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PAULISTINHA DESIGN AND ANALYSIS

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Abstract: Paulistinha was the first airplane developed and constructed in industrial form in Brazil. It was inspired in the initial designs of the Taylor Cub in US, having however several differences, to accommodate local technological possibilities, mostly. It resulted from a semi-empirical approach, having suffered many changes during its long maturation life, from its start in Ipiranga, São Paulo in the 1930´s up to the end of its serial fabrication in Botucatu, in the late 1970´s. In this research starting, from the drawings of the airplane, a model of the structure is constructed. Wings and fuselage are compiled to detail, from local measures in a real airplane. A model is then developed in computer, from the drawings, to ascertain aerodynamic and structural characteristics. Finite element procedures are used in the analysis. Results show large safety values and therefore margins for improvements with the model. Its concept may be extended to new planes using alternative propulsion, construction materials and applications including the much required versatility of hydroplanes.

Keywords: Paulistinha airplane, drawing, model, stress-strain analysis, failure.

Introduction

Project of Paulistinha started with Empresa Aeronautica Ypiranga, created in 1931, by Fritz Roesler, Orthon W. Hoover and Henrique Santos Dumont. In the beginning only sailplanes were built. But in 1934, the EAY-201 Ypiranga was constructed. It was 6 m long with a wing span of 10.1 m. It was based in the famous american Taylor Cub. It was equipped with a Salmon 9 engine, radial, with only 40 hp of power. Shortly after a Franklin motor of 65 hp was incorporated. Maximum velocity was around 142 km, cruzing at 119 km/h [1].

In 1942 the company was sold to Companhia Aeronáutica Paulista, CAP, whose owner was Francisco Pignatari,an important businessman in Santo André, SP. At the new place, engineers Romeu Corsini and Adonis Maitino implemented modifications to the EAY-201. The first CAP, the number 4, based part of its project in the Piper J- 3, a higher power Cub plane. It was biplace, high wing, steel tubular fuselage structure and balsa win with a shoe at the lower tail. Height of the plane was 2.08 m. New modifications came soon, with a new engine being used: the Continental 65A of 65 hp to turn the wood propeller constructed at the Instituto de Pesquisas Tecnológicas. Now maximum velocity was of 155 km/h, and cruze velocity was 140 km/h.

During the WWII, a new Paulistinha was fabricated everyday, being all components built in Brazil, except for the engine. More than 20 mil pilots obtained their brevet with this airplane for its low cost of maintenance and high reliability. This is also the reason it was adopted as the airplane to equip newly created air clubes in the country. By 1954 with the creation in Rio de Janeiro of the Sociedade Aeronáutica Neiva, the project of Paulistinha turned to new hands. The craft construction was transferred to Botucatu in the interior of São Paulo State, where from start modifications to CAP-4 were addressed. A new engine, a Lycoming of 100 hp, was installed and a new model called P-56, the number referring to the year of 1956 came out.

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Variations of the basic model, according to the engine option appeared with time, but the most important modification was the increase in size of the fuselage, now with 6.76 m in length and 10.76 m in span. The new model was able to fly for 4.5 hours, with the new tanks of fuel. About 260 of these airplanes were constructed in Botucatu. Paulistinhas were used in several applications under modified versions until the company was undertaken by Embraer. By the end, a model able of burning alcohol was introduced in the market, before the project was abandoned and production of Paulistinha ceased. Figure 1 shows the airplane in a museum [2].

Model

Wing Drawing

Paulistinha series was characterized by the use of a high wing, fixed to the fuselage, having two lateral supports, at each side, tied to the landing gear carriage. The semi-wings overall dimensions include length $l_W = 5.38$ m, width $w_W = 1.60$ m and maximum airfoil thickness of circa $t_W = 0.90$ m.

Structural arrangement of wings include a set of seventeen transverse airfoil elements, not equally disposed along

the wing length, with ten complete airfoils, Fig. 2, seven enshortened foils connected to ailerons, Fig. 3 and a special profile element to close the wing. Two small transition elements are also used. These profile parts are fixed to two longitudinal spars, completed with attack and trailing edge elements. All elements are constructed with frejo wood but the aileron elements, that are constructed with aluminium.

In the development of the model, elements of the wing were separated one by one, photographed and measured in detail. Geometric forms in each part were verified and a drawing of the part performed in the ambient of SolidWorks™ program [3]. Complete assemble of the wing structure is shown in Fig. 4.

Fuselage Drawing

Main body of Paulistinha incorporates the fuselage, vertical and horizontal stabilizers, in the tail area, and the landing group. The inner structure of the plane is tubular, with four diameter sizes: 31.75 mm for the passanger area, 25.4 mm in the front region where the engine is, 19.05 mm for inner and diagonal connector tubes and finally 15.875 mm for those at the tail region. Figure 5 shows a photo of the tubular structure of the plane taken at the AeroClube de Bragança Paulista. AISI 4340 steel is used throughout. Corresponding thicknesses are of 3.35 mm for the first two types – number 3 in red in the figure - and of 2.65 mm for the last two – number 2 in red also. This tubular primary set is complemented by a set of plate elements used to conform the external contour of the plane. These plates are constructed in wood. They are fixed to the tubular frame, at transversal sections along the tail region of the plane.In all the structural arrangement of the fuselage is mix, with transverse sections being connected by longitudinal and diagonal bars. The primary structures behaves like a 3D truss system mostly. The exterior envelope is covered using soft tissue working as a membrane. This tissue is

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Figure 1. Photo of Paulistinha in the Museum of TAM

Figure 2. Main airfoil used in Paulistinha

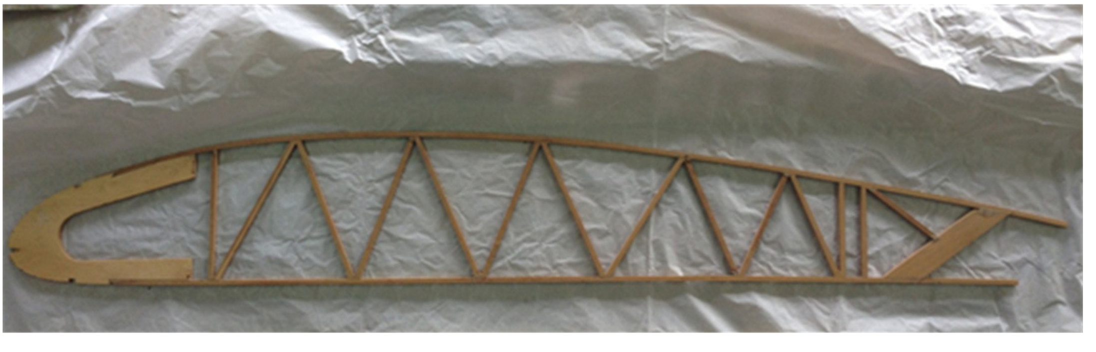

Figure 3. Aerodinamic profile used with allowance for aileron

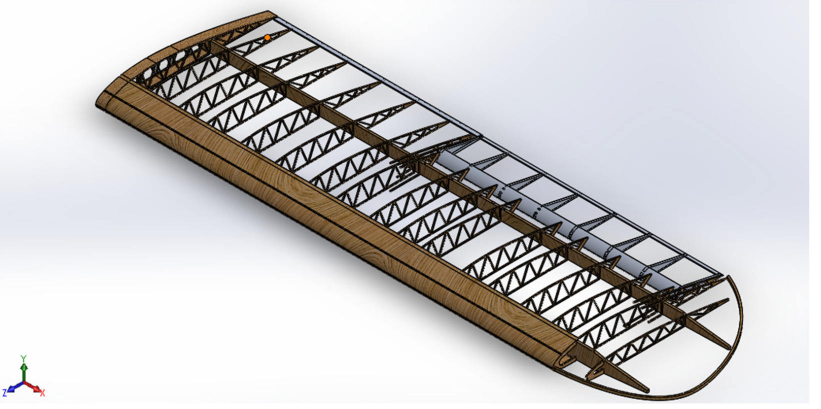

Figure 4. Semi-wing assemblage without soft fabric cover.

Figure 5. Photograph of the tubular structure of Paulistinha

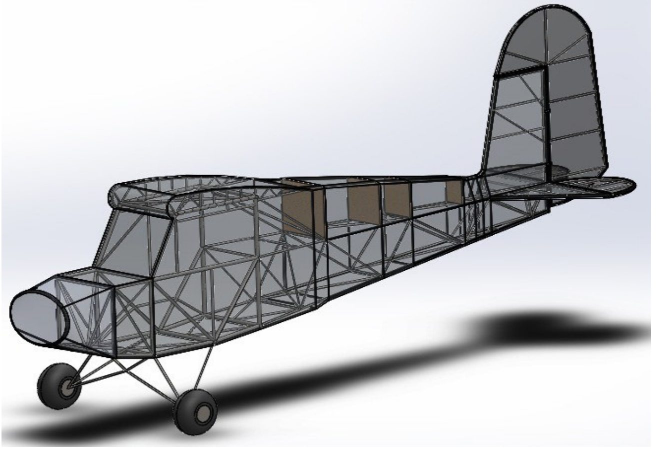

Figure 6. Assembled main structure of the airplane

protected against humidity and have high tearing resistance.

Drawing of the structure proceeded with the construction of sectional planes parallel to the frontal plane, complemented with horizontal and vertical, be it transversal or longitudinal, planes aside connecting planes with diverse inclinations. At total of about 50 planes were used. Sequence envolved drawing tubular elements in the transversal planes, followed with the connecting elements in the longitudinal and horizontal planes. Diagonal elements came next, complemented with the plate forms to strengthen transverse sections. Vertical and horizontal control surfaces followed. Figure 6 shows the assembled strutrure without the wing and supports.

Finite Element Model

Once the drawings of the structure was completed, discretization was undertaken. As tubular and plate elements were basic to the primary structure, shell elements were chosen. Solid elements were discarded as the amount of elements was too large. Even with this simplification, the model was still quite large. Surface loading applied to the external soft skin of the airplane was then substituted for its line action on the inner frame. Body forces were replaced by point loads, before a static analysis under level flight would be considered. When flying with constant cruze velocity v ¥ in the +x-direction, equilibrium of efforts in the motion and vertical directions give

$$\boldsymbol{T} = \boldsymbol{D}$$
$$\boldsymbol{L} = \boldsymbol{W} \qquad (1),$$

where $\boldsymbol{T}$ is the thrust force from engine and transmission system, $\boldsymbol{D}$ is the drag force, both resultants acting in the direction of motion. Perpendiculat to it, in the vertical direction then, $\boldsymbol{L}$, the resultant lifting and W the complete weight of the plane including structure and mechanical parts, fuel, crew and payload balance each other.

As the plane was drawn in two sets: a main sub-structure containing the fuselage, landing carriage and tail control surfaces, horizontal and vertical. The other was the wing and truss system of support. Discretized with finite

elements, these sub-structures give rise to two stiffness matrices, $\boldsymbol{K}_{\mathrm{m}}$ for the main sub-structure and K_l for the lateral wing sub-structure [4] Zienckiewicz:

$$K_m d_m = B_m + S_m - R \quad (2),$$

being $K_m = K_f + K_c + K_h + K_v$ the sum of the matrices from fuselage, landing carriage, horizontal and vertical control surfaces. The load vectors include the body forces B_m and the surface resultants S_m, translated into point loads and line loads, under uniform distributions, plus the fuselage-wing interface resultant R. If the R vector is known, the above equation may be solved to give the displacement field in the main sub-structure:

$$d_m = K^{-1}[B_m + S_m - R] \qquad (3),$$

In order to make possible this solution, the wing sub-structure has to be solved. Similarly to the above, lateral sti-

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ffness matrix K_l and displacement field d_l product give:

$$K_l d_l = B_l + S_l + R \qquad (4),$$

with $d_m = d_l$ at the fuselage-wing interface. Body and surface resultants include here the weight and wing lift. Wing is loaded mostly by air pressure, which generates lifting and some drag. Half weight is sustained by each wing. Higher air pressure occur in the lower surfaces of the wing, and lower in the upper surface. Distribution is not uniform. As the flow problem is not considered here, a linear distribution of the lift force per unit length over the wing span, for the complete cord length, may be assumed:

$$\lambda = \alpha + \beta y \qquad (5),$$

defined along the wing width l_w. Considering boundary values at the root position, in the interface with the fuselage, , $\lambda(0) = \alpha$ and the wing tip $\lambda(l) = 0$ make that:

$$\lambda = \alpha[1 - \frac{y}{l_w}] \qquad (6),$$

Integration of this distribution along the semi-wing will produce half of the lifting L so that:

$$\alpha = {}^{L}/_{l} \qquad (7).$$

Using the expedient of transferring the equivalent static of load from the skin to the airfoils, and from these to the longituginal spars, allows solving the resulting frame problem to get the resultant force R from the lateral sub- structure to the main structure.

$$\boldsymbol{R} = \sum_j \Delta f_j \qquad (8).$$

Once each $\Delta f_j \Delta c \lambda_j \Delta y_j$ is the point load-vector transferred from the aerodynamic elements to the spars of the wing at position y_j being Δy_j the load contribution.

Results

Using the solver of general finite element analysis programs, [5] Abaqus™ and [6] Ansys™ , a stress field for Paulistinha was obtained. Engine weigth and thrust force appear at support points of motor. Fuel tanks are in the top and bottom area around the pilot cabin. With the weight of crew and load transferred from the wings, this region is critical. Results below, Fig. 7, corroborate this fact. In this figure undeformed and deformed configurations are also present. Total deformations appear in Fig. 8. Properties of the materials used in the structure are shown in Table 1:

It is seen that the steel structure is quite rigid, showing stresses well below the elastic resistance, S_y of the material, with safety factors quite large. It was a commom practice of the days the plane was designed.

The wing is supported at three points: the root, or fuselage, at ¼ of the length and at ½ length of the wing, by bars fixed to the landing carriage, itself fixed to the lower part of the fuselage. These points appear

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Material	Steel AISI 4340	Balsa	Aluminum 6061-T6
Density gcm^{-3}	7.85	0.178	2.70
Modulus E, GPa	207	6.00	69.9
Poisson's ratio u	0.3	0.25	0.33
Yield Strenght S_y , MPa	417	25.	276.
Ultimate Strength, S_u MPa	655	75.	310
Maximum strain, e_u	0.257	0.10	0.17

Table 1. Mechanical Properties of Structural Materials

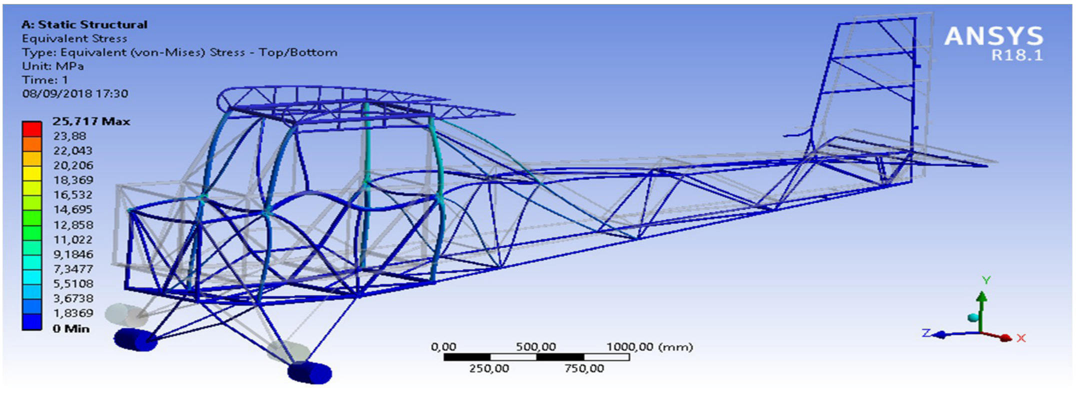

Figure 7. Stress field in the main sub-structure

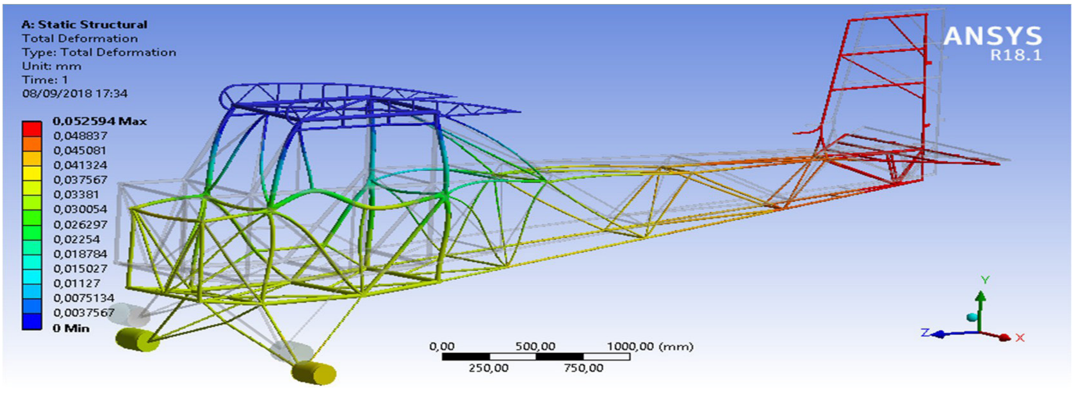

Figure 8. Total deformation field in the main sub-structure.

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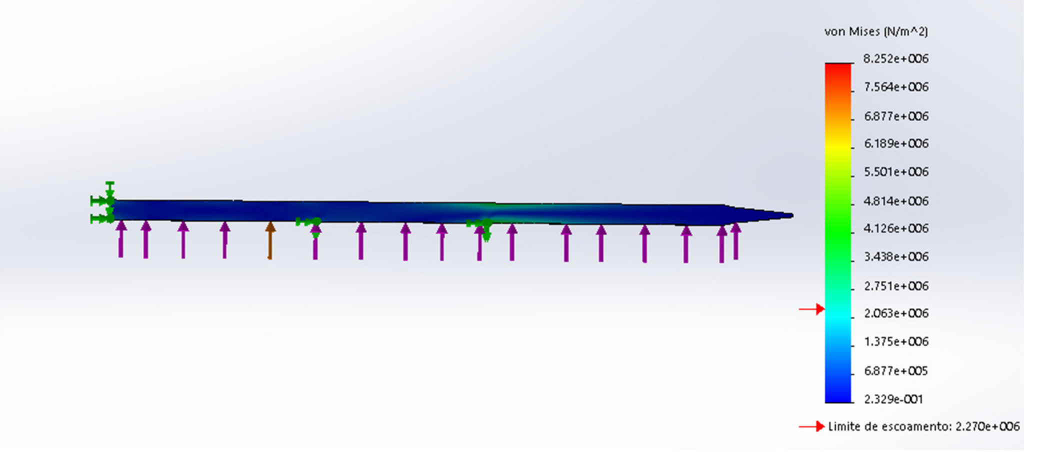

Figure 9. Stress field in the main spar of the wings

in green, as interconnection points. Finite Element solution determines the externall resultants. From these, bending stresses of the main spar, with its point loads, results, as shown in Fig. 9. Obtained Mises stresses show at critical points a safety factor not as large as at the fuselage, meaning this sub-structure is almost at optimum stiffness.

Conclusions

The model analysis has shown that the concept used in the construction of the airplane, based on reliability and endurance, reflects in low stress leveld and large safety factors in general. More than 50 years after the last plane was built, a large number of Paulistinhas are still flying, what is consistent with this fact. Being a good concept, clean motorization and use of hidrofoils would entail many new possibilities of use of the plane in regional flights in the Amazon region, for example, where low altitude and velocity flights are common.

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Authorship statement

The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

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