minimum pressure and maximum flow speed. For the graph of $C_p$ in upper surface shows that, with increasing angle of attack, the suction peak moves in the direction of the leading edge and its value increases in module, which is explained by the increase in curvature the stream line. The intensity of the adverse gradient pressure that is present after the peak suction also increases with increasing angle of attack due to the radial gradient of pressure which varies with the curvature of the stream lines around the airfoil.

In the lower surface this behavior is approximately the inverse of the upper surface.

$C_L$ along the span

The distribution of $c.C_L/c_{med}$, proportional to $L_{2D}$ and to circulation $\Gamma$ at the wing along span is showed bellow. The results are relative to $\alpha=8^\circ$.

![Figure 7 - $C_{L2D}/C_{L3D}$ along the span](image)

![Figure 8 - $c*C_L/c_{mean}$ along the span](image)

The evolution of $C_{L2D}$ is approximately constant for $y/s \leq 0.4$ and the maximum value of $C_{L2D}$ occur for $y/s = 0.7$.

The figure shows that this distribution is similar to elliptic wing (Brederode, 1997) (page. 585). A low taper ratio, such as the rectangular wing, causing a high load on the tip zone, while a wing with high taper ratio, such as triangular wing, will have an opposite effect. In this case, a trapezoidal wing with 0.5 taper ratio, has a medium effect similar to the elliptic wing.

5. Finite element method - Wing C-130

In most cases the aerospace structures are very complex structures, consisting of a combination of different structural elements (beams, plates, boxes) and different materials. These structures cannot be described or approximated by a mathematical equation due to its complexity, so the traditional methods of structural analysis cannot be applied. It is thus necessary to use finite element method to formulate structures in algebraic equations.

Let's then the present of the structure under study. The C-130 aircraft is constructed mostly of materials in aluminum. Steel and titanium are used only for special purposes such as protection of exhaust and basic structural members. The fuselage of this aircraft was designed to be pressurized and sealed only by the fuselage skin and panels doors. The wing were designed to sustain a high lift force, with “cantilever” type of construction and incorporates six fuel tanks of approximately 6700 liters of fuel with an option for additional external tank of 1300 liters.

The "wing" group, consist in a central wing that extends to both sides until station 220 and two lateral wings, attached to central. Each section of the wing is a "box" formed by a front and rear spar covered by a upper and lower panel and sectioned by ribs. Spar and panels are reinforced by stringers for increase its rigidity.

In the next figure the structure of the lateral wing of the C-130H is presented. The numerical model will be constructed from this type of information and information available in the technical drawings.

![Figure 9 - Wing structure](image)

Technical approach

This work was done in finite elements using the software ANSYS.

The model created here, tried to represent the structure as close as possible to reality, but due to the structural complexity of the wing some approximations would be made. Elements of connection between sections are not considered. Also it was considered that the elements of the structure would be solidly connected (welded).

The wing was modeled by a set of lines and areas describing the position of the different structural components, this model is shown in the figure below:
Thereafter the panels were applied to cover this structure and its reinforcements, providing stability to the bending of the panels.

Defined the geometry of the structure, it was necessary to apply in each line and area a corresponding component. For this structure three types of finite elements were used: the Beam188 for the beams and Shell99 and Shell63 for the areas.

It was necessary to define the sections of each component. This step was made in the program, individually, creating each type of sections and storing the information on file with the name of the section, thus providing a library of sections. To clarify this step, we show the creation of Section LS-5004. It created the geometry and the corresponding mesh section. Below the section applied along a line through the element Beam188 is showed.

With all sections applied a wing model is created. The following picture is a zoomed section of the wing where the application of sections is visible.

The final model is shown in the figure below.

6. Aircraft load - C-130 wing

In literature there are four basic conditions aircraft flight that create the maximum tension in component wing, they are:
- Positive high angle of attack (PHAA);
- Positive low angle of attack (PLAA);
- Negative high angle of attack (NHAA);
- Negative low angle of attack (NLAA).

These flight conditions represent symmetrical flight maneuvers.

In the case of an airplane in flight with no horizontal acceleration, the engine thrust is equal to the airplane drag, and the horizontal components of the inertia and gravity forces are zero. The weight and the inertia force on the airplane act down and will be equal to the lift. The airplane lift \( L \) is the resultant of the wing and tail lift force. The load factor is defined as follows:

\[
L = Mg = Ma \iff L = Mg + Ma \iff
L = Mg(1 + a \, g) = W(1 + a \, g) = nW
\]

\[
n = 1 + \frac{a}{g}
\]

In case where the aircraft makes a stationary flight load factor is \( n = 1 \), since \( L = W \) the weight is balanced by lift.
If you combine the weight and inertial load on each element, the component in the z axis can be defined as follows:

\[ L - W \cos \theta = \left( \frac{W}{g} \right) a_z \Rightarrow L = W \left( \cos \theta + \frac{a_z}{g} \right) = nW \]

\[ n = \cos \theta + \frac{a_z}{g} = \frac{L}{W} \]

The aviation regulations require that the combination of speed and load factors to be illustrated by a diagram called V-n diagram. In this diagram the indicated airspeed (IAS-Indicated Air Speed) is showed because is proportional to dynamic pressure \( q \), which means that this diagram is equal to any altitude, when neglected effects of compressibility.

7. Results and discussion

Analysis of bending

Boundary conditions

For the tests performed, the wing was fixed on root, i.e. the points of connection between the lateral wing and center wing are barred from any degree of freedom (displacements and rotations). This condition is not as close to reality, because it will cause points with high tension loads. This happens because the wing cannot transfer the stress to the central wing.

Maximum bending

For the study of the maximum bending on a wing two fixed positions for loading were imposed. The intensity of the load is increased linearly until the value of maximum stress in components of the wing. The values for each load vs. displacement and load vs. stress be recorded and presented in graphs in order to monitor the behavior of the structure.

We chose to apply the loads in two ribs, at 0.6 wing span and another on the wing tip, ribs 22 and 33 respectively. The applied load is proportional to the distribution of CL obtained in stationary flight. In graph of the distribution of CL with the span we see that the lateral wing supports about 70% of the aerodynamic load. Considering a new image including only the lateral wing, the load applied in ribs is proportional to the area in graph.

The load is expressed in G’s, 1G correspond to the weight of the aircraft which is for 155,000 lbs maximum takeoff weight. As the two sides of the wings support 70% of the load, in our case 1G will be 54,250 lbs for each lateral wing.

The limits of the V-n diagram are -1G and 2.5G, the structure should be capable to resist of these loads, although we have some approximations.

The following figure shows the deflection of the wing with the loading of 2.5G, there is a maximum deflection at the tip of the wing about 48 in. The points with color red corresponding to maximum deflection and color blue minimum.
The following figure shows the distribution of stresses on the wing, we can see in figure that the maximum tensions occur in proximity the root of wing in upper surface.

The maximum value occur in the corner of the wing, and its' value is 75,172 psi. Near the corner there is a high gradient stress, this is caused by the boundary condition (fixed wing), that prevents the transmission of the efforts. This value will be ignored, since they make no sense.

For the analysis of stress, the rib closest to the root will be used, corresponding to rib number 2, at 18 inches of the root. Then we present the evolution of displacement and stress for points 73 and 102 of the numerical model located in rib 2. The point 73 corresponds to a point on upper surface, as identified in the figure and the point 102 is located on the lower surface.

In graphs presented above we can observe an evolution of the linear displacement and of the stress as could be expected. They do not exceed the permissible limits of materials used. Whereas for an aircraft of this type a maximum load factor is 2.5G (AA Agency, 2007) and assuming that the maximum stress occur in point 73 and has a value of approximately 60,000 Psi, we that the safety factor of 1.5 is not satisfied. For this safety factor, is necessary to obtain a value of 3.75g, but this model has only reaches a value of 3.46g for maximum possible loading. This is limited by the allowable stress of the material used (Alu 7075-T6) of 83,000 Psi. The factor of safety obtained for this model in this type of test is approximately 1.38.

**Analysis of the four main flight conditions**

This section will study the behavior of the wing for the four main conditions of flight. The type of load applied on the wing will be obtained using maximum weight takeoff 150000lbs and load factors of the V-n diagram. The resulting force applied to the aircraft center of gravity is obtained by:
\[ n = \frac{R}{W} \]

For load factor of 3 and maximum weight takeoff, we have a normal force equal to:
\[ R = nW = 3 \times 155000 \text{ lbf} = 465000 \text{ lbf} \]

Obtained the resulting force, the wings will be able to balance normal component, i.e.:
\[ F_z = nW \cos(\alpha) \]

Knowing that the lateral wings are responsible for creating 70% of this force, we obtain the load to be applied on each lateral wing, which corresponds to 35% of the total force.

The load will be distributed by 29 points in each rib, in a total of 928 points. The distribution over the span and the chord is made considering the data obtained in the chapter of aerodynamics. The load will be distributed considering the normal component of resulting force in the wing, considering a distribution along the chord and the span for the angle attack of desired flight condition. In the analysis of the four flight conditions is considered only the normal component of the resulting force, is easily understood that the horizontal component of the resulting force causes a compression in leading edge and a traction in trailing edge for conditions in which its x component points in the leading edge direction (conditions NHAA and PHAA) and the reverse when points to the trailing edge (conditions PLAA and NLAA). The treatment of these data is done in an Excel sheet and then added to the file in ANSYS.

Following figure illustrates the loading in ANSYS environment for PHAA condition.

Positive high angle of attack (PHAA)

The PHAA is a condition with load factor of 3. We obtain thus the following loading:

Doing the analysis of stresses and displacement for the proposed loading, we obtain the following distributions with a maximum displacement of 26,783 in.

It can be observed that this condition causes a compression in the upper surface and traction in a lower surface, but that due to the uneven distribution of the load it also causes a negative moment torsor (clockwise looking). The combination of bending moment and torsor caused by this type of loading causes the greatest tension is transmitted to the front, namely in the upper cap of front longeron.

For this flight condition the maximum stress is approximately 57,000 Psi, corresponding to a safety factor of 1.45.

From this analysis it is identified as critical areas, the surface of the wing in the regions closest to the root and front and connecting on these.

Positive low angle of attack (PLAA)

Corresponding to this condition of flight small angle of attack and also positive load factor of 3G, we can observe the load distribution is not so concentrated on the front longeron which will reduce the intensity of the torsor moment created.
The distribution of stresses for this flight condition is similar to the bending test, but getting a better safety factor due to the load distribution across the wing. For this flight condition, the displacement and the maximum stress shown to be below that recorded for the condition PHAA. Although the twisting moment is lower for this condition, it exists. The compressions appear at the top and traction on the bottom. If we had also considered the horizontal component, in this case it would be contrary to the PHAA, the stress will be transfer to the trailing edge. There by transferring maximum stress for the rear upper cap.

**Negative high angle of attack (NHAA)**

For condition of negative angle, the total load applied is much lower than the other conditions, this is associated with a load factor of -1G. The figure illustrates the distribution of load to the condition NHAA, high negative angle of attack.

![Figure 31 - Load distribution for lateral wing of NHAA](image)

Is clear, that this produces the opposite to condition PHAA, i.e., compression at the lower surface, traction at the upper surface and a positive moment (anti-clockwise). The horizontal component of resultant force will cause the maximum stress is transmitted to the front, occurring in the lower cap of front longeron.

**Negative low angle of attack (NLAA)**

This condition is from small negative angle of attack also with load factor of -1G.

![Figure 32 - Load distribution for lateral wing of NLAA](image)

These conditions produce compression at the lower surface, traction at the upper surface and a moment torsor of low intensity in a positive direction. The horizontal component of this condition transmits stress to rear of wing.

**Modal analysis**

For the study of natural frequencies of the wing, it should be ensure that they are not within the values of the frequencies of operation of the components aircraft, such as engines or external sources, such as gusts. The main sources of vibration in the wing are engines. In present aircraft, the engine operates in a range between 13820rpm and 2500rpm, which corresponds to a frequency range between 40Hz and 230Hz. The propeller attached to the engine operates between 184rpm and 1020rpm, which represent 3Hz and 17Hz respectively.

The natural frequencies of the structure were calculated using the program ANSYS. We present the natural frequencies of the wing with coating.

**Natural frequencies**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Freq. (HZ)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>0.13745</td>
</tr>
<tr>
<td>2</td>
<td>0.26195</td>
</tr>
<tr>
<td>6</td>
<td>0.55062</td>
</tr>
<tr>
<td>14</td>
<td>1.0064</td>
</tr>
<tr>
<td>17</td>
<td>1.1202</td>
</tr>
<tr>
<td>19</td>
<td>1.1770</td>
</tr>
<tr>
<td>36</td>
<td>1.8546</td>
</tr>
<tr>
<td>43</td>
<td>2.0839</td>
</tr>
<tr>
<td>53</td>
<td>2.4437</td>
</tr>
</tbody>
</table>

**Table 3 – Natural frequency’s**

![Figure 33 – 1º, 2º and 3º vibration mode](image)

**8. Conclusions**

The complex structure of the wing forced a number of approaches. These approaches proved to be satisfactory. For the tests proposed, the root of the wing is fixed support, this boundary condition is not a ideal one, but the results proved to it to be a good approach.

The wing model created by finite element has been tested for different proposes:

- Maximum Deflection;
- Torque;
- Main conditions of flight;
- Modes of vibration.
The results are in good agreement with the conditions of operation of the aircraft and validate the numerical model created.

The condition of high positive angle of attack proved to be the worst flight condition, causing high tensions in components of the wing. It was found that the critical areas for this flight condition are located near the top of the front longeron and panels covering the wing near the root.

Even the case of a finite element model in not fully defined, the tests revealed that the structure is capable of supporting the efforts for which the aerodynamic design and has been calculated a safety factor for flight condition more demanding of 1.45.

For the natural frequency, the values were expected since the model is not fully defined. We can also say that none of the natural frequency is in the range of operation of components associated with the wing, including the engines.

Further improvements should be made to the finite element model to provide a better approximation of the results with reality.

9. Suggestions for future works

In future work the model could be analyzed in the fatigue test. The model accuracy may also be increased and include areas of control and flaps/slats.

The refine model could then be tested to problems of aerelasticidade both in the static, load distribution, and inversion of control, as well in flutter, dynamic response and buffeting.

These are some of the possible future work to perform on this first version of the finite element model wing C-130H.

10. References

- Lloyd, B. C-130 Center Wing Teardown Programs. NAVAIR. Integrated Systems Solutions Inc.