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EXPERIMENTAL AERODYNAMIC DRAG ANALYSIS OF A ROCKET MODEL WITH STRAIGHT AND ANGLED FINS

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Abstract

The drag generated by the fins attached to a model rocket was studied experimentally. Rocket models (designed for 100 meters of apogee) were tested in a didactic wind tunnel in two situations: with straight and angular fins (at 5° and 10°), under wind speeds of 3, 4, 5 and 6 m/s. The results obtained experimentally were compared to the results of the theoretical analysis, allowing a better understanding of the effect of the fins.

Keywords: Rocket models, didactic wind tunnel, fins, drag force.

1. INTRODUCTION

A rocket model is a small launch vehicle used to both educational and commercial purposes. It basically consists of an engine, frame and warhead, with or without accoupled fins (Fig. 1). In this context, a model rocket can be defined as a rocket that has no limitations on the materials used and is powered by an experimental or non-commercial engine [1].

Used for educational purposes, the rocket model allows engineering students to apply theoretical knowledge about aerodynamics, electronics, materials, propulsion and safety.

Propulsion, stability and safety are critical factors that must be considered by designers during the design stage. The ambient wind exerts a significant force on the trajectory of the model rockets, which can result in instabilities and deviation from the theoretically predicted route [2]. Small-scale rockets present specific challenges to designers, mainly regarding their stability – due to the drag generated during flight.

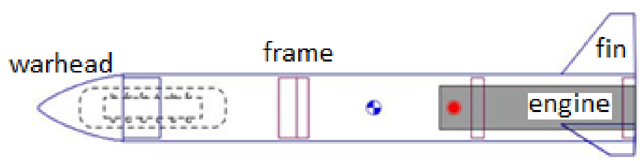


Fig. 1: Rocket model with straight fins.

1.1. Drag Force

Stability is essential to ensure the rocket flies safely. The stability of a rocket model refers to its ability to maintain a theoretically predictable flight path. In other words, the rocket can remain balanced and withstand external (e.g., wind) or internal (e.g., variations in propulsion) perturbations [2].

Since the flight of a rocket model is not controlled, aerodynamics is the only tool available to the designer.

Drag is an aerodynamic force acting in the opposite direction to the motion of the body - the force that a moving fluid exerts on a body in the direction of flow. The drag force can be experimentally measured using a load cell and is mathematically expressed as:

$$F_D = C_D * A * \frac{\rho V^2}{2} \tag{I}$$

Where F_D is the drag force (N), C_D is the drag coefficient (dimensionless), A is the cross-sectional area (m²), ρ is the specific mass (kg/m³) and V is the relative velocity between the body and the fluid (m/s).

According to Eq. (I), the drag force increases proportionally to the cross-sectional area, the drag coefficient, the fluid density at 24 °C and the flow velocity [6]. The coefficient C_D depends on several physical parameters, including geometry, flow regime, angle of attack, surface roughness, and the variation of density with altitude [13].

For a rocket model, which flies for short intervals of time and at high speeds, the increase in aerodynamic drag results in instability. The use of fins can be an option to improve stability during flight.

1.2. Rocket Fins

A fin is a surface that extends from the body of the rocket to promote flight stability. A variety of fin shapes, sizes, materials and attachment modes are available to the designer.

Angular fins generate a rolling moment that reduces the harmful effects of wind, improving the stability of the rocket during flight. The study of the geometry and position of the fins allows quantifying the effects of aerodynamic forces and, therefore, the stability of the rocket [3,5].

As specified in Eq. (I), the area exposed to the flow increases the drag force. The cross-sectional area of a rocket model can be estimated by adding the areas of the circle (Eq. II) and the rectangle (Eq. III), corresponding to the cross-sections of the rocket and the fins, respectively, where the area of the rectangle is multiplied by the number "n" of fins.

$$A_c = \frac{\pi * d^2}{4} \tag{II}$$

$$A_r = (b * h) * n \tag{III}$$

Where "d" is the rocket's diameter (m), "b" is the fin thickness (m) and "h" is the height of the fin (m).

Eq. (III) is applicable to a straight-finned rocket. When the fin is angled, the flow cross-sectional area increases. Then, the projected area of the trapezoid must be added and the value multiplied by the number of fins, according to Eq. (IV).

$$A_t = \left(\frac{((L+l) * a)}{2}\right) * n \tag{IV}$$

Where, in the area of the trapeze shaped fin (due to the angulation), "L" is the long side of the projected area of the fin (m), "l" is the short side of the projected area (m) and "a" is the height (m) between these sides of the projected area (including the "h" value).

To perform the drag force calculation, it is not necessary to consider the complete rocket area, but the frontal cross-sectional areas of the rocket with straight fins (Eq. V), 5° (Eq. VI) and 10° angled fins (Eq. VII).

$$A_{straight} = A_c + A_r \tag{V}$$

$$A_{5°} = A_{straight} + A_{t5°} \tag{VI}$$

$$A_{10°} = A_{straight} + A_{t10°} \tag{VII}$$

1.3. Theoretical investigation

Fin design requires reliable theoretical and experimental analyses. It is interesting to start studying the effects of fin coupling on rocket flight dynamics through computational simulations.

The *OpenRocket* software provides a fast approach to investigate rocket aerodynamic behavior [8]. However, in this case, it is important to be aware that there are limitations regarding the reproduction of real flight conditions.

1.4. Experimental investigation

Essential to the study of aerodynamics, the wind tunnel is a complex and expensive tool, therefore not always available. However, it is possible to obtain reasonable results through a didactic wind tunnel [10].

The didactic wind tunnel is a device used for experimental classes in Fluid Mechanics. It has some controlled conditions, such as temperature and wind speeds, and can generate air flows with characteristics relatively close to the flight environment of a rocket model.

Experiments in wind tunnels provide data on aerodynamic forces. The comparison between experimental and theoretical data (from computer simulations) allows a better understanding of the behavior of the model rocket [9,10].

2. MATERIAL AND PROCEDURES

Universities offering undergraduate engineering degrees must have laboratories equipped with an infrastructure that allows the eternal confrontation between theory and experiment. Unfortunately, this does not always happen, which forces the researcher to improvise. The present research was developed using low-cost instrumentation and self-built devices.

The objective of this study is to evaluate the drag generated by model rockets equipped with straight and angled fins (5° and 10°) under the influence of winds with velocities of 3, 4, 5 and 6 m/s. For this purpose, theoretical analysis was performed as well as experimental tests in a didactic wind tunnel with operating settings of minimum 3 m/s and maximum 6 m/s due to wind tunnel design limitation. These combined approaches allow a comprehensive and integrated analysis of the behavior of model rockets under different flight conditions.

2.1. Rocket Model

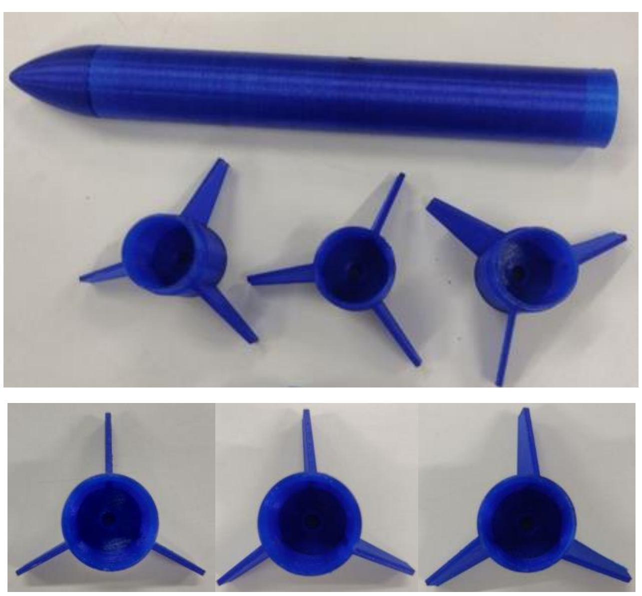
The rocket model considered in this study was designed by the Potiguar Rocket Design Members (PRD) to reach an apogee of 100 m and be operated from the Barreira do Inferno Launch Center (CLBI).

The CLBI provides a secure environment. However, high surface wind velocities (with average varying pose a challenge to the rocket stability, as they mainly influence the propelled phase of the rocket (up to 100 m), the wind average velocities are 3.5 to 4.2 m/s [4].

To provide necessary stability for the model rocket to face the wind, fins with different angles of attack were used. This option requires knowledge about the aerodynamic drag force generated by the fins.

The investigation of drag through experimental tests is done by means of a load cell, used to measure the total resulting force on the model.

The study consists of comparing theoretical data on the drag force on the model, obtained in computer simulation, with data from experiments in a wind tunnel, and observing the effects of changing the angle of attack of the fins: 5° and 10° in relation to straight fins. The rocket model and fins (Fig. 2) were built in a 3D printer.



(S) (5) (10)

Fig. 2: 3D printed rocket model and fins.

Angled fins: straight (S), 5° (5), and 10° (10).

The rocket model dimensions are: 0.245 m in length and 0.027 m in maximum diameter. The sketches of the rocket model and the three fins are presented in Figure 3.

The fins have equal dimensions (height = 0.025 m, root chord = 0.03 m, rope tip = 0.01 m, and thickness = 0.002 m), changing only the angle; thus, having different cross-sectional areas.

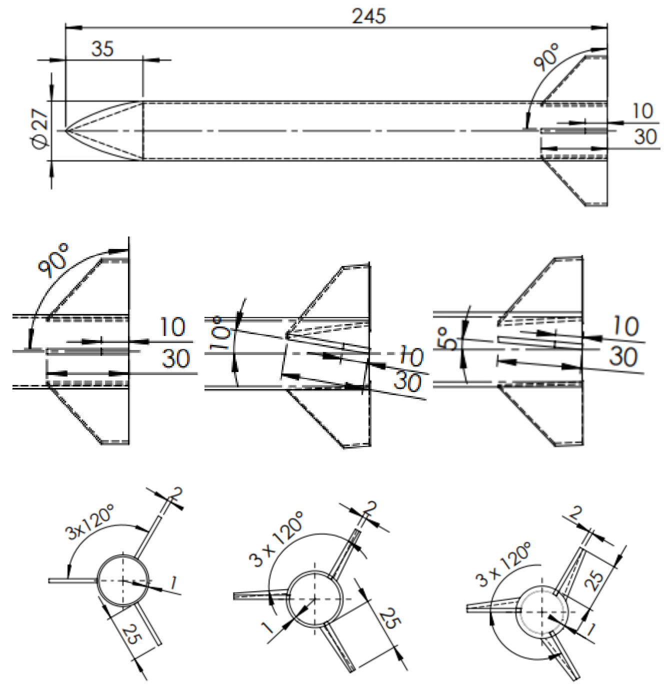


Fig. 3: Drawing of the rocket model and fins.

The masses of the rocket model and fins were measured using a digital scale, resulting in: model with straight fins = 0.051237 kg, model with 5° fins = 0.051221 kg, and model with 10° fins = 0.051208 kg, as can be seen in Figure 4. These mass differences can be a fused filament fabrication (FFF) derivation problem, due to the inaccuracy of polymer deposition.

Fig. 4: Measuring the mass of model rocket 3D printed.

The calculations of the cross-sectional areas were performed using the *SolidWorks* software. The model rocket has a diameter of 0.027 m and therefore a cross-sectional area of approximately 7.22 x 10^{-4} m². The cross-sectional areas of the fins are 1.24 x 10^{-2} m² (5°) and 1.84 x 10^{-1} m² (10°).

2.2. Instrumentation

Before carrying out experiments in the didactic wind tunnel, the instrumentation and the wind tunnel itself were calibrated. Airflow was measured using a digital vane anemometer, which was previously compared to a digital hot wire anemometer.

The load cell was calibrated using a 0,5 kg steel disc, whose mass was determined at the UFRN Metrology Laboratory. This calibration was important to ensure reliability of data acquisition, as illustrated in Figure 5.

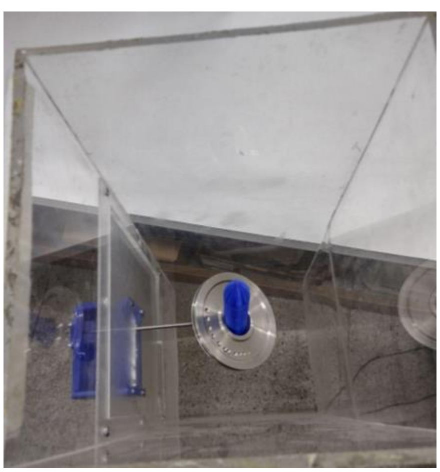


Fig. 5: Load cell during calibration procedures.

The load cell was connected to an analog-to-digital converter and the system was turned on. The fan was turned off and the wind tunnel was kept at rest. The system was then tared to establish the zero-reference point. A message was sent to request that a known mass be placed on the load cell. After 20 seconds for stabilization, the mass value was recorded and the value sent to the software, resulting in a calibration factor.

The calibration factor was stored in the instrument's memory. Data recording started after checking the load cell value through serial connection software. Logged data included date, time, minutes, seconds, and weight [10].

The model was balanced so that at the pivot point (where the fixing rod is located) there was no weight interference in the load cell - corresponding to a neutral balance.

Data were collected for one minute. The procedure was repeated four times for each fan speed considered in the experiment (3, 4, 5 and 6 m/s). During the anemometer calibration, it was observed that the speed presented a maximum variation of 0.2 m/s, as can be seen in Figure 6.

2.3. Preliminary Tests

The *OpenRocket* software was used to simulate the flow over the models, allowing to predict the behavior in flight under defined conditions. As input parameters, the characteristics of the engine developed by the PRD Team were used: material density, wind at CLBI (average speed, direction, turbulence intensity), launch site coordinates, azimuth and launch angle.

The CLBI is located at latitude 5.92° S and longitude 35.16°W and 32 m above sea level. The average wind speed was considered to range from 6 to 7 m/s. The prevailing wind direction was 135° SE [4]. The launch direction was selected to match the wind direction and thus result in maximum drag force. Atmospheric conditions and turbulence intensity were arbitrarily selected for the turbulent flow.

Fig. 6: Anemometer calibration set.

2.4. Wind tunnel tests

A set of practical experiments was carried out using a didactic wind tunnel (Fig. 7).

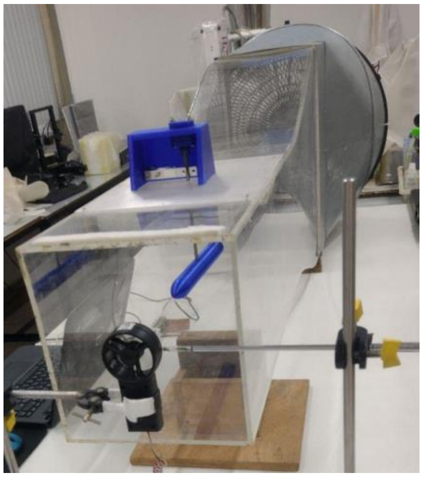


Fig. 7: The didactic wind tunnel.

The model was fixed in the test section of the wind tunnel (Fig. 8) and the drag force generated in each situation was measured and recorded. There were four experiments for each speed (3, 4, 5 and 6 m/s) and each fin angle (0°, 5° and 10°).

As the model built on a 3D printer became light (0.02887 kg), the drag values of the support rod itself were added to the total drag forces. Therefore, it was necessary to perform tests to determine the rod drag for each speed and then subtract the measured value from the total.

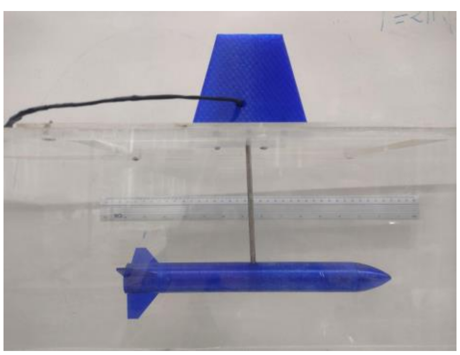


Fig. 8: Model rocket in the didactic wind tunnel.

2.5. Downsampling, Normalization, and Data Analysis

The data generated using the OpenRocket software corresponds to the general data of the rocket and its apogee. The collecting data in txt format (4 measurements of each fin configuration and each velocity of the wind tunnel = 600 measurements, with 1 minute each) were converted to csv., allowing processing through Excel software.

The data were normalized using the average drag force every second (10 points / second). The total average of the averages was calculated. The Weighted Moving Average (MMP) method was applied in time series analysis. In this method, a weight is assigned to each data of the second average; the sum of these data weights must be equal to one. This is because the data incorporate different weights from the previous ones. Thus, the line of force of drag is smoothed [11].

A comparison was made between the individual mean and the global mean. Then, the same procedure was applied to all global averages of the experiments, resulting in a final trend line, used to identify patterns or differences in drag force for each fin configuration and flow velocity. The drag force of the models was calculated using equations (I, II, III and IV) for each speed considered in the wind tunnel. The results obtained in the experiments and in the simulations were compared.

3. RESULTS AND DISCUSSION

The values of the drag forces by the analytical and experimental methods were obtained through Eq. (I). Based on the 3D rocket model, for the straight fin (0°), the value of 0.75 was used [12]. In the case of models with angled fins (5° and 10°), the drag coefficients were obtained based on data from the literature, relative to the 3D cone, the short cylinder and the square, added and divided by three, resulting in 0.84. The fluid density for 24 °C (experiment temperature) was considered equal to 1.1839 kg/m³ [6].

For the areas of the frontal cross-sections of the models with straight fins (Eq. V), with an angle of 5° (Eq. VI) and with an angle of 10° (Eq. VII), the following results were obtained (calculated using the excel software):

$$A_{0^\circ} = 0.000722265 \text{ m}^2 \quad \text{(V)}$$

$$A_{5^\circ} = 0.000852765 \text{ m}^2 \quad \text{(VI)}$$

$$A_{10^\circ} = 0.000982515 \text{ m}^2 \quad \text{(VII)}$$

3.1. Drag Forces and Velocities

Analytical results for drag force as a function of speed are shown in Figure 9.

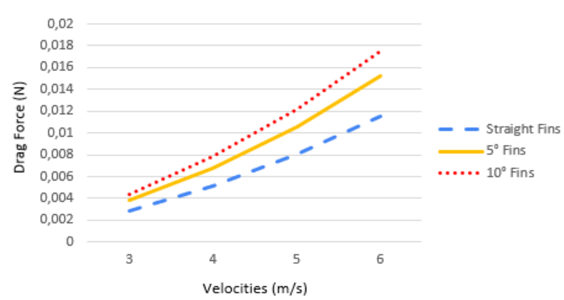


Fig. 9: Drag Force x Velocities - Analytical Results.

As observed (Fig. 9), at low velocities the variation in drag is small. As velocity increase, there is a considerable increase between the values between the configurations (0°, 5° and 10°). Experimental global averages of drag force as a function of velocity are presented in Figures 10, 11 and 12.

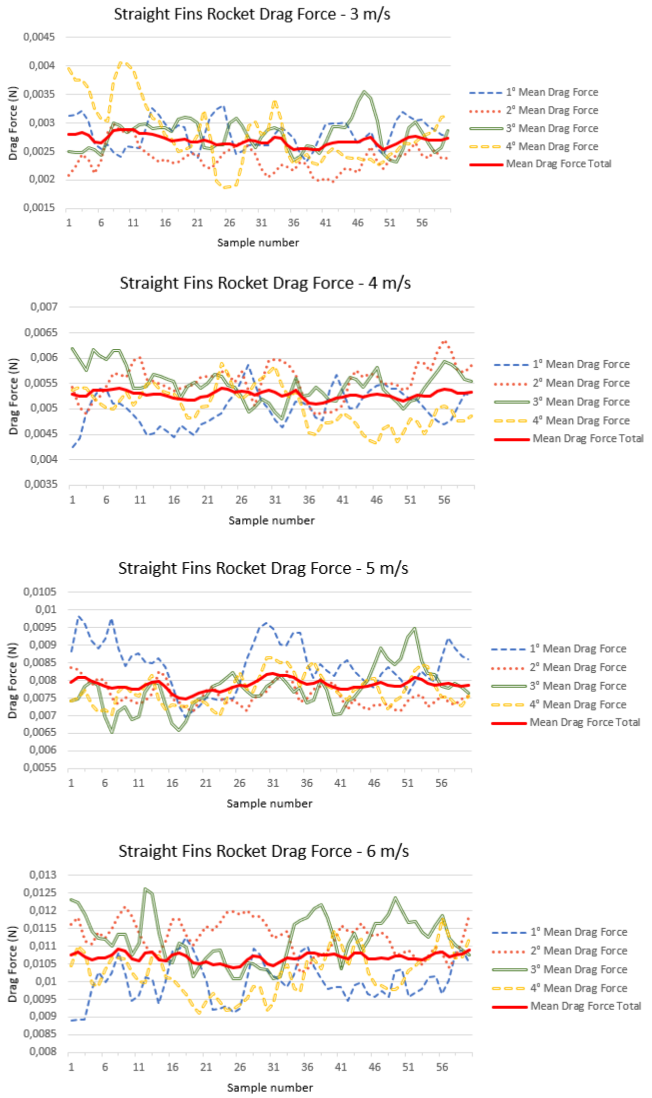
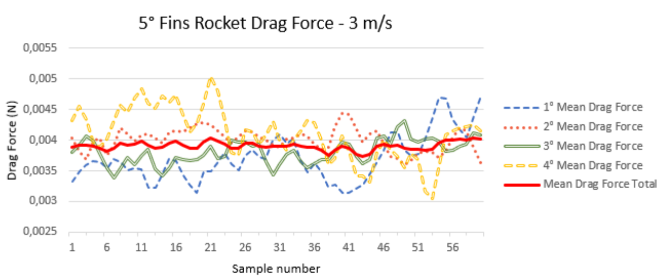


Fig. 10: 0° fins rocket drag force - experimental results.

In Figure 10, the values are approximately between 0.0025 and 0.0030; 0.0050 and 0.0055; 0.0075 and 0.0080; 0.0105 and 0.0110 for all four straight fin rocket drag experiments.



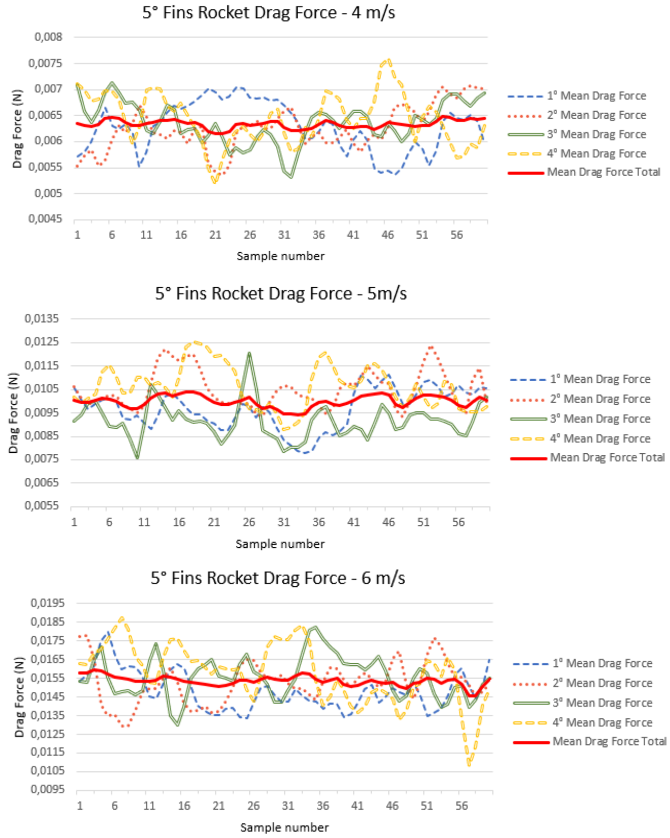
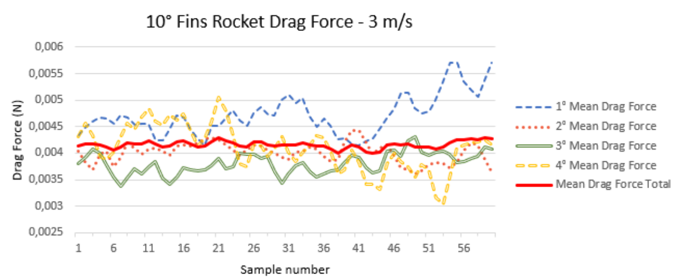


Fig. 11: 5° fins rocket drag force - experimental results.

In Figure 11, the values are approximately between 0.0035 and 0.0040; 0.0060 and 0.0065; 0.0095 and 0.0105; 0.0145 and 0.0155 for all four straight fin rockets drag experiments.

In Figure 12, the values are approximately between 0.0040 and 0.0045; 0.0075 and 0.0085; 0.0115 and 0.0125; 0.0155 and 0.0175 for all four straight fin rockets drag experiments.

Since the didactic wind tunnel is intrinsically turbulent, low wind velocities are difficult to measure. This is a consequence of the low mass of the models used in the experimental analysis. So, calibration was quite laborious, and the resulting drag force was quite low – around a tenth of a gram.



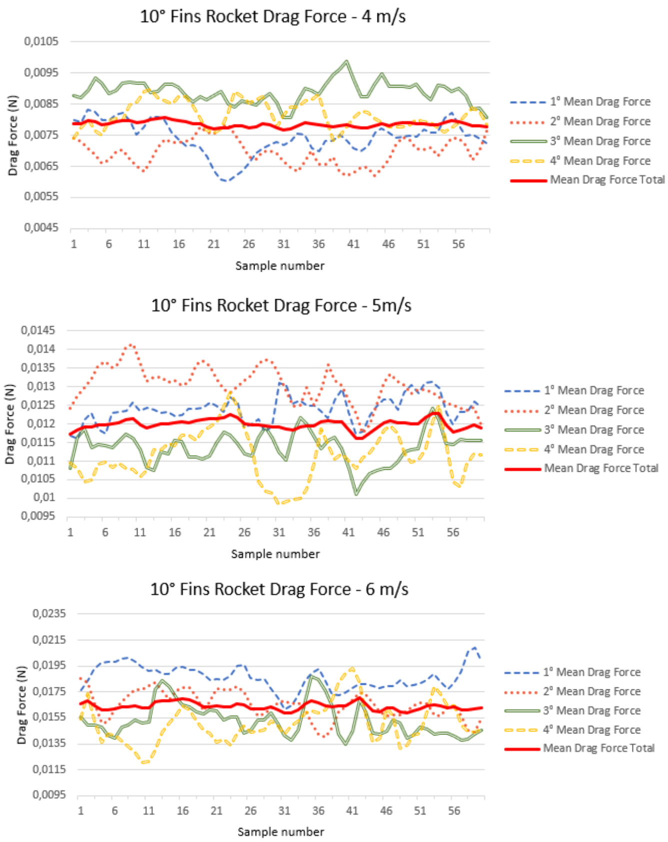


Fig. 12: 10° Fins Rocket Drag Force - Experimental Results.

Drag force versus velocity for each global average of fins configurations are presented in Figures 13, 14 and 15.

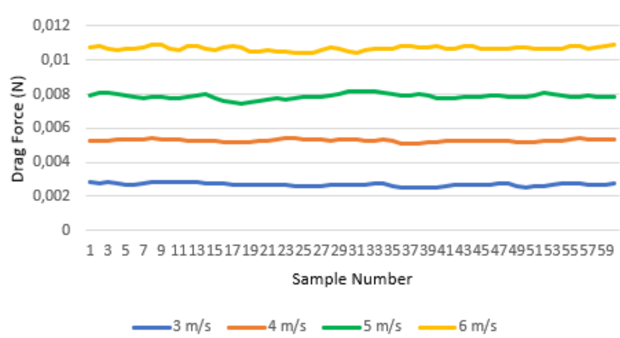


Fig. 13: 0° fins rocket drag force x total velocities (Experimental).

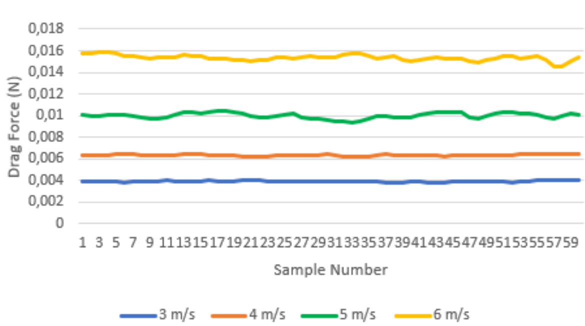


Fig. 14: 5° fins rocket drag force x total velocities (Experimental)

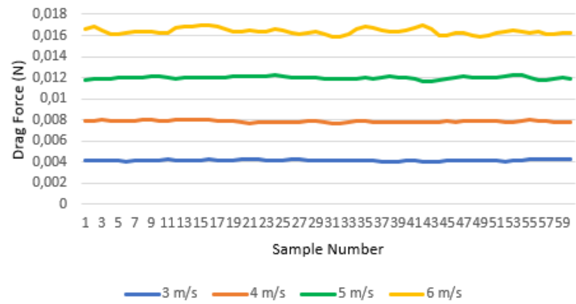


Fig. 15: 10° fins rocket drag force x total velocities (Experimental)

As observed in Figures 13, 14 and 15, with the progressive increase in the speed and angle of the fins, there is an increase in the drag forces acting on the rocket models [3,5].

3.2. Analytical x experimental F_D x V comparison

The comparison between the analytical and experimental results are presented in the figures 16, 17 e and 18.

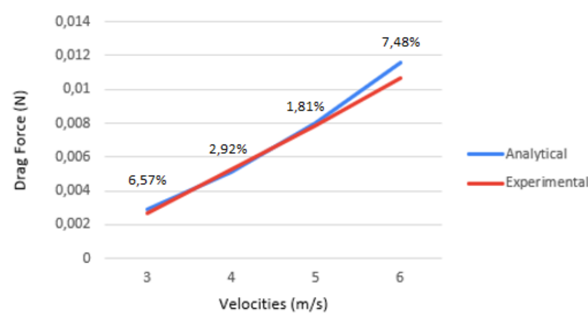


Fig. 16: 0° fins, F_D x V - Analytical x Experimental.

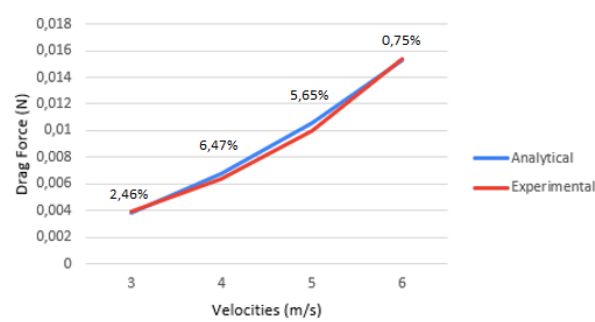


Fig. 17: 5° fins, F_D x V - Analytical x Experimental.

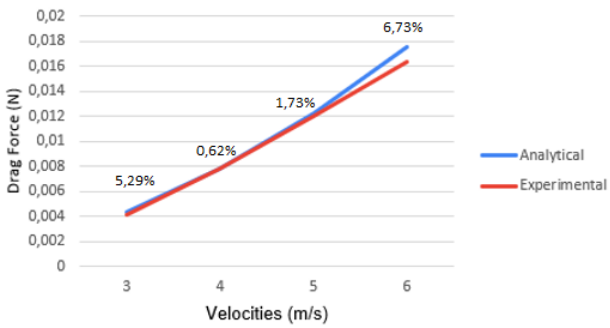


Fig. 18: 10° fins, F_D x V - Analytical x Experimental.

Observing Figures 16, 17 and 18, it appears that the discrepancies are within the expected range. Therefore, there was consistency in the deviations, reinforcing the credibility of the experiments.

Comparing the theoretical and experimental results, it can be deduced that the experiments in the didactic wind tunnel allowed the theoretical results to be reliably reproduced with a maximum error of 7.48 % (for the F_D of the model with 0° vane and at 6 m/ s).

As expected, the drag produced by the rocket models increases with increasing flow velocity and fin angle. Small differences (less than 1%) were found when comparing the values between straight and 10° fins.

The errors found were acceptable for a turbulent wind tunnel designed for didactic purposes. In any case, there is a possibility that the mass of the model is a factor causing the errors observed in the experiments. In addition, the vibration of the equipment itself must be considered. This may be associated with the oscillations found in the values.

4. CONCLUSION

A comprehensive analysis of the behavior of model rockets under different flight conditions was obtained through experimental tests and theoretical data.

The drag force generated by the fins of a rocket model was quantified in experiments conducted in a didactic wind tunnel.

The solution adopted by members of the PRD to improve the stability of the model rocket was the incorporation of angled fins. These fins, while generating a rolling moment, provide a stabilizing force that counteracts the effects of wind. Thus, the fins increase the rocket's ability to maintain a predictable trajectory during flight [3,5,6].

As the objective of the work was to achieve the best stability through the angulation of the fins and thus to study the value of the drag generated by each configuration, the 10° angled fin is the most efficient, according to the results. This is because reliability is increased by improving the stability observed by the *OpenRocket* software and there is still a small increase in drag compared to straight fin, about less than 1%.

The experimental errors were low. The errors were possibly due to the constant variation generated by the vibration and also because the masses and the object of study were small. Therefore, this error in each experiment had an impact on the final results and was identified as a potential source of overall error.

Model rockets, although scaled down, share many of the same principles and technical challenges faced by commercial rockets. They provide a valuable opportunity for students to apply theoretical and practical concepts, understand how technology works, and enhance their skills in design, manufacturing, and testing, preparing them for market challenges and driving innovation in the aerospace industry [7].

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Orientador: Prof. Dr. George Santos Marinho.
Coorientador: Prof. Dr. Giovani Pozza Azoni.

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FOLHA DE APROVAÇÃO

EXPERIMENTAL AERODYNAMIC DRAG ANALYSIS OF A ROCKET MODEL WITH STRAIGHT AND ANGLED FINS

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