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ANALYSIS OF GEOMETRIC AND FLYING CHARACTERISTICS OF SANTOS-DUMONT'S 14-BIS

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Abstract. *On November 12th 1906, Brazilian inventor Alberto Santos-Dumont flew a distance of 220 meters in 22 seconds with his 14-Bis at Bagatelle Field in France. He was the first to officially prove to the world that manned powered flight was possible for heavier than air machines. With that flight he also set the first aviation record and won the Aéro-Club de France Prize, given to the first manned airplane to take off and fly a minimum distance of 100 meters by its own means. This paper describes some of the geometric and flying characteristics of Santos-Dumont's 14-Bis. Determination of those characteristics are based on a historical review and on first order theoretical evaluations. Unfortunately most of the relevant information about the airplane was lost or never properly recorded. A great effort was made to consider and weigh all available information about the 14-Bis, but the obtained results and conclusions are certainly not final.*

keywords: *Santos-Dumont, 14-Bis, Geometric characteristics, Flight characteristics*

1. Introduction

Alberto Santos-Dumont was born on July 20th 1873 in Brazil. In 1892 he went to Paris, France, to advance his studies on engineering (Villares, 1953). He had always been attracted to machines and, when he learned about lighter-than-air vehicles, he immediately tried to arrange a flight. High costs discouraged him until he met Mr. Lachambre who asked 250 Francs for a four hour flight. After that flight, Santos-Dumont started his aeronautical career constructing and flying balloons. On 4 July 1898 his first balloon, named Brasil, took flight in the skies of the French capital. The spherical balloon, filled with Hydrogen, had mere 113 m^3 (diameter of 6 meters) but was able to lift Santos-Dumont who weighted only 50 kg. He innovated balloon design by using Japanese silk for the envelope, much lighter than other materials used at that time. Balloon makers expressed concern about the stability of such small craft but that was adjusted by extending the basket suspension cables thus lowering the center of gravity. He made several flights with Brasil and built two other balloons: the Amérique and the Deux Amériques.

When Santos-Dumont started his plans to use an internal combustion engine to propel an Hydrogen filled dirigible people tried to discourage him. The obvious concern was that sparks could ignite the highly flammable gas. That did not stop him and the history of success of his dirigibles proved he was right. That gave him an advantage in terms of power to weight ratio when compared to steam or electric propulsion (energy source included). Between 1898 and 1901 he built five different dirigibles naming them No.1 to No.5. Santos-Dumont made several flights always attracting much attention and giving him great popularity in France.

In 1898 the Aéro-Club de France was founded and, in 1900, organized the first dirigible competition which was named the Grand Prix Deutsch de La Meurthe. The one hundred thousand Franc prize was to be given to the first dirigible which, starting from Saint-Cloud, went around the Eiffel Tower and back to the starting point in less than 30 minutes. Many competitors were attracted by the prize including Roze, Firmin Bousson, Smitter, the Lebaudy brothers, Bradsky and, another Brazilian, Augusto Severo. Santos-Dumont knew his dirigibles could complete the established course but their speed was not high enough. He then built No.6 with length of 33 meters, diameter of 6 meters and a Buchet 20 HP internal combustion engine. On October 19th 1901, Santos-Dumont won the Grand Prix Deutsch de La Meurthe with No.6 and his popularity spread throughout Europe and the Americas. He gave half of the prize to his assistants and half to poor people in Paris.

He continued his experiments with dirigible No.7, which was intended to exceed 80 km/h speed. In June 1904 the aircraft was sent to Saint Louis to participate in a race during the World Fair. Upon arrival the dirigible envelope was found ripped apart as if it had been cut by a knife. Very expensive, it was never rebuilt. Dirigible No.9 was built to serve as a personal transport (he skipped No.8 due to superstition). Very small, 12 meters in length, 5 meters in height, it could land on small spaces and became known as the flying chariot. Dirigible No.10 was designed as a transport for up to 20 passengers but flew only a few times, always arrested by cables, and was abandoned.

Practical research on airplanes started in the beginning of the 19th Century. George Cayley conducted experiments with gliders in 1804 and was followed by the Le Bris, in 1857, by Mouliard, in 1865, then by Otto and Gustav Lilienthal, between 1891 and 1896, and by Octave Chanute. Motorized airplanes had already been tested by Stringfellow around 1857 but without success. Samuel Langley built several motorized airplane models which made very successful flights. In 1903 he tried to fly a platform launched manned airplane without success. Before that, others had already tried to fly manned powered heavier than air machines, most notably Hiram Maxim who conducted experiments with a steam powered airplane running on tracks. Clement Ader was financed by the French Government to build the Eóle in 1890. Although Ader claimed to be the first to fly an airplane, official reports of the time do not sustain his claim.

The Wright brothers had been developing gliders since 1899 when, in 1903, they started to fly a motorized version of their No.3 glider. They did not wish to publicize their achievements however and, although some news spread throughout America and Europe, they were not confirmed until late in 1908. At that time the Wright brothers performed public flights in Europe for the first time and set several aviation world records.

Santos-Dumont was also very interested in heavier than air aircraft and, by the end of 1904, he started to explore the possibility of powered flight. He designed a monoplane, No.11, for which he did not find a suitable engine. He also built the prototype of an helicopter, No.12, with two large propellers powered by a 24 HP, eight cylinder engine. He never tried to make it fly. His next balloon, No.13, combined hot air and Hydrogen for aerostatic lift. It was destroyed during a storm before it could be tested. In the beginning of 1905 he designed and built dirigible No.14 as a fast, highly maneuverable aircraft.

2. The 14-Bis

To motivate further advances in aeronautics the Aéro-Club de France instituted, in the end of 1905, a 1,500 Franc prize for the first aeronaut to accomplish a 100 meter long flight on an airplane taking-off, by its own means, from level ground (a maximum 10% slope). At the same time Ernest Archdeacon, club president, offered 3,000 Franc for a 25 meter long flight. Captain Ferber, of the French Army, was experimenting with gliders and kept contact with Chanute and the Wright brothers. Louis Blériot got associated with Gabriel Voisin to build an airplane based on the Voisin-Archdeacon glider. At that time Santos-Dumont recognized that the Antoinette type engines, developed by Levasseur for racing boats, were light and powerful enough to be used in aviation. He and his assistants then started to work on a biplane aircraft based on Hargrave's box kites (Fig. 1) and powered by a Levasseur engine. Lawrence Hargrave's work with box kites was well known and respected in Europe. The large lift generation capacity of his kite designs is probably what made Santos-Dumont choose that configuration.

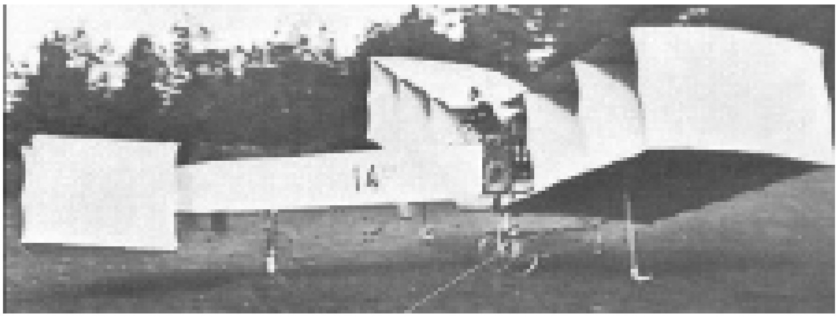

Figure 1: A side view of the 14-Bis.

The aircraft, made of bamboo poles and silk covering, with aluminum fixtures, was powered by a single 24 HP Antoinette engine. The engine, placed at the airplane rear end, drove a two blade, paddle type propeller in a pusher configuration (Fig. 2).

The pilot was placed standing up in a balloon type basket located in front of the engine strut. Longitudinal control was effected through a lever and directional control through a wheel. Landing gear was composed of two bicycle wheels attached to the engine strut. A third small wheel was placed behind the main gear but was removed, later on, during development of the aircraft. A front pole, placed under the fuselage, gave longitudinal support and two side poles, placed under the wings, gave lateral stability while on the ground.

Each wing was composed of three Hargrave's cells and were attached to the engine support with a dihedral angle. A single box kite cell was placed at the aircraft nose to provide pitch and yaw control. The engine strut and canard were connected by a silk covered, square section fuselage. According to Napoleão, 1988, the inventor chose the canard configuration to avoid lift reduction during take-off. Gibbs-Smith, 1985, mentions that the canard configuration was

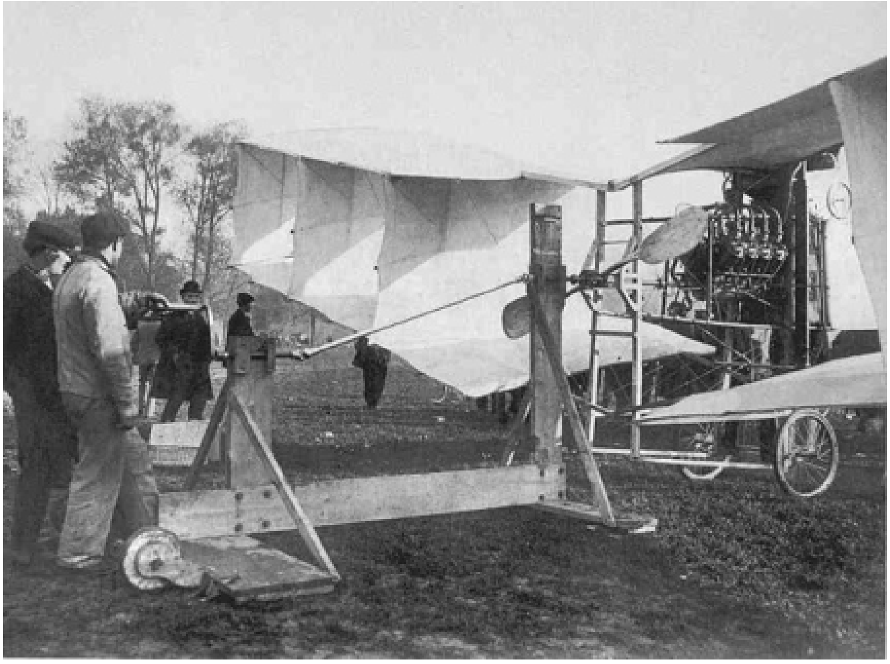

Figure 2: Engine starting mechanism (Musa *et al.*, 2001).

chosen (and that applies to the Wright brothers too) to avoid nose down tendencies presented by Lilienthal's gliders. Approximate airplane dimensions were: length of 10 meters. wing span of 12 meters, wing chord of 2.5 meters. The canard had a span of 2 meters, chord of 2 meters, height of 1.7 meters. Canard section profile was a flat plate for both vertical and horizontal surfaces. Take off weight was about 300 kg.

Santos-Dumont started testing his airplane by attaching it to his dirigible No.14 (Fig. 3). He intended to conduct experiments with the airplane stability and control. Those tests produced some good results but were limited in speed by the high drag generated by the dirigible.

He continued with the stability and control tests now by hanging the airplane on a trolley running on an inclined suspended cable (Fig. 4).

It was August 1906 when Santos-Dumont decided to start testing the aircraft at Bagatelle field. After several runs he recognized that the engine was not powerful enough and replaced it with a 50 HP, V-8 Antoinette. Other modifications made during the initial phase of development included elevation of the fuel reservoir, removal of the rear wheel, coating of the wing, reduction of propeller axle length and reduction of wing incidence angle. He deduced that the excessive incidence was slowing down the 14-Bis. He also considered that the side surfaces of the Hargrave's cells would give enough directional stability to the airplane. With those modifications the 14-Bis was able to leave the ground for the first time, during tests, on September 7th 1906.

Santos-Dumont was now decided to try to win the Archdeacon and Aéro-Club de France prizes. On September 13th 1906 he was ready for the first trial before the Aéro-Club members and the habitual crowd. After a failed first attempt, the 14-Bis took off under the enthusiastic applause of the audience, flew 13 meters and made a hard landing, braking the propeller. Ernest Archdeacon and the other Club members run to Santos-Dumont to congratulate him. He did not win the prize but everyone was convinced that the airplane had flown. Santos-Dumont fixed the aircraft and, on October 23rd 1906, he was ready to try again. At four o'clock in the afternoon, after some testing, the aviator climbed on the airplane and started the take off run. The 14-Bis slowly gained speed, rotated nose up and the wheels left the ground smoothly. The airplane flew at a height of about 3 meters then made a slight left turn and landed, 60 meters away from the take off point (Fig. 5). Ernest Archdeacon ran to meet with Santos-Dumont accompanied by a cheering crowd. The repercussion was the greatest possible for the time. The major newspapers in Europe and the Americas announced the conquest of air. The most prominent aeronautical authorities recognized that the heavier-than-air manned flight had been proved.

Santos-Dumont also wanted to win the Aéro-Club de France prize and set the date of November 12th 1906 for the official attempt. During preparations for the flight, he installed two control surfaces inside the outboard Hargrave's cells. Those ailerons were commanded by cables hooked to the pilot's coat shoulders. They were intended to give additional directional control. On the day set for the attempt Voisin showed up to compete for the prize with a biplane he and Blériot had built. Santos-Dumont conceded the lead to his colleague and, after several unsuccessful attempts, Voisin's airplane was damaged and left the competition. During the rest of the day the 14-Bis made four flights. The distance was registered

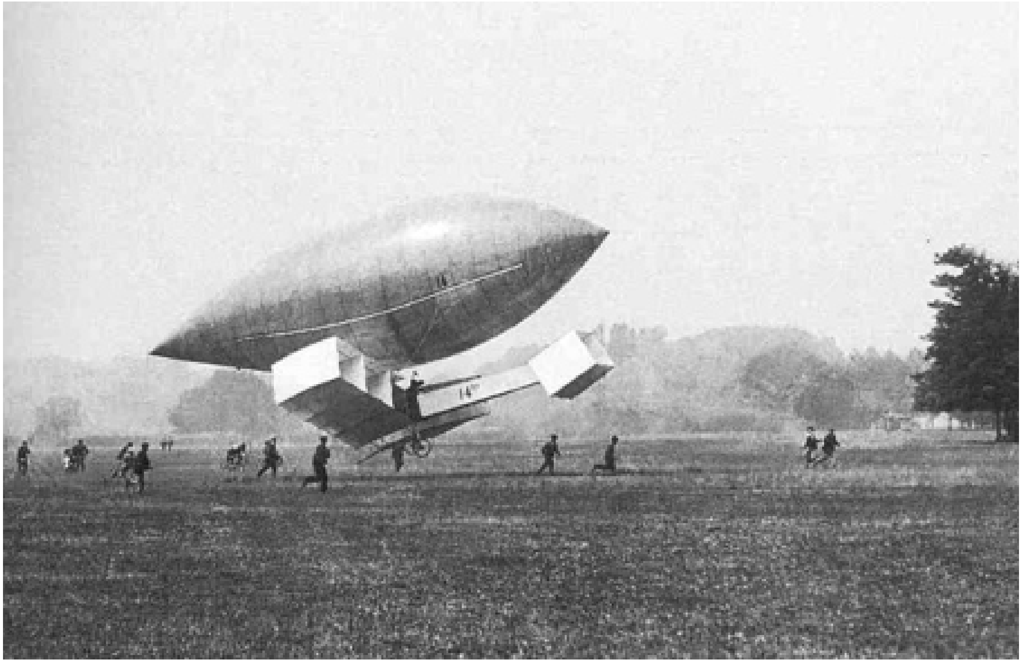

Figure 3: The 14-Bis attached to dirigible No.14 (Musa *et al.*, 2001).

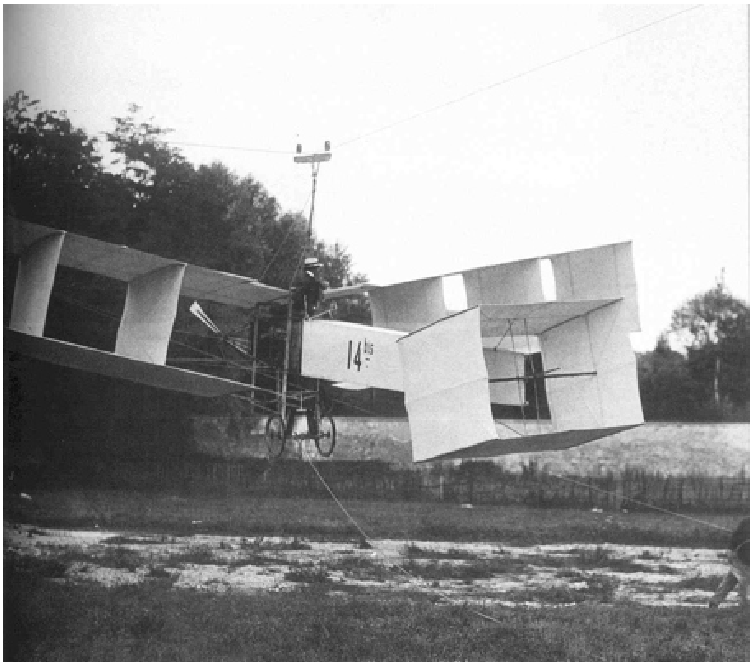

Figure 4: The 14-Bis suspended by cables for stability tests (Musa *et al.*, 2001).

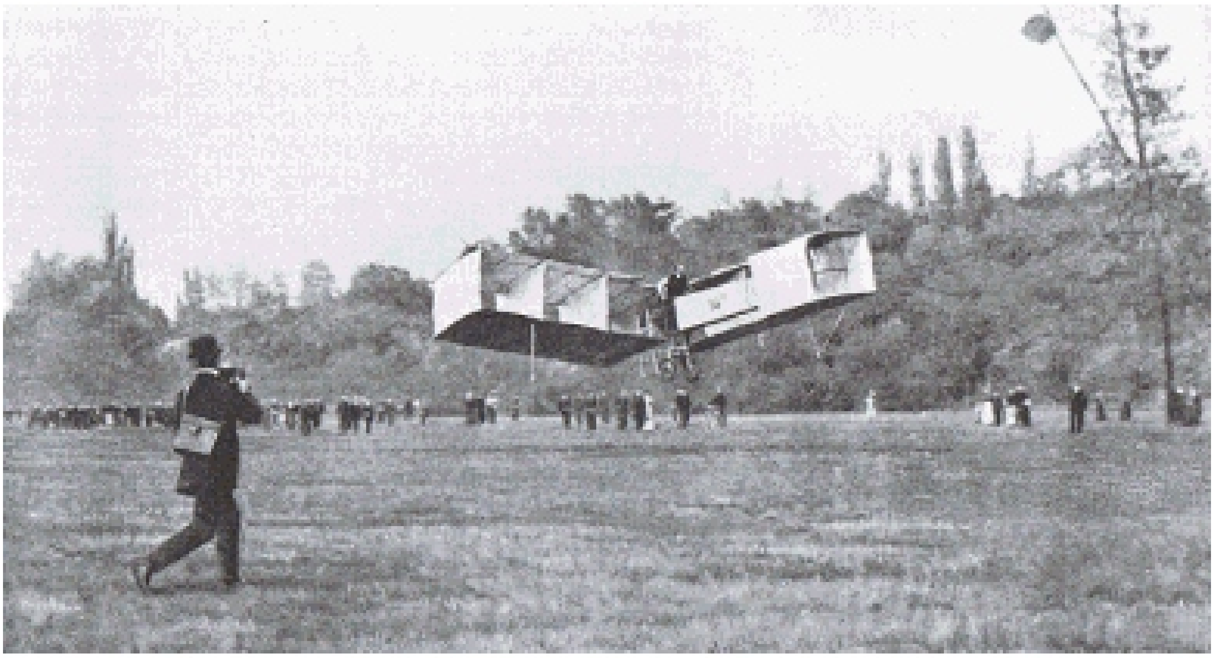

Figure 5: Photograph of Santos Dumont's 14-Bis flight on October 23rd 1906 (Musa *et al.*, 2001).

by plates dropped from a car which followed the airplane running by its side. On the fourth flight, at 4:45 pm, the 14-Bis took off very quickly against the wind. To avoid the crowd, who had invaded the field, Santos-Dumont commanded the airplane to rise to about 6 meters almost reaching stall, made a right turn and, stopping the engine, made a landing. The right wing touched the ground during landing but caused no damage. The chronometers registered 22 seconds of flight and the distance from take off to the landing point was 220 meters. He had won the Aéro-Club de France Prize and set world's first aviation record.

Santos-Dumont tried only once again to fly with the 14-Bis. During that trial the airplane was severely damaged and never repaired. By then he wanted to design new and more efficient aircraft. Recognizing the problems he had to control de 14-Bis, Santos-Dumont designed airplane No.15, still a biplane based on Hargrave's cells but now with the control surfaces in the rear. No.15 never took off and its development was suspended after an accident during a take off run. He then started working on No.16 a hybrid dirigible with a large amount of lift generated by aerodynamic surfaces. Flying attempts failed as it was uncontrollable. Airplane No.17 was a modification of No.15 with conventional biplane wings, a 100 HP engine and three blade propeller. At the same time he built a racing boat , No.18, with the same engine and propeller of No.17, trying to exceed the speed 100 kilometers per hour. Neither No.17 nor No.18 produced good results.

Still in 1907 Santos-Dumont had the idea of building a very light airplane. In 15 days he designed and built No.19, the Demoiselle, an ultralight aircraft with a 8 meter wing span and a 20 HP engine of his own design. By then several European aviators had been able to successfully fly on their airplanes although they still had severe control problems. The Demoiselle was very successful in flying, became very popular and its development continued as No.20, No.21 and No.22 (his last airplane). The Clément-Bayard company sold 50 of those airplanes, each one costing 7,500 Franc. Santos-Dumont never intended to patent his Demoiselle and did not earn any money for his invention. In 1909 Santos-Dumont received the first pilot license from the Aéro-Club de France along with Henri Farman, Louis Blériot, Wilbur Wright, Orville Wright, Léon Delagrange, Robert Esnault-Pelterie and Captain Ferber. He made his last flight as a pilot in January 1910.

3. Geometric Characteristics

An analysis of the 14-Bis flying characteristics requires knowledge of its geometric characteristics. The original aircraft plans, however, are presumed lost, so data on the airplane was collected from several different sources. The original airplane was also destroyed shortly after its last flight. Only the pilot's basket remains stored in a museum (Fig. 6). Basket measured height is 940 mm. Conflicting data was resolved through comparison with actual photographs of the airplane. Photographs can be found in the References listed in this paper but also in the Internet and in museums. The same is true for reproductions of the 14-Bis plans. Figure 7 shows 14-Bis plans made by Sandoval Menezes Lima in 1956. Those plans are stored in the Aerospace Museum of Rio de Janeiro.

Sandoval notes that the underlined dimensions in Fig. 7 have different values in the various sources he used as basis

Figure 6: The original 14-Bis basket (Museu da Aeronáutica).

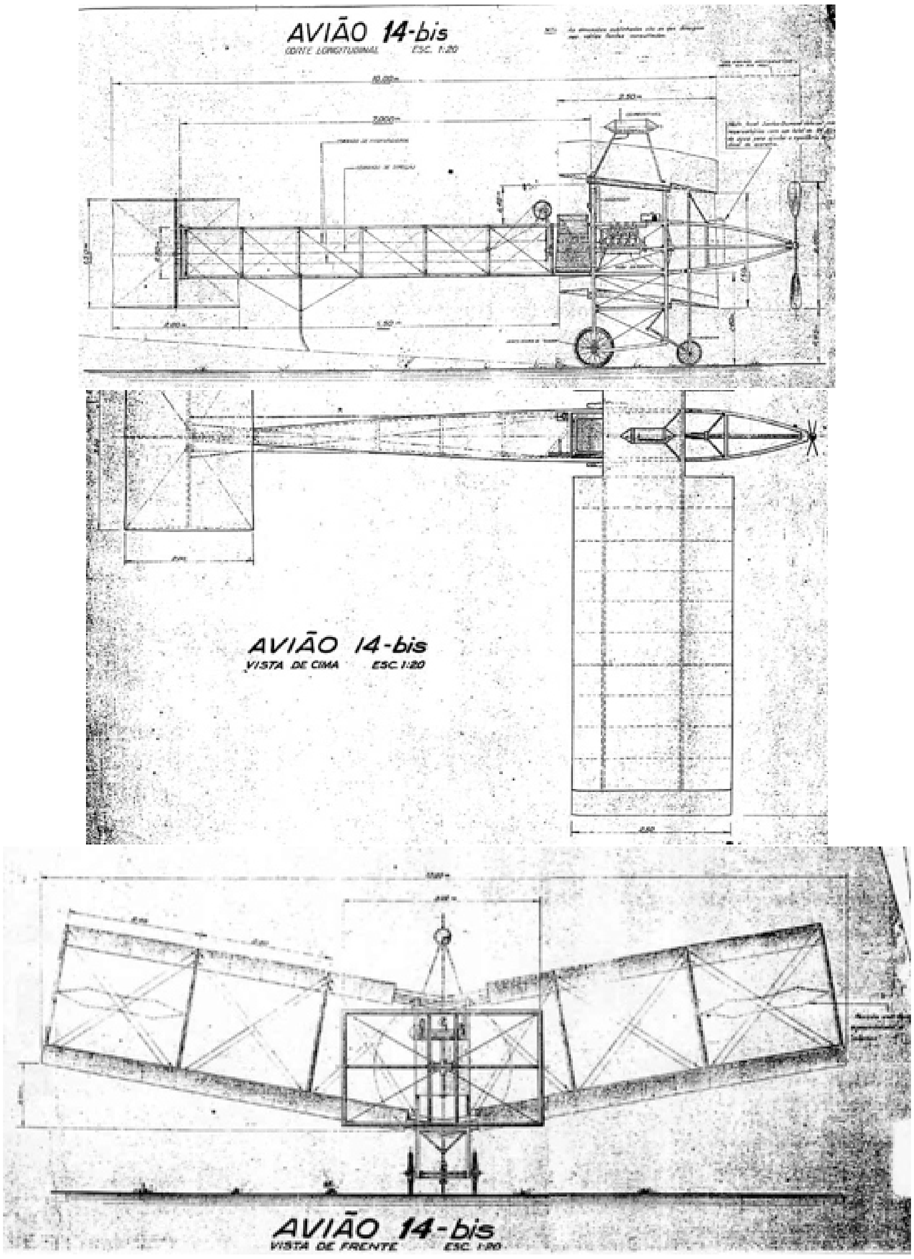

Figure 7: 14-Bis plans obtained from the Aerospace Museum of Rio de Janeiro.

for the drawings. Another plan reasonably accurate is shown in Fig. 8 (Lissarrague, 1983). Comparison of the two plans (Fig. 7 and Fig. 8) shows that the canard dimensions are quite different.

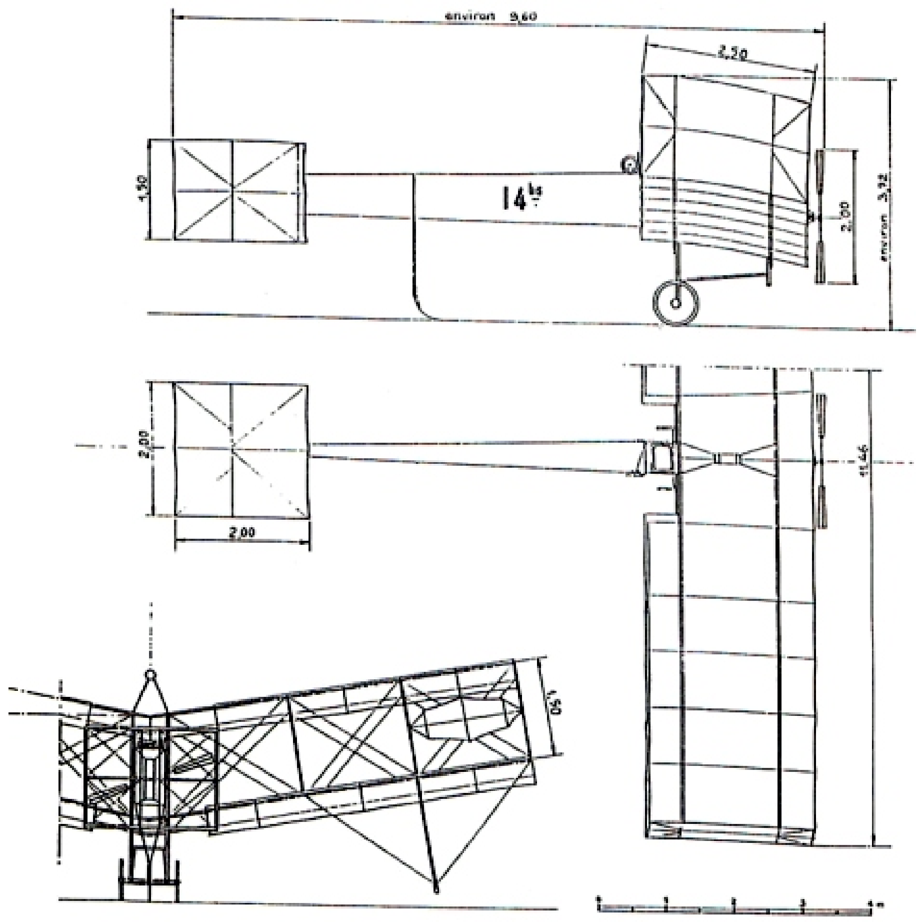

Figure 8: 14-Bis plans reproduced from Pégase magazine (Lissarrague, 1983).

A few replicas of the 14-Bis were built but the ones available for analysis until now are not accurate and could not be used as basis for the present study. Recently a very accurate flying replica was built.

An effort was made to collect and evaluate as much information about the 14-Bis as possible in an attempt to find reasonable values for key airplane dimensions. Even the most accurate available plans such as those of Figs. 7 and 8 contain imprecisions. Photographs of the 14-Bis were used as a basis for verification of the results and a three-dimensional drawing of the airplane was made (Figs. 9 and 10). Some dimensions were extracted directly from the photographs. Scale was resolved using the pilot's basket dimensions (height of 940 mm).

4. Flying Characteristics

After establishing the geometric data, the stability and control derivatives were estimated using first order theoretical methods and a panel method. The center of gravity is estimated to be close to the wing leading edge. The photographs also aided in checking the C.G. position. In Fig. 4, for instance, it can be assumed that the airplane was hung close to its center of gravity. There is indication that Santos-Dumont provided the 14-Bis with means to allow some adjustment of the C.G. position. The stability analysis was conducted with the C.G. located at three different positions close to that indicated by the suspension cable in Fig. 4.

A vortex-lattice panel method code (JkayVLM) was used to estimate the stability derivatives. The three C.G. locations were at 7.0, 7.1 and 7.5 meters from the aircraft nose. Only the most forward position (7.0 m) produced a longitudinally stable airplane. Table 1 shows the longitudinal stability derivatives for that C.G. position.

For that C.G. location the airplane is marginally stable in pitch ($C_{m\alpha}$ close to zero) but unstable in yaw (negative $C_{n\beta}$).

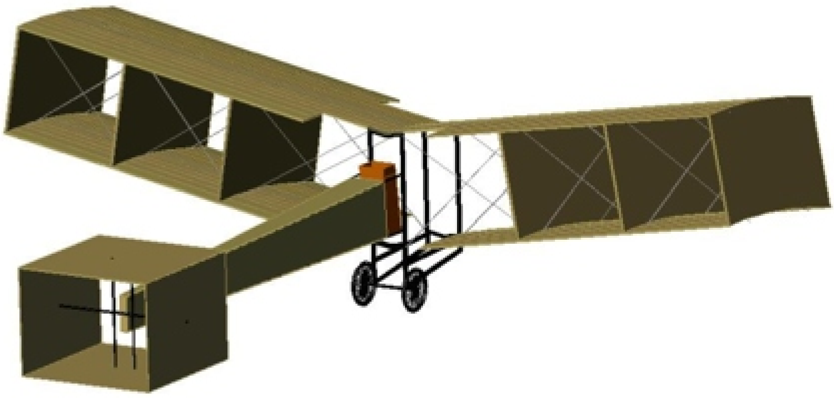

Figure 9: Three-dimensional drawing of the 14-Bis.

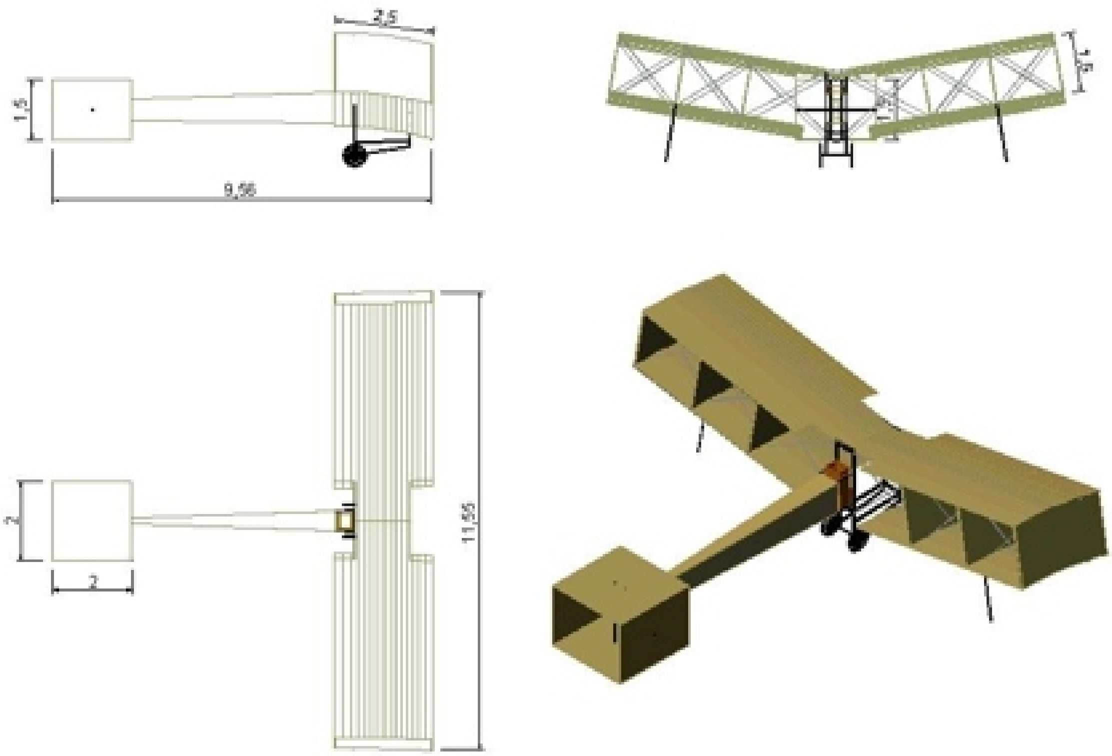

Figure 10: Three view drawing of the 14-Bis.

Table 1: 14-Bis stability derivatives.

Variation of lift coefficient with angle of attack	$C_{L\alpha}$	3.6 1/rad
Variation of pitching moment coefficient with angle of attack	$C_{m\alpha}$	-0.03 1/rad
Variation of lift coefficient with pitch rate	C_{Lq}	4.4 s/rad
Variation of pitching moment coefficient with pitch rate	C_{mq}	-5.4 s/rad
Variation of side force coefficient with sideslip angle	$C_{n\beta}$	-0.12 1/rad
Variation of yaw moment coefficient with yaw rate	C_{nr}	-1.5 s/rad
Variation of rolling moment coefficient with roll rate	C_{lp}	-0.41 s/rad

Santos-Dumont recognized the stability problems, mainly for directional control, saying that "it was like trying to shoot an arrow with its feathers in the front".

5. Conclusion

The geometric characteristics of the 14-Bis were obtained using information from different sources and partially verified through comparison with photographs. Although great effort was made to obtain accurate results they can not be considered as final. This subject still deserves much discussion and perfectly accurate results may never be obtained.

Theoretical estimates for stability and control characteristics indicate that the 14-Bis was marginally stable longitudinally and directionally unstable. The very low speed operation of the airplane would warrant control of those instabilities by the pilot. In fact, recent flight demonstrations of the accurate replica built by Alan Calassa showed a perfectly controlable 14-Bis in straight flight. Controllability of the airplane under cross wind conditions was not accessed in the present study. Again, Alan's demonstrations showed that the 14-Bis could become uncontrollable under cross wind conditions.

This article also tries to summarize the trajectory of Alberto Santos-Dumont as the inventor, the engineer and the pilot who always had the conquest of air as driving force for his work. His contribution to the advancement of aeronautics can not be contested. He not only was responsible for several technical advances but also helped disseminate aeronautics with public demonstrations. Finally, he was a pioneer, setting records and risking his life when so many still believed his objectives were impossible to be accomplished.

6. Acknowledgments

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