São Paulo Airplane: Model and Evaluation

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Abstract. *Dimitri Sensaud de Lavaud developed the first airplane designed, constructed and tested in Brazil. The flight of the São Paulo airplane, as named, took place in 1910 in Osasco, nearby São Paulo. The design was inspired in a monoplane of Louis Blériot. Dimitri himself was the pilot. The airplane construction, included structural and mechanical components, the engine for example, used materials and shop machines available in the country on those days. The plane flew a short, but certified distance, before it crashed with the soil due to an engine stop. Little is known of the design of that important airplane however. Hence, in this work a model of the airplane is created in computer to make an analysis. From drawings and a replica of the plane, a structural model is developed using the finite element method. Based on its characteristics, some airplane parameters are also estimated. An evaluation of the structure to some forms of failure is then conducted. Aside the simplicity of design, materials and inherent technological difficulties, the design reveals being fit and robust*

Keywords: history, drawings, structural model, finite element analysis, evaluation.

1 Introduction

Born in Spain, Dimitri Sensaud de Lavaud arrived in Brazil when he was 16 years old. His father was a French engineer that came to Brazil to help develop the ceramics industry. Her mother was a Russian artist. As the Family used to travel, Dimitri knew several languages and culture. With the help of another Italian immigrant, Dimitri's father in a short time period became an important business man in Osasco, where his ceramics industry was located.

Dimitri liked many sports and was very dedicated to industrial activities, having mastered many engineering sciences by himself. At 20 Dimitri got married and set residence in Osasco. From there on, and with the progress of the ceramics industry of his father, he got resources to put into practice some of his ideas. On those days, Santos Dumont and the Wright Brothers were making success with biplanes. Dimitri, instead, sought to develop an airplane with only one wing. This would confer some advantages, including maneuver capacity. Defined the concept, Dimitri started developing the drawings, computing some physical quantities until he identified the main problem: manufacturing machines, tools and construction processes had to be developed in order to produce the airplane Dimitri had imagined.

The solution was developing equipment and bring people able to operate machines and make the parts required to bring to reality his invention. Dimitri hired a young graduate of the Escola de Artes e Ofícios, Lourenço Pellegatti to construct the São Paulo Airplane. Pellegatti with the help of two other colleagues constructed the airplane in front of the house were Dimitri lived, in Osasco. The parts of the airplane were developed and constructed in house, what shows the idea of Dimitri of creating national aeronautic capability. The structure was constructed in wood – pinho, peroba and cedro – in the Tiete River border by naval constructers. The engine had to be developed from scratch. It was definitely a big step towards the success: a rotative engine, with 6 cilinders, distributed radially weighting about 200 N, and with a power of 25 Cv, running at 1800 rpm. In January of 1910 the engine ran for 2 hour non stop, so the first test of the airplane was scheduled to January, 7. [1]

Early in the morning of the flight, lots of people were around the chalet of the family in Osasco. Press was present as well. One of the worries was the overheating of the engine, because it was refrigerated with air, not water, which was too heavy for the airplane. At the time set, the airplane started moving in the improvised run way, for some

70 m, downhill. The airplane reached enough velocity for takeoff, and flew for 103 m, at a high oscillating between 2 and 4 m, for a little bit more than 6 seconds, when the engine came to a stop, causing the airplane to hit the soil. Dimitri suffered light injures but the aircraft suffered important damages. On that day it wouldn't fly again. There no news of other flights of the first airplane to fly in South America, Fig. 1.

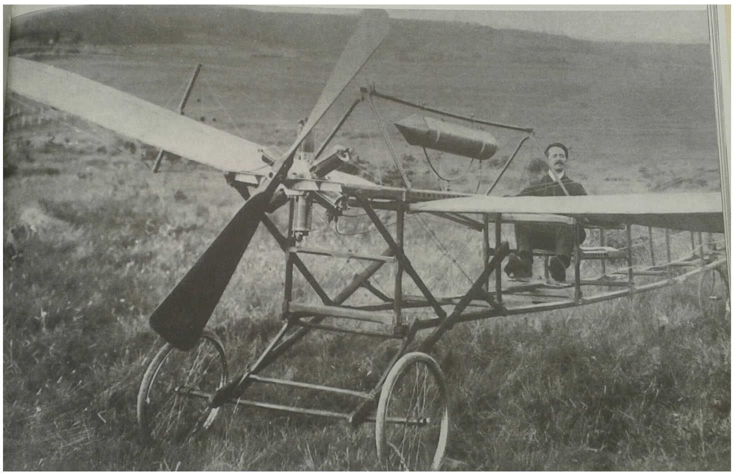


Figure 1: Photography of São Paulo Airplane just before takeoff in January, 1910

1.1 Airplane Structure

The drawings of the structural parts of the airplane were based on dimensions and forms used in the replica of the airplane in the Museu of TAM as well some old blueprints of the it.

1.2 Drawings

The drawing procedure followed division of the structure in four units: wings, fuselage, control surfaces and landing gear. A listing of components in each unit was constructed next, with forms and dimensions included. Interface elements and conditions of fixation were informed, with indication of materials.

Wings of São Paulo Airplane were constructed with 20 airfoil elements – ribs - supported by two spars, a main and a secondary one. It was possible, however, to adjust the attach angle of the wings. Stringers were also missing in the arrangement. A cut-end type of wing was used. Structurally the skin, a soft tissue, was responsible for transferring the aerodynamic loading to the airfoils, and from these to the spars, that were held by the fuselage structure.

The wings had a length $L_w = 4.69$ m, a width $B_w = 0.60$ m with a height $H_w = 0.10$ m. They were rigidly fixed to the fuselage, fixed in a straight lateral form to the top of the fuselage, just up in the pilot seat. In Fig. 2 the drawing of the wing is presented [2].

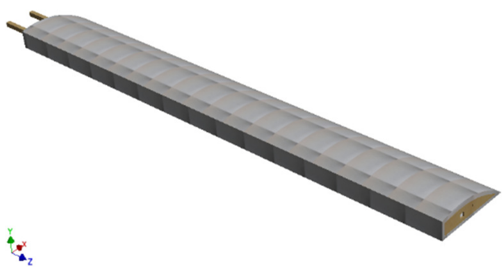


Figure 2. Wing structural drawing

Wings on those days didn't have fuel tanks or engines. These elements were placed in the fuselage of the airplane. The internal combustion engine developed by Dimitri was fixed in the front of the truss fuselage, just ahead of the pilot seat. The fuel tank was placed on the top part of the fuselage, just after wings. The landing group was fixed in this same region, the most loaded one, and at the end of the fuselage where the control surfaces were placed, Fig, 3.

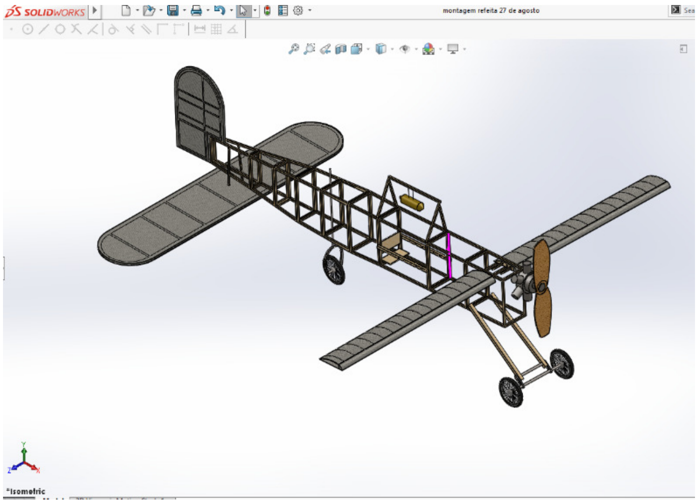


Figure 3. Assemblage drawing of the airplane

The landing and takeoff set used bicycle wheels able to sustain the impact with the soil to moderate level. There were three metallic wheels of the same diameter, with the front pair disposed in an inclined fashion.

1.3 Takeoff

Dimitri's São Paulo airplane was able to reach flight over a quite short distance, with no level flight attained. Therefore, loading to be included in the model should consider the acceleration in the runway, up to full throttle, when takeoff takes place. From that point on, it flew for a short distance when an engine failure caused the sustained elevation to come to a stop. Hence for the acceleration part of the runway motion:

$$\begin{aligned} M a_h &= T + (H_r + H_f) - D \\ M a_v &= (L + L') + (V_r + H_f) - W \end{aligned} \tag{1}$$

being M the mass of the airplane, v the velocity whereas T and D are the thrust and drag forces. The horizontal and vertical accelerations are denoted as $< a_{h,}, a_v / a_h = \dot{v}_h >$. Horizontal and vertical contact forces with the soil are $< H, V >$, from front and rear wheels. This equation is valid until the contact with the soil disappears. As the plane detaches from soil, the forces $< H, V >$ become zero. Here the thrust will depend upon the angular velocity $\omega = \hat{\omega}(t)$ of the engine, the drag D will be a function of the velocity as well as the lift, from main wing L_w and stabilizers L_s. From the second equation, vertical component of acceleration is zero, so that:

$$(V_r + V_f) = W - (L_w + L_s) \tag{2}$$

This result may be introduced into the top equation, if we consider a wheel-soil contact friction coefficient μ, to give, after integration:

$$v_h = \int_0^t \frac{T - D + \mu[W - (L_w + L_s)]}{M} dt \tag{3}$$

where initial velocity $v_h(0) = 0$ at initial position $x = 0$. New integration will give the position in the runway:

$$x = \int_0^t v_h dt \tag{4}$$

This solution will be valid up to the detach instant t_d, where position at the runway is x_d. From that point on the soil contact forces disappear and vertical velocity will be given by:

$$v_h = \int_{t_d}^t (T - D)dt - v_h(t_{d)} \tag{5}$$

With associate horizontal position:

$$x = \int_{t_0}^t v_h dt + x_d \tag{6}$$

The vertical motion is described by a similar equation. With null velocities in the vertical direction until the moment the airplane takes off:

$$v_v = \int_{t_0}^t [L - W\}dt;\ L = L_w + L_s, \tag{7}$$

being L the lift sum and W the total weight, that includes the structural weight W_s, the engine and transmission weight W_e, fuel W_f, pilot W_p and load W_l. New integration will render the vertical position:

$$y = \int_{t_d}^t (L - W)dt \tag{8}$$

This set of equations require knowledge of the aerodynamic profile as well as the engine power curve. In a design scenario, a combination of extreme values of thrust and lift will render the loading conditions for the problem.

1.4 Wing Sizing

By the time Dimitri designed São Paulo Airplane two concepts were in use: torsional wings and ailerons. Dimitri conceived wings that could be adjusted, rotated, from the cockpit so as to change the angle of attack. An interval between 2 and 16 degrees was available. The airplane as a monoplace, with a pair of high wings, at right angle to the fuselage used a very low dihedral. The wings were thin, constructed in pinus and covered with a tissue, cotton possibly. Wings were of constant cord, with almost no camber, with ends in elliptical form. They had a length $l_w = 5$ m with a plan area of about 16.5 m^2. As there is little documentation on the airplane, we cannot ascertain as to which type of airfoil best approaches the one used: it was quite thin and short, different from the ones being tried on those day. A maximum coefficient of lift $C_L^{max} = 1.2$ in the interval 12-15 degrees was achievable then and a drag coefficient around 0.04. Wing arrangement included a series of airfoils, distant each other of s_z supporting the pressure load provided by the skin. This point resultants were supported by a system of two spars, a main and a secondary. Wingbox construction concept was used to transfer the shear and moments across the fuselage.

Over the surface of the wing, sum of the combination of normal pressures and tangential stresses, integrated over the surface result in the lift and drag resultants. On the design view point the lift distribution may be assumed uniform, $\lambda = L/l_w$ along the length l_w. The drag will lead to a two-plane flexure, but due to the high ratio $L/D \cong 40$, its effect may be disregarded.
This loading is applied to the skin of the wing, transferred as point loads λs_z, being $s_z = l_w / n$, being n the number of airfoil elements in the wing. This point load is supported by two spars, the main and the secondary one. Assuming a regular array of airfoils, the distribution of loading over each of these spars is different, but yet uniform. Let the load per unit length in these spars be m and s, respectively. If the distances of the main spar and secondary spars to the attack and trailing edge of the foil are $< p, q >$ respectively, then:

$$m + s = \lambda \quad (9)$$

Assuming no torsion of the spars, then:

$$m(\frac{c}{2} - p) = s(\frac{c}{2} - q) \quad (10)$$

Solution of this pair of equation, leads to values of load of each spar. Under the obtained loading, and supposing clamped-free conditions for the spars, lead to a linear distribution of shear forces and a parabolic distribution of bending moments:

$$S(z) = < m, s > (1 - \frac{z}{l_w}) \quad (11)$$

$$M(z) = < m, s > [\frac{l_w}{2} - z + \frac{z^2}{2l_w}] \quad (12)$$

These internal resultants have extreme values at the connection with fuselage. With different profiles of beams, constructed in pinus, different dimensions under the same loading, are possible. Assuming an allowable value σ_a the required sectional modulus in either case is:

$$W^{<m,s>} = \frac{M^{<m,s>}}{\sigma_a} \quad (13)$$

1.5 Fuselage Sizing

Fuselage of the São Paulo was inspired in the solution developed by Blériot, with a truss of rectangular section $b \times h$ being used, Fig. 3. This structure had compartments of different size, numbering eight. The first compartment was responsible to hold the engine and support the front gears and shear forces from wings. In a normal assemblage, engine weight and thrust load are supported in four points, almost at the frame nodes. Not only those but the fixing forces of spars of the wings. These loads appear also at the corners of the frame. The bending moments at the end of the right spars are compensated from the left spars. This compartment is overstressed and in general it withstands the critical stresses.

Next compartment does not show point loads. It seems to be designed in this was in order to set the position of the center of mass along the length of the fuselage. On the third compartment, pilot seat is placed, with the fuel tank on top. From there on, three compartments appear, with no point load. On the following, horizontal and vertical control surfaces are placed, this wing structure resembles that of the main wing [3], Fig. 4.

The fuselage structure may be sized taking a beam approach, with axial loading composed by engine thrust, concentrated, being equilibrated by the distributed drag forces. The distribution of drag force is complex, but it may be taken as approximately uniform, This par will give rise to normal resultant along the beam, with maximum $N = T$, distributed among the frame elements. When acceleration is present, the axial inertia must be included.

The lateral loads, include the weight components being equilibrated by the shear forces coming from the wings, main and rear.

Equilibrium of each compartment, from the rear of the fuselage, with lengths numbered from that end, give a set of equations for internal resultants:

$$0 < x < l_1; N = dx; S = M = 0 \quad (14)$$

$$l_1 < x < \sum_{1}^{2} l_i : N = dx; S = M = 0 \quad (15)$$

$$\sum_1^2 l_i < x < \sum_1^3 l_i;\ N = dx;\ S = -2S_c;\ M = -2S_c[x - \sum_1^2 l_i] \tag{16}$$

$$\sum_1^3 l_i < x < \sum_1^4 l_i; N = dx\ S = -2S_c;\ M == 2S_c[x - \sum_1^3 l_i] \tag{17}$$

$$\sum_1^4 l_i < x < \sum_1^5 l_i; N = dx; S = -2S_c - W_p - \frac{W_f}{2}; M = -2S_c(x - \sum_1^2 l_i) - (W_p - \frac{W_f}{2})(x - \sum_1^5 l_i) \tag{18}$$

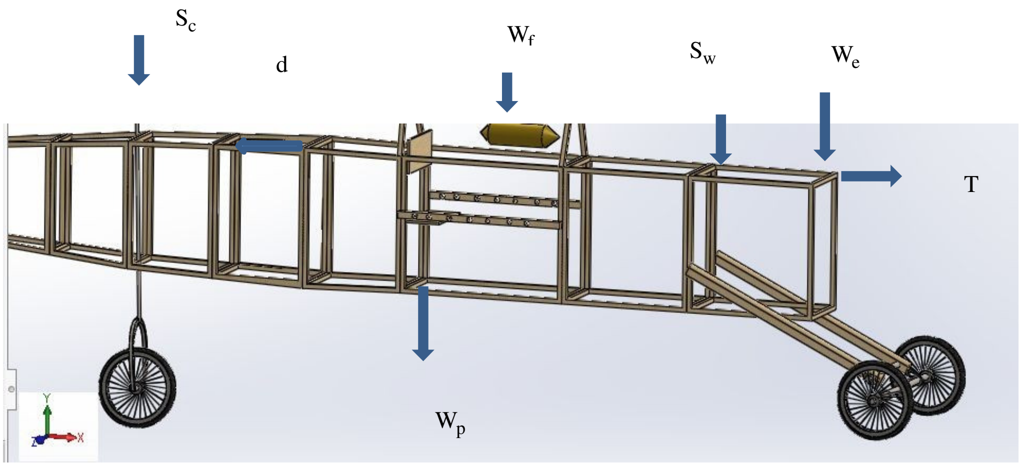


Figura 4. Simplified drawing of the fuselage of the airplane

From the set of internal resultants along the fuselage, it is seen that critical compartment is the frontal one, having normal $N/4$, shear $S/4$ acting in the cross sectional area of each horizontal beam element. Theses resultants have to render the bending moment in the section, also. Being each beam of square cross section, this set of equations lead to the members' dimensions.

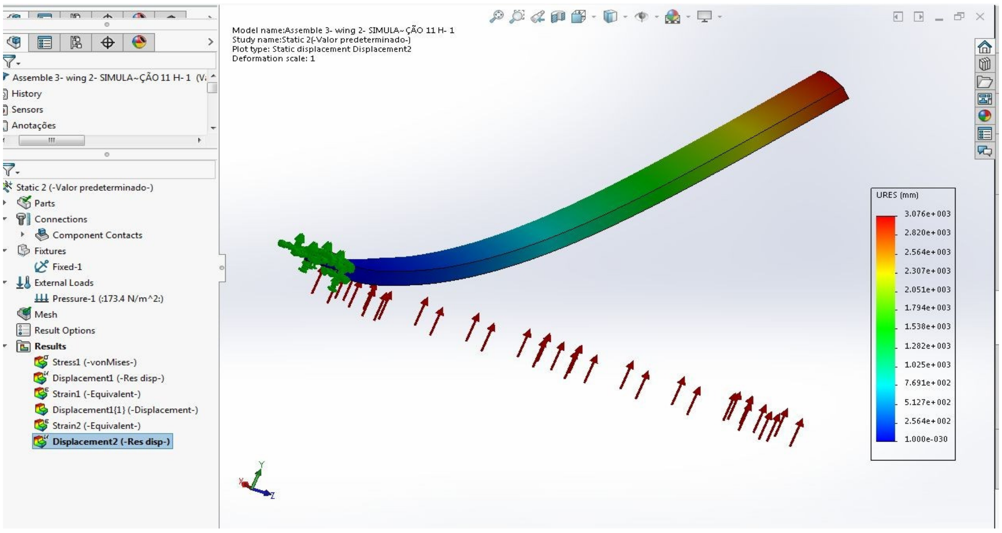
1.6 Analysis

Once the dimensioning of the possible structure of the airplane was developed, a finite element discretization of structural sets was made in the virtual ambient of SolidWorks. The main spar of the wing was modeled and submitted to a uniformly distributed lift. In the model, 3D elements were used. The resulting displacement field and stresses are shown in Fig. 5. It is seen that the wing was quite flexible, resisting however to the applied load.

Computation of the stress field inside the structure of the plane as a whole follows the same procedure. Resultants will depend on the flight conditions. In the takeoff part of flight, inertia forces have to be included. From the flow loading, stresses in the airplane may be computed with Eq. (19), for linear behavior of the structure:

$$\mathbf{M}_p \ddot{\hat{\mathbf{d}}}_p + \mathbf{K}_p \hat{\mathbf{d}}_p = \mathbf{R} \tag{19}$$

In this equation airplane mass matrix is identified by $\mathbf{M}_p$ whereas the stiffness is $\mathbf{K}_p$ with nodal displacements written as $\hat{\mathbf{d}}_p$. Loading vector is represented as $\boldsymbol{R}$ [5].



Figute 5. Main spar modeled with finite elements

2 Conclusions

As documents of airplane São Paulo only included the structural arrangement, without profiles and dimensions, a possible structure of the airplane had to be sought. The procedure used in face of the type of structure is shown above. It derived from equations of beams under simplified quasi-static conditions. Average properties of the materials were also considered. In this way the dimensions of the elements of front and rear wings were obtained, as well as of the elements of the truss-like fuselage. The overall airplane weight was close to the one of the original. With sizing done, a finite element model, based on the drawings of the structure, under the SolidWorks virtual ambient was used. Yet some doubts still remain as with other aerodynamic profiles, differences in the dimensions would appear.

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References

[1] Alexandria; Nogueira, 1910- O Primeiro Voo do Brasil. São Paulo, Brasil, Aleph, 2010.
[2]Machietto, Julia S., Desenho, Modelo e Análise do Avião São Paulo, Iniciação Científica, UFABC, 2018
[3] Raymer, D., Aircraft Design and Analysis, 2002
[4] SolidWork^{TM} 2015, Dassault Systèmes Inc, Paris, France
[5] Zienkiewicz, O, Taylor, R. and Zhu, J.Z. ¨The Finite Element Method: Its Basis and Fundamentals¨, 7th edition, 2003, Elsevier