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# DEVELOPMENT OF A SUBSCALE AIRCRAFT OF A CESSNA 177

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***Abstract.*** *The use of subscale aircraft for aerodynamic, stability, and control testing is generally used for aircraft design studies. Subscale aircraft can be used in free flight testing for aircraft dynamics testing, which is a relatively simple and low-cost technique compared to others, such as wind tunnel testing, which is expensive and difficult to perform. Some limitations regarding the accuracy of results in free flight tests are that external factors such as air currents and atmospheric turbulence can affect the subscale aircraft. Free flight subscale models are an alternative for dynamic wind tunnel testing and dynamic sizing. Several techniques can be used to design a subscale aircraft for dynamic testing, and it is a topic that has been studied and used by the industry for decades. One of the techniques is the Froude number scaling, used when one intends to predict the behavior of an aircraft in different flight conditions, from the flight at low take-off and landing speeds to the flight at high cruising speed. The Froude number is generally defined as the ratio of speed to the square root of the aircraft span, length, and gravity limitation. This work will present the development of a subscale aircraft of the Cessna 177 Cardinal, capable of performing tests in free flight and a wind tunnel. This aircraft was chosen because in the 1970s NASA (National Aeronautics and Space Administration) carried out the instrumentation of this aircraft and carried out a flight to collect data which culminated in the document "Flight Test Data for a Cessna Cardinal" which presents the results of these tests. The technique of scaling by Froude number will detail all the criteria used to determine the scale factor in the flight conditions that the aircraft will be subjected to, finally, the results obtained in wind tunnel testing will be presented, and the obtained for Computational Fluid Dynamics (CFD) simulation and the* $C_{L\alpha}$ *and* $C_{m\alpha}$ *curves.*

***Keywords:*** *Subscale Aircraft, Froude Number, Free flying test, Wind Tunnel, CFD.*

## 1. INTRODUCTION

Sub-scale use of Remotely Piloted Aircraft (RPA) has been used in the aerospace industry on a small scale for many years. In the 1930s, the United States of America (USA) undertook a preliminary evaluation of radical configurations such as flying wings and disks with the National Advisory Committee for Aeronautics (NACA), now the National Aeronautics and Space Administration (NASA) undertook the preliminary evaluation of radical configurations such as flying wings and disks (Chambers, 2009). In the 1950s there was an expansion of USA interest in the experimental investigation of V/STOL (Vertical/Short Take Off and Landing) configurations, motivated by the investigation of various projects that had been initiated in WW2 (Second World War). Many V/STOL concepts were tested in the 1950s, 1960s, and 1970s with RPAs as tail-seaters (Bates *et al.*, 1953) and Lovell *et al.* (1951) or with tilt-wings Tosti (1961).

In Brazil, there are some initiatives for the use of subscale RPAs for studies and development, such as the Generic Future Fighter (GFF) project, developed in partnership between Brazil and Sweden, presenting several studies on this aircraft are presented, (Nepomuceno *et al.*, 2022), (Monteiro *et al.*, 2017), in addition to the initiatives for the development of flexible subscale aircraft such as Cesnik *et al.* (2010) and Zuñiga *et al.* (2019).

The development of scaling techniques has a long tradition in the development of aviation systems. A 1979 technical paper by Wolowicz *et al.* (1979) summarizes a review of similarity requirements applicable to a wide range of test conditions, ranging from low-velocity incompressible flows to high-velocity supersonic flows. Limitations of test techniques are also noted, with emphasis on the free-flight model. Sizing procedures for free-flight models in incompressible and compressible flows are also demonstrated. For incompressible flows, we preserve kinematic properties by using velocities scaled based on Froude number similarity requirements (Froude scaling). For compressible flows, we preserve the compressibility effects using velocities scaled according to Mach number requirements (Mach scaling).

Once the physical effects to be observed are defined, the appropriate technique for their observation must be employed. The role of the similarity requirements is to establish the relationship between the nondimensional aerodynamic features of the scale model and the model. For the requirements, the dependence of the characteristics on others involved in the flight test must be the same for the original model and based on the intended purpose of the scale model. Essentially, the similarity requirements are derived from the forces and moments in the geometry, kinematics, and aerodynamics of the aircraft.

The most common scaling methods are aerodynamic scaling, which has the similarity to the flow considering the similarity to the motion of the aircraft itself, dynamic scaling, which resembles the rigid body motion of the aircraft as well as the behavior of the aerodynamic loads that cause it. Aeroelastic scaling is similar to dynamic scaling but involves the deformation behavior of the vehicle itself, and demonstrative scaling is used to determine a particular technology or capacity, partially or disregarding the similarity conditions of similarity of the aircraft Sobron *et al.* (2021) and Wolowicz *et al.* (1979)

Free-flight models are used to determine the behavior and dynamics of the aircraft, as well as to make configuration changes necessary to improve stability and control characteristics (Wolowicz *et al.*, 1979). In general, free-flight subscale models cannot meet all the similarity conditions required to simulate the accurate behavior of a full-scale aircraft because atmospheric conditions cannot be controlled as they are in modern wind tunnel facilities. However, when certain similarity aspects are prioritized for different sizes and applications, the results become consistent. Different scaling procedures must be used for free-flight models. Depending on the importance of compressibility and Reynolds effects, it can be quite difficult to combine Mach and Reynolds similarities.

The study of subscale aircraft includes numerous applications and planning techniques for various interests, one of the techniques that resumed the use of subscale aircraft in free flight experiments, since the miniaturization and the decrease in the cost of systems embedded electronics for data acquisition made this technique more attractive and with an improvement in the quality of the data collected.

The purpose of this paper is to present the development of a sub-scale airplane designed using the Froude number method so that it can be used for various tests and comparisons of dynamic and aerodynamic behavior with a real airplane, as well as to present the preliminary results of wind tunnel and computational fluid dynamics (CFD) tests.

## 2. DEVELOPMENT

The development of this project begins with the analysis of data from the technical report "Flight Test Data for a Cessna Cardinal" (Kohlman, 1974), which presents flight performance data for a Cessna 177B Cardinal, see Fig. 1. In this case, the airplane was instrumented and tested in flight to obtain the steady-state performance, the stick-fixed dynamic stability, and the roll response. This work also presents the curves $C_L$ x $\alpha$ and $C_D$ x $C_L$.


Figure 1. Cessna Cardinal 177B (Roskam, 2016).

In order to reproduce the flight tests and to verify the methodology for the development of sub-scale aircraft that represent the flight dynamics of full-scale aircraft, an analysis was started for the development of a sub-scale aircraft, which is presented in this study. For the desired representation, it was analyzed and found that the best scaling method to achieve the desired results is to use Froude number (Fr).

The Froude number is computed by:

$$F_r = f\Big(\frac{Inertial force}{Gravitational force}\Big) = \frac{V^2}{lg}, \tag{1}$$

where $V$ is the velocity, $l$ is the characteristic dimension, and $g$ is the acceleration due to gravity.

Project points were selected in the following steps: First, the flight test points performed with the Cessna Cardinal 177B presented in the study were analyzed. Considering all the points of the conducted tests, the flight conditions presented in Tab. 1 were selected.

Table 1. Flight conditions of the Cessna Cardinal 177B used in flight tests.

| **Variable** | **Value** | **Unit** |
|---|---|---|
| Airspeed, $V_A$ | 58.33 | m/s |
| Altitude, $h_A$ | 2286 | m |
| Weight, $m_A$ | 1134 | kg |
| mass density of fluid, $\rho_A$ | 0.978 | kg/m$^3$ |

For the scale factor (n), the largest vehicle that could be tested in the wind tunnel was chosen (TA -2). With the team that conducted the tests, it was decided that the ideal wingspan was 2.4 meters. Considering that the wingspan of a full-size aircraft is 10.82 meters (CESSNA, 1971), which results in a scale factor of 22.2 %.

The model was built from composites such as fiberglass and carbon fiber, as well as balsa wood and marine plywood. Fig. 2 shows the prototype built and installed in the wind tunnel for testing.


Figure 2. Cessna 177 subscale.

The flight test conditions for the sub-scale aircraft were chosen so that the flight tests could be conducted in the city of São José dos Campos (SJC) with a height AGL(Above Ground Level) of about 46 meters. Tab. 2 shows the desired flight conditions for conducting the test.

Table 2. Intended flight conditions for Cessna 177B subscale flight test.

| **Variable** | **Value** | **Unit** |
|---|---|---|
| Altitude from SJC, LFE (Landing Field Elevation) | 600 | m |
| Test Flight Altitude, $h_m$ | 640 | m |
| mass density of fluid, $\rho_m$ | 1.1516 | kg/m$^3$ |

To obtain the data for the test velocity and weight of the model, the flight conditions given in Tab. 1 and Tab. 2 are applied in Eq. ( 2) and Eq. (3) from (Wolowicz *et al.*, 1979) the results show that the mass of the model is 14.60kg and the test speed is 27.48 m/s. For this project, the $Fr$ calculated by Eq. (2) is $Fr = 32.05$:

$$m_m = m_A\Big(\frac{\rho_m}{\rho_A}\Big)n^3 \Rightarrow m_m = 1134\Big(\frac{1.1516}{0.978}\Big)0.222^3 \Rightarrow m_m = 14.60kg \tag{2}$$

$$V_m = V_A\sqrt{n} \Rightarrow V_m = 58.33\sqrt{0.222} \Rightarrow V_m = 27.48 m/s \quad (3)$$

The proportions of the geometrical dimensions of the airplane resulting from the direct relation of the scale factor $n$, and the values of both the airplane and the projected scale model are shown in Tab. 3

Table 3. Geometric dimensions of the aircraft and projected model of the Cessna 177B.

| | Wings | | Horizontal Stabiliser | | Vertical Stabiliser | | |
|---|---|---|---|---|---|---|---|
| **Variable** | **Aircraft** | **Model** | **Aircraft** | **Model** | **Aircraft** | **Model** | **Unit** |
| Length | 10820 | 2402 | 3607 | 801 | 1523 | 338 | $mm$ |
| Area | 16.26 | 0.80 | 3.25 | 0.16 | 1.74 | 0.09 | $m^2$ |
| Root chord | 1768 | 392 | 902 | 200 | 1453 | 323 | $mm$ |
| Tip chord | 1237 | 275 | 902 | 200 | 832 | 185 | $mm$ |
| Dihedral Angle | 1.5 | 1.5 | - | - | - | - | $deg$ |
| **Fuselagem** | - | - | - | - | - | - | |
| Length | 7720 | 1714 | - | - | - | - | $mm$ |
| Maximum width | 1200 | 266 | - | - | - | - | $mm$ |
| Maximum height | 1304 | 289 | - | - | - | - | $mm$ |
| **Control Surfaces** | **Flap** | | **Aileron** | | **Rudder** | | |
| Length | 2920 | 648 | 1692 | 376 | 1453 | 323 | $mm$ |
| Total Area | 2.74 | 0.067 | 1.80 | 0.089 | 1.19 | 0.059 | $m^2$ |
| Root chord | 512 | 114 | 564 | 125 | 516 | 115 | $mm$ |
| Tip chord | 425 | 94 | 500 | 111 | 304 | 67 | $mm$ |
| Deflection | 30 | 30 | 20 up 15 down | 20 up 15 down | ± 24 | ± 24 | $deg$ |
| There is no elevator because the vertical stabilizer is all moving. | | | | | | | |
| Deflection | 20 up 5 down | 20 up 15 down | - | - | - | - | $deg$ |

The propulsion system was selected to be capable of achieving the test speeds. For this purpose, a 40cc DLE motor with a power of 4.8 HP /8500 RPM was selected and the propeller recommended by the manufacturer of the 20X10 motor (DLE, 2014)

## 3. RESULTS

The preliminary results obtained up to this point are the CFD simulations and the results of the wind tunnel tests. The results of CFD were obtained by creating a CAD (Computer Aided Design) model based on aircraft manuals and data available in (Kohlman, 1974). This model was converted into a structured mesh using the software CFD. The fluid dynamic analysis was performed using the Reynolds Averaged Navier-Stokes (RANS) method and the Sparlat-Allmaras turbulence model. A simulation case is shown in Fig. 3.

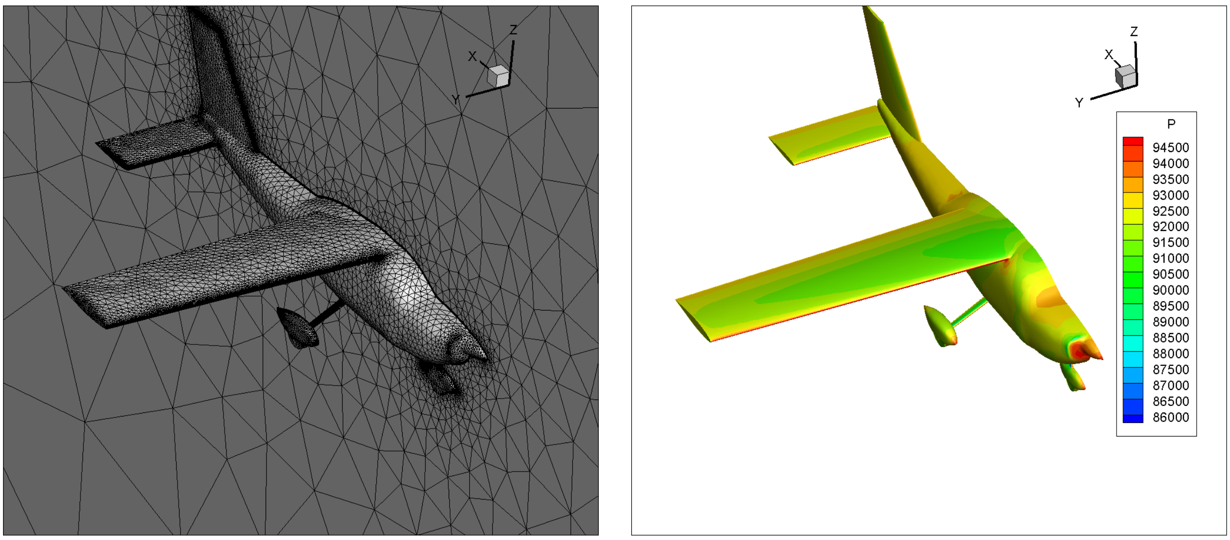


Figure 3. Created mesh and simulation for the 2286 m condition.

The results from the Cessna Cardinal 177B flight test, the curves in Fig. 4 and Fig. 5 that are presented in the paper by

(Kohlman, 1974), were obtained.

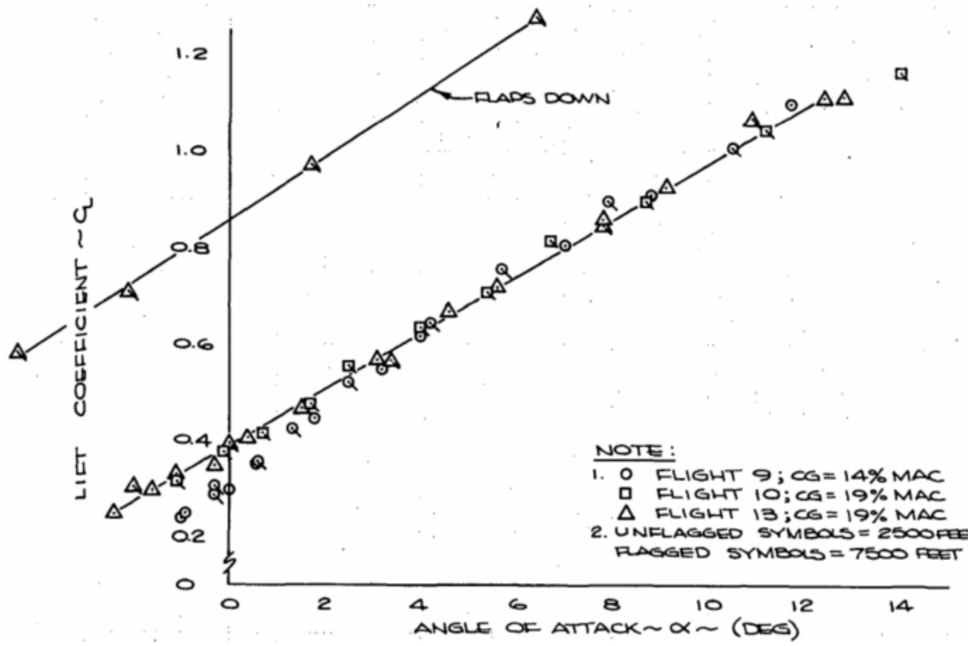


Figure 4. Lift Curves for Cessna 177B (Kohlman, 1974).

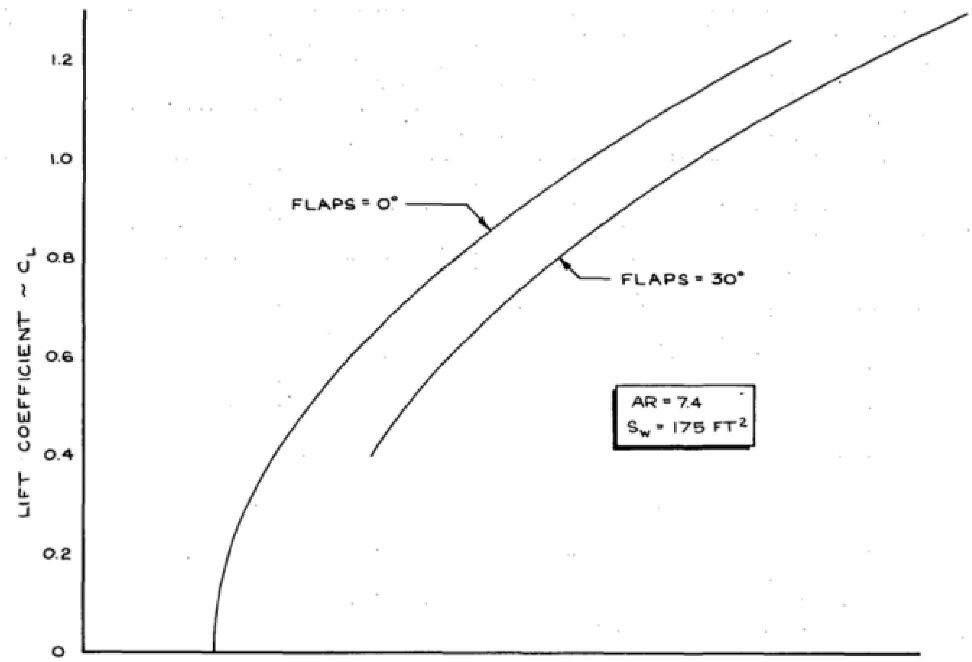


Figure 5. Flight test drag polars for Cessna 177B. (Kohlman, 1974).

Several tests were performed in the wind tunnel, both in the longitudinal and in the lateral direction, in this work the data obtained for the test at two different speeds of 25.3 m/s and 27.5 m/s, the latter being the speed intended for performing the tests in free flight.

In Figure. 6, the lift curves as a function of angle of attack for the two flight tests are shown, as well as the Cessna curve obtained for a flight test at an altitude of 2286 m at a speed of 27.71 m/s. This speed is lower than the design speed because the tests to determine drag and lift curves were obtained from reduced speed tests and the data for the flight modes for which this project is intended were obtained from a higher speed. The data obtained from the CFD simulation are also shown.

It can be seen that the data from CFD and the data obtained in the wind tunnel have the same behavior, with the exception that the $C_{L_{max}}$ is lower for the data obtained in the wind tunnel. The curve for the full-size Cessna shows a different behavior, which can be explained by the fact that the Reynolds for the data obtained from the airplane in flight was $2.22 \times 10^6$ and the Reynolds number for the data obtained in the wind tunnel was $0.614 \times 10^6$. As mentioned earlier, when developing the sub-scale using the Froude number, it is difficult to reconcile the Reynolds number, which may have led to this small difference.

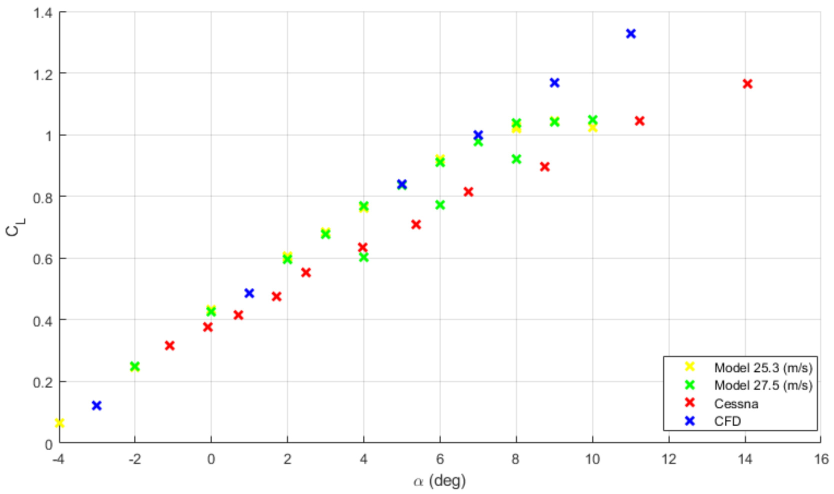


Figure 6. Lift curves comparison for the Cessna 177B, subscale and that obtained in CFD.

Figure. 7 shows comparisons of the polar drag curves for the same velocities tested in the wind tunnel model, as well as for the real Cesnna data from Fig. 5 and those obtained in CFD. It can be observed that in this case the drag polar of the Cessna are more coherent with those of CFD and there is a divergence in the data obtained for the scale model, which in turn is explained by the impossibility of performing the model simulations with the same number of Reynolds of the scale Cessna full-scale

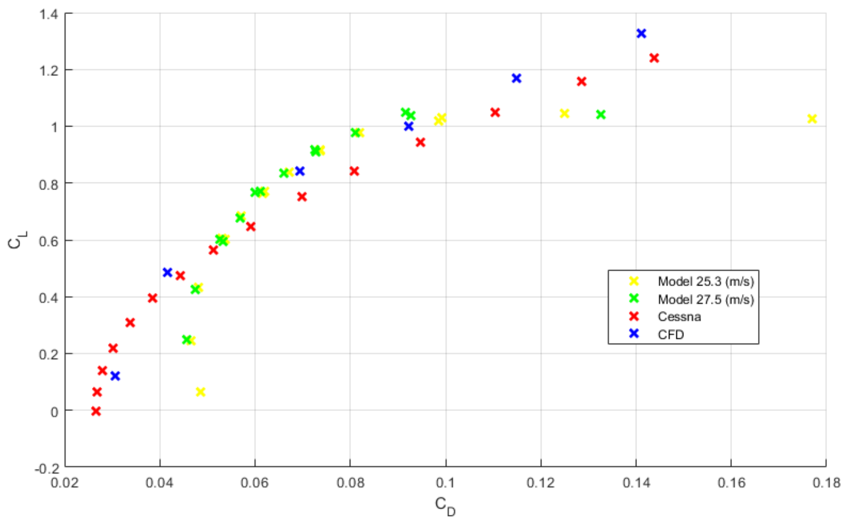


Figure 7. Comparison of drag polars for the Cessna 177B, subscale and that obtained in CFD.

## 4. CONCLUSION

This paper presented in detail the design methodology of a sub-scale aircraft using the Froude number technique, as well as the results obtained in the wind tunnel and their comparison with the same results obtained in a free-flight test of a Cessna Cardinal 177B aircraft full-scale.

The aircraft lift results, obtained from wind tunnel tests with the subscale model, and sub-scale model show remarkable similarity to results obtained from CFD simulations. Moreover, these results are much closer to the data collected during free-flight tests with the full-scale aircraft. However, a more significant discrepancy is observed between the subscale model and the CFD simulation data is observed for the drag polar. However, it should be emphasized that the data obtained by CFD simulations agree well with the data obtained from the tests with the full-scale aircraft.

The discrepancies in the results are due to the complexities associated with wind tunnel tests of a scale model, employing the Froude number, and free flight tests of a full-scale aircraft, which cannot replicate the same Reynolds number. These difficulties arise due to the difficult nature of identifying aerodynamic properties in subscale projects where flight dynamics are sought. Such characteristics can be difficult to identify using scaling techniques such as the Froude number.

The next work in this project is to perform free-flight tests to determine the flight dynamics and to verify the performance of the techniques used to determine the results of the flight dynamics using the Froude number scaling techniques.

## 5. ACKNOWLEDGEMENTS

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