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Mathematical Modelling, Computational Fluid Dynamics with Ansys CFX and Experimental Analysis of a Hovercraft Prototype's Air Cushion Lift System

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Abstract. Hovercrafts are amphibious vehicles lifted by an air cushion produced by the pressurization of air between its hull and surface below due to a propeller inside a cavity commonly rounded by a flexible material, known as skirt. These vehicles can be applied in missions such as cargo or coast guard patrolling, rescues, environmental monitoring etc. Aiming to apply some control methods of hovercraft tracking trajectory, it was developed a low cost hovercraft prototype at UFABC using a brushless motor, a MyRio board, aluminum round cake pan, flexible plastic skirt and a three-blade propeller. Therefore, to characterize such hovercraft prototype's air cushion lift system this paper presents its mathematical modelling based on Bernoulli's principle, the design of the 3D geometric domain at SolidWorks® and the internal air flow's CFD performed using Ansys CFX®. Some air cushion pressure experimental data were also taken using a Pitot tube in function of the lift force and about the height from the ground surface and were presented through graphics. The CFD experiments show how the air flow is distributed externally and inside de skirt, through pressure, velocity and streamlines maps that were presented both in 2D and 3D figures.

Keywords: Hovercraft prototype's air cushion, CFD Ansys CFX, experimental pressure analysis

1. INTRODUCTION

Hovercrafts are amphibious vehicles that are capable of navigating above solid or liquid surfaces as land, ice or water due to an air cushion between its hull and the surface below formed by the pressurization of the air supplied by one or more fans. These fans are placed inside a cavity on a flexible structure known as skirt as presented in Hinchey and Sullivan (1993) and Omijeh (2013). They are supported by fans creating a local pressure distribution in the opposite direction of the gravitational force (Kuznetsov, 2009) as shown in Figure 1. This air pressurization is both responsible for lifting the vehicle and minimizing its contact with the ground or water by creating a ground effect which consists of a thin air layer that lubricates the base of the vehicle. Consequently, it reduces the drag forces and provides not only excellent performance on rough surfaces but also the high speed that other conventional marine vehicles cannot achieve (Chung and Jung, 2004).
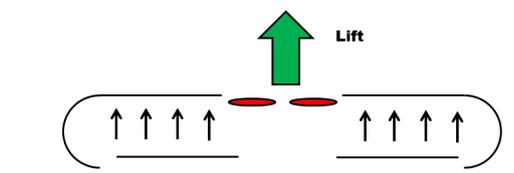

Figure 1. Lift caused by pressure distribution inside the hovercraft air cushion.

This sort of vehicles were developed by Christopher Cockerell studies at the mid of 1950's and since that assume

many applications such as cargo or passengers transporting, coast guard patrolling, rescues, environmental monitoring and many others as presented at (Yun and Bliault, 2000). In (Pagotti *et al.*, 2019) it was developed the control problem formulation in order to track a reference trajectory of a hovercraft dynamical model using the SDRE (State Dependent Riccati Equation) control method and there were performed some numerical simulations about it. Then, in order to achieve the real implementation of that control method it was developed a low cost hovercraft prototype presented in Figure 2.
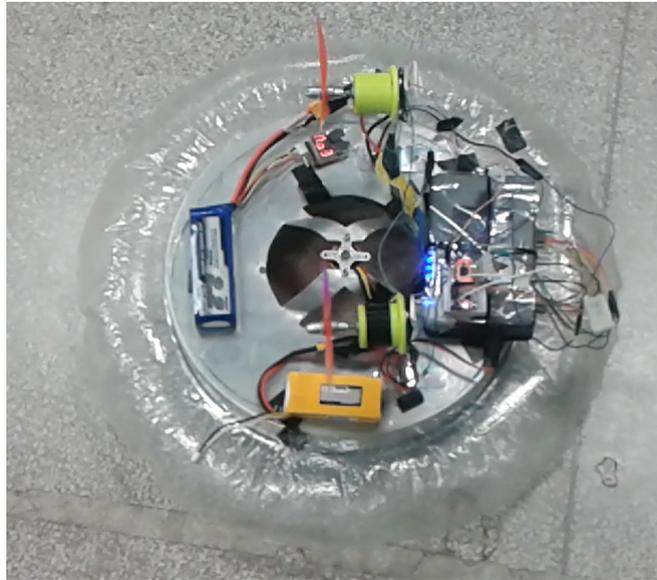

Figure 2. Low cost Hovercraft Prototype developed at UFABC.

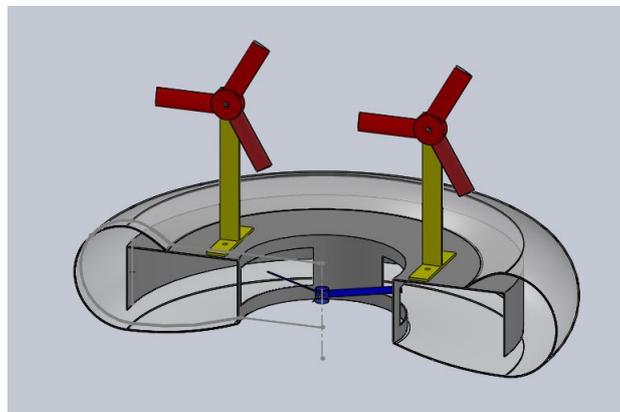The hovercraft prototype 3D-CAD section view is shown in Figure 3.

Figure 3. Hovercraft Prototype 3D-CAD Model developed at UFABC.

To understand more precisely the Hovercraft prototype performance, it was planned to model it mathematically, implement its computational fluid dynamics (CFD) through Ansys CFX® and identify its lift system by taking some experimental pressures data. Finally, the aim of the present paper is to characterize the fluid mechanics of the lift system of the low cost hovercraft prototype designed and developed at UFABC.

In the following section it is developed a mathematical modelling of the air cushion lift system based on Bernoulli's principle. It is shown the steps of preprocessing the CFD simulations that consist of designing it on Solidworks® (a 3D CAD software), arrange it correctly on Ansys CFX ® - setting properly its domains of inlet and outlet, the boundaries conditions and generating its mesh. It is also explained how the experimental pressure air cushion data were taken using a Pitot tube. In results section it is calculated the lift force mathematically modeled of the hovercraft prototype, the results of CFD simulations performed at Ansys CFX® of the air flow both inside the hovercraft skirt as in its surroundings through pressure and velocity maps of some vertical sections and the streamlines in 3D model. Finally, it is presented the experimental air cushion pressure data acquired as a function of lift motor power and the distance between some internal points and the ground surface.

2. METHODOLOGY

In this section it is proposed a mathematical model of a Hovercraft air cushion lift system based on Bernoullli's principle, the procedures to the implementation of the hovercraft air cushion's CFD including its 3D modelling at SolidWorks®, processing at Ansys CFX® and also the procedure of taking experimental air cushion pressure data's using a Pitot tube.

2.1 Mathematical Model

As presented at (Pozzi *et al.*, 1993) heavier and powerful Hovercrafts could include compressibility effects in the description of the fluid-dynamic field. Although, for small ones, it was common to analyze them considering the incompressible regime because the Mach number of the jet required in typical operation is less than 0,3. As this work refers to a small Hovercraft prototype, according to the experimental data acquired, this one presents a maximum outlet air flow velocity of 16 m/s which means that the Mach number remains around 0,05. Other condition to adopt incompressible regime pointed at (Pozzi *et al.*, 1993) is that the lift coefficient needs to be on the order of magnitude of 1. Considering this Hovercraft prototype presents a maximum pressure inside its air cushion of 150 Pa, its lift coeffient becomes around 0,95. It is also mentioned at (Pozzi *et al.*, 1993) that the ratio between distance from ground and total cushion width needs to be less than 0,1 and it it remains nearly 0,05 to this Hovercraft prototype. Fulfilling all these conditions, finally, it characterizes an incompressible air flow regime inside the air cushion of the prototype.

It is seen at (WEST, 1967) that the Bernoulli's principle was applied to calculate critical forward speed of a Hovercraft. At (Spurk, 1997) the Bernoulli's principle is also used to determine the volume flux to be supplied by the blower if the craft is to hover.

So that, considering an incompressible fluid with constant properties, that there isn't no friction forces, a steady state flow and a three dimensional geometry it is possible to propose a mathematical model based on the Bernoulli's principle to determine the lift force of the air cushion. Assuming that Bernoulli's principle is applied over the same streamline it is possible to derive the model to the inlet using the following equation:

$$p_0 + \frac{1}{2}\rho V^2 + \rho g h = cte \tag{1}$$

where p_0 ρ,V, g and h represent the atmospheric pressure, the air density, the air velocity at the inlet, the gravitational constant and the relative height of the inlet nozzle to the ground, respectively.

The air velocity can be rewritten in terms of the flow rate as follows:

$$V = \frac{Q}{A} = 4\frac{Q}{\pi d_i^2} \tag{2}$$

where Q is the flow rate, A is the section area, and d_i is the internal diameter of the air inlet hovercraft's nozzle. So that, Eq.1 becomes Eq. 3:

$$p_o + 8\frac{\rho Q^2}{\pi^2 d_i^4} + \rho g h = cte \tag{3}$$

As presented in (De Izarra and De Izarra, 2010), it is known that the velocity profile into a radial geometry in given by 4:

$$\overline{u} = \frac{Q}{2\pi r h} \tag{4}$$

From other points inside the skirt, denoted by z, the pressure is considered as a function of the cushion radius, also being described by Bernoulli's principle:

$$p(r) + \frac{1}{8}\frac{\rho Q^2}{\pi^2 r^2 h^2} + \rho g z = cte \tag{5}$$

Considering the equation of the Pitot tube, as follows:

$$V = \sqrt{\frac{2p_p}{\rho}} \tag{6}$$

And that the outlet area of the air jet could be described as Eq. 7, where D is the Hovercraft external diameter and t is hovering height or the width of the air jet on the outlet:

$$A_f = \pi D t \tag{7}$$

It is possible to associate the Equations, 3 and 5 on the same streamline, also Eq.6 in therms of the Pitot pressure p_p and Eq. 7 obtaining the Eq. 8:

$$p(r) = 2p_p D^2 t^2 \left(\frac{8}{d_i^4} - \frac{1}{8r^2 h^2}\right) + \rho g(h - z) \tag{8}$$

The lift force is obtained by the integration of the pressure difference between r_2 and r_1 :

$$F = \int_{r_1}^{r_2} p(r)2\pi r dr \tag{9}$$

The lift force produced by the inflow, as function of the internal pressure, and considering h = z is obtained Eq. 10:

$$F = \pi D^2 p_p t^2 \left[\frac{16}{d_i^4}(r_2^2 - r_1^2) - \frac{1}{2h^2}ln(r_2/r_1)\right] \tag{10}$$

2.2 Computational Fluid Dynamics

First of all it was created a domain of simulation using SolidWorks® as software of 3D modelling. So that, the base of hovercraft prototype was drawn including the skirt which rounds it and the propeller inside its cavity, as shown in Figure 4a. The domain of simulation needs to be the negative form of the geometry which would be processed. Then, once we want to analyze the air flow at both the interior and exterior of the prototype the die was designed considering a thickness of 20 mm further the limits of the skirt as shown in Figure 4b. Figure 4c shows the final domain after the operation of subtraction of Figure 4a from Figure 4b.
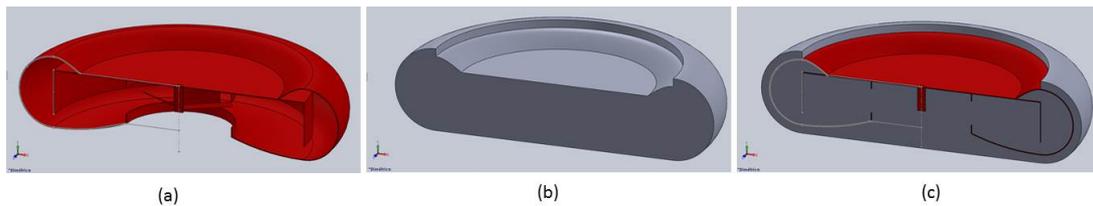

(a)   (b)   (c)

Figure 4. Hovercraft Prototype 3D simulation domain designed at SolidWorks®.

Once finished the creation of the domain, it is imported to the Ansys Workbench® and connected to CFX that is a module which is responsible for CFD simulations. The preprocessing steps of CFD consists of creating a mesh of the selected geometry and determine which geometry faces corresponds of the boundary conditions as well as its numeric values of pressure and velocity. Here it is important to consider carefully the number of elements and nodes used in the mesh that could direct influentiate the final result of the simulation. Before run the simulation it is necessary to set the number of interactions are desired, the numeric precision and the kind of mathematical model that it will be used to solve it and that it does not consider turbulence etc. The computer used for the simulations has a Intel™ i5 processor and 4GB of RAM memory. The software also outputs the iteration processing time. When the processing step finishes it is able to see as results the streamlines in 3D geometry, its animation and also pressure and velocity maps choosing a plane that cuts the geometry, for example. In the simulations done in this work all the entries where based in the experimental data obtained by the essays made before using the Pitot tube as it will be presented at the results section.

## 2.3 Experimental Pressure Acquisition

The experimental tests were done using a Pitot tube connected at TecQuipment's Versatile Data Acquisition System (VDAS®) which makes feasible to measure the static and total pressure of the air flow inside the skirt of the hovercraft prototype. It is important to mention that this Pitot tube has 2mm of diameter and was initially positioned in the outlet of the air cushion as shown in Figure 5. To obtain the variation of pressure inside the air cushion it was chosen a fixed motor power thrust point of operation and the pitot was slowly moved taking the pressure measurement at intervals of 5mm. As indicated in Figure 6.

The velocity profile was also determined using this experimental test, using Eq. (11) where R is the gas constant (R = 287 J/kgK), p_A is the atmospheric pressure, T_1 is the local temperature and (p_t-p_u) is the pressure data taken from the Pitot tube.

$$V = \sqrt{\frac{2(p_t - p_u)RT_1}{p_A}} \tag{11}$$
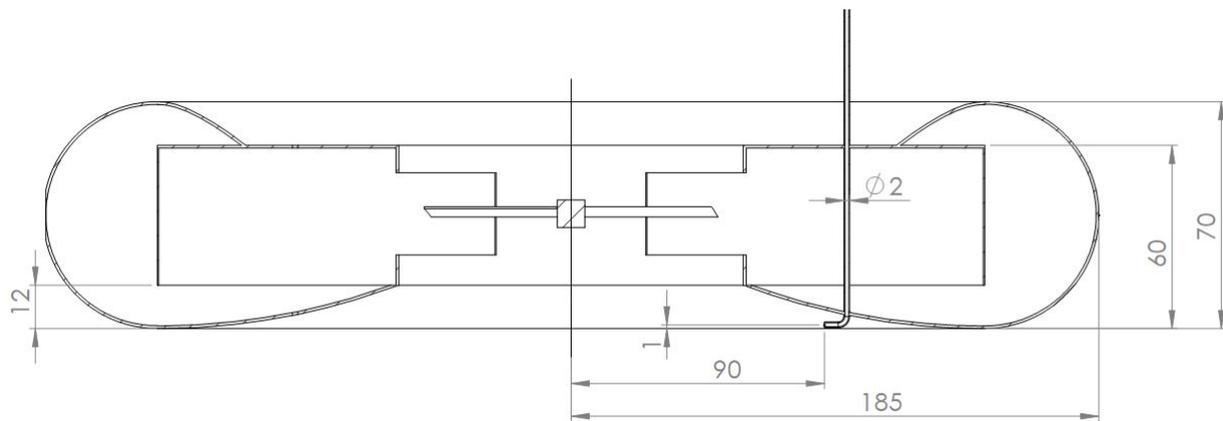
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Figure 5. Pitot position at Hovercraft Prototype
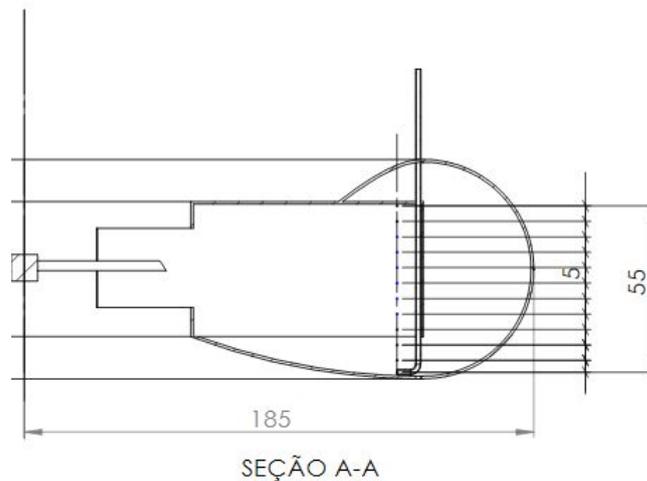
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Figure 6. Pitot position at Hovercraft Prototype

3. RESULTS

Considering that the Hovercraft Prototype's has the following physical parameters presented at Table 1 it was performed the mathematical and computational fluid dynamics model simulations.

Table 1. Hovercraft Prototype's physical parameters

Total Weight	0,8 kg
Total Height	60 mm
External Diameter	370 mm
Internal Diameter	130 mm
Propeller Radius	64 mm
Hovering height	12 mm
Brushless Motor	2200 KV

3.1 Numerical Results of the Mathematical Model

As the lift force due to the air cushion depends only on its geometry and its internal pressure as showed in Eq. (10), applying the parameters of the prototype to the mathematical model it is possible to determine the air cushion lift force in function of its internal pressure, as presented in the graph of Figure 7.

Given that the hovercraft prototype has a constant value for its mass it is possible to determine the extra load it could carry depending on the mission it would be engaged in. For example, the use of extra sensors as cameras etc. Then, the extra load that could be transported by the prototype as function of the pressure inside the air cushion, is illustrated in

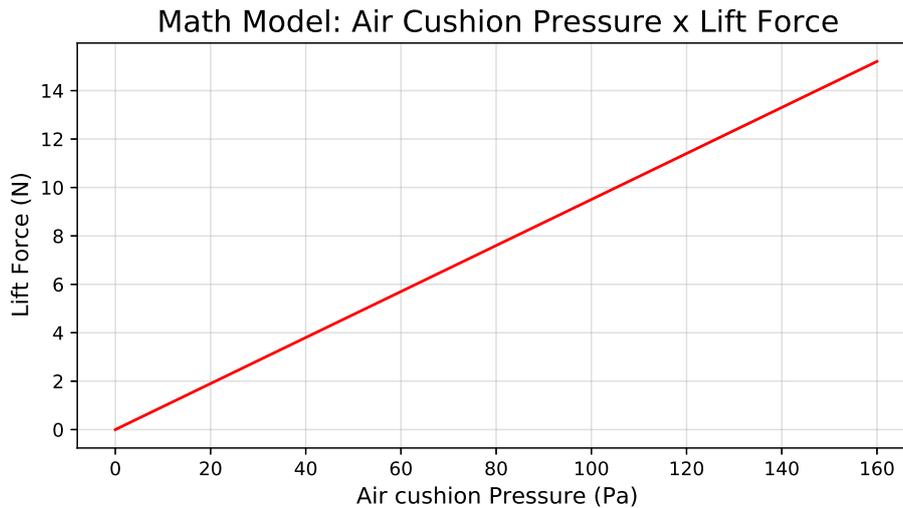## Math Model: Air Cushion Pressure x Lift Force

Figure 7. Lift force of Hovercraft Prototype according to its air cushion pressure.

the graph in Figure 8 where one might notice that the maximum extra charge that considering the mathematical model the prototype could carry is about 6,4 N. From Figure 8 it is noticed that it needs nearly 85 Pa of pressure inside the air cushion to lift the hovercraft prototype without any extra load.
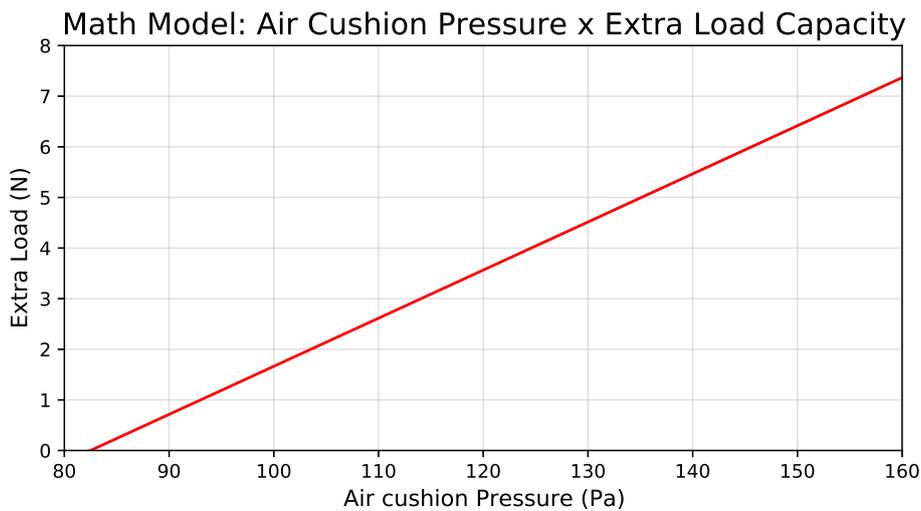
Math Model: Air Cushion Pressure x Extra Load Capacity

Figure 8. Extra load capacity based on the mathematical model.

3.2 Computational Fluid Dynamics

The CFD simulations were made using Ansys CFX® platform, the mesh applied to the domain was about 513468 elements and 94123 nodes. Setting the velocity at the inlet as 12 m/s and considering the external domain pressure is the atmospheric pressure at 27ºC as 101325 Pa to be the outlet of the system, it was able to obtain as results the pressure and velocity maps inside the set third-dimension geometry domain. To better visualization, it was chosen a plane cutting vertically the domain, resulting in a two dimensional map of pressure and velocity as shown respectively in Figure 9 and Figure 10.

For the pressure map in Figure 9 it was possible to notice that the green regions correspond to the atmospheric pressure, and that they round the external domain of the hovercraft prototype as expected. The yellow and orange regions indicate high pressures and show that they're located inside the air cushion and in the propeller region respectively. The lighter blue regions corresponds to pressures little lower that the atmospheric pressure and they indicate that the air tends to escape passing through it. The legend on the left side of Figure 9 presents the correspondences between colors and pressure values.

The velocity map is presented in Figure 10 where the blue regions correspond to the ones where the fluid is closed to stagnant state. The green and yellow regions correspond respectively to velocities about 13 m/s and 15 m/s caused by the
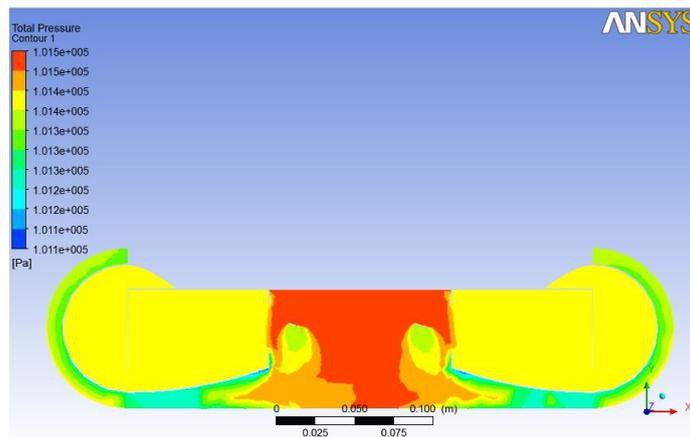
Figure 9. CFD Hovercraft Prototype' air cushion section pressure map at Ansys CFX®.

propeller rotation. The orange region presents velocities about 17 m/s that are at the air outlets.
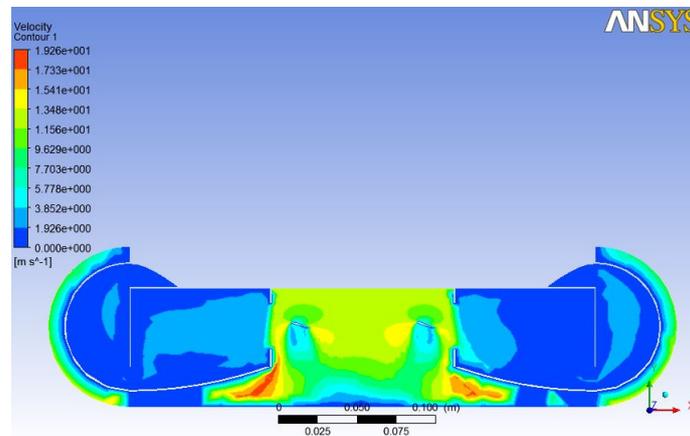

Figure 10. CFD Hovercraft Prototype's air cushion section velocity map at Ansys CFX®.

It was also avaiable to obtain the air streamlines in the chosen plan section as showed in Figure 11a, inside and out of the hovercraft skirt as shown respectively in Figure 11b and Figure 11c.

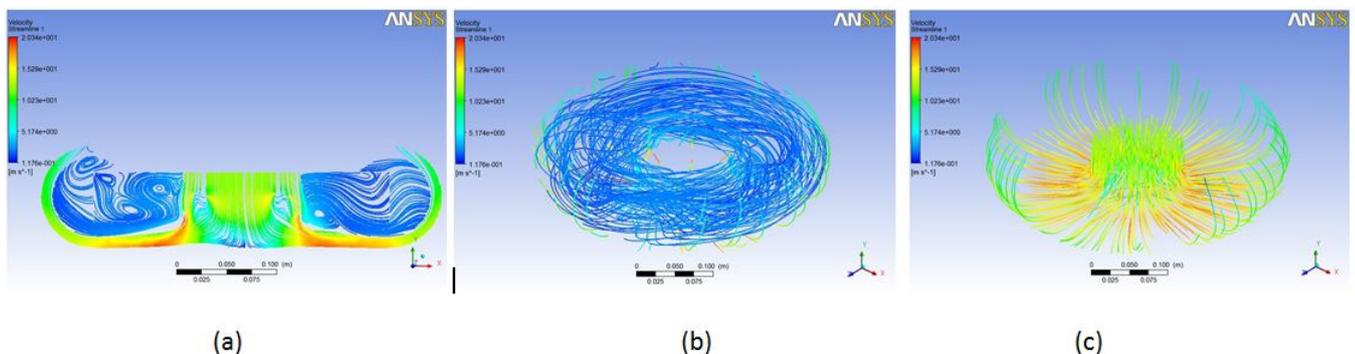(a)   (b)   (c)

Figure 11. CFD Hovercraft Prototype's air cushion 3D streamlines at Ansys CFX®.

For the streamlines diagram one can notice the way the air flows both inside the cushion air and how it escapes of it. The color of the streamlines correspond to the air velocity in the respective point, as indicated in the legend on the left of each figure 11.

3.3 Experimental Results

The motor thrust force was previous measured using a semi-analitical table weighing scale and relationed to the pwm (Pulse Width Modulation) used to control its rpm that was also measured using a tachometer. The experimental results

were presented at Table 2.

Table 2. PWM, RPM and Motor Thrust Force (g) and (N) experimental data

PWM %	RPM	Motor Thrust (g)	Motor Thrust Force (N)
0,0830	2857	38,5	0,377
0,0835	3463	43,0	0,421
0,0840	3805	47,2	0,462
0,0845	4236	55,0	0,539
0,0850	4460	62,0	0,607
0,0855	4830	74,5	0,730
0,0860	5140	77,8	0,762
0,0865	5487	86,4	0,846
0,0870	5569	94,3	0,924
0,0875	5850	97,6	0,956
0,0880	6140	106,2	1,040
0,0885	6305	109,0	1,068
0,0890	6547	120,9	1,184

The pressure measurement inside the Hovercraft skirt was taken using a Pitot Tube, then to start the tests the lift propeller was turned on increasing its power thrust slowly through its pwm control and it was able to acquire the variation of pressure in the outlet and related it to the corresponding motor thrust force, as follows in the graph in Figure 12.
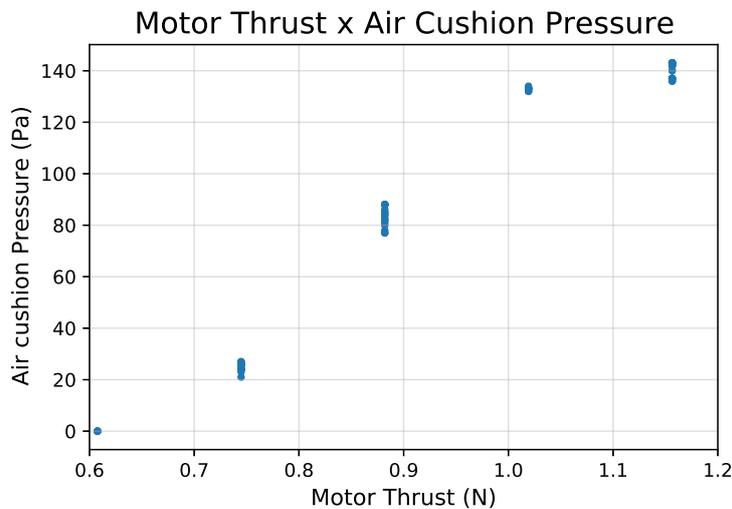

Figure 12. Experimental data pressure of Hovercraft Prototype's air cushion increasing its Motor Thrust.

Figure 12 shows that as the motor thrust increases the pressure increases as a parabolic function, it stabilizes at the pressure of 140 Pa that corresponds to maximum thrust of 1,15 N supported by the electric source battery.

A second test was done attaching some extra load on the Hovercraft Prototype and checking the motor correspondent thrust force. Figure 13 shows a graphic with the result of that experiment. The maximum extra load achieved experimentally was about 550 grams. It is important to compare here that according to the graph in Fig 8 the mathematical model gives a maximum extra load value of 654 grams which probably is not achieved because some losses in the real system.

It was also made a test varying the position of the Pitot tube inside the skirt, maintaining the motor thrust constant at 1.15 N and it was obtained the graph as showed in Figure 14.

According to the graph of Figure 14 the pressure inside the skirt may follows a soft parabolic profile. It indicates a difference of about 10 Pa between the points located from 10mm. For points located near the walls of the upper part of the air cushion it presents a difference of 50 Pa comparing to the ones in the middle height of the skirt, probably because of border effects.

The velocity data of the test is calculated using Eq.11 and is illustrated in Figure 15. It may be observed that the velocity behavior is linearly proportional to the pressure data in Fig.11.
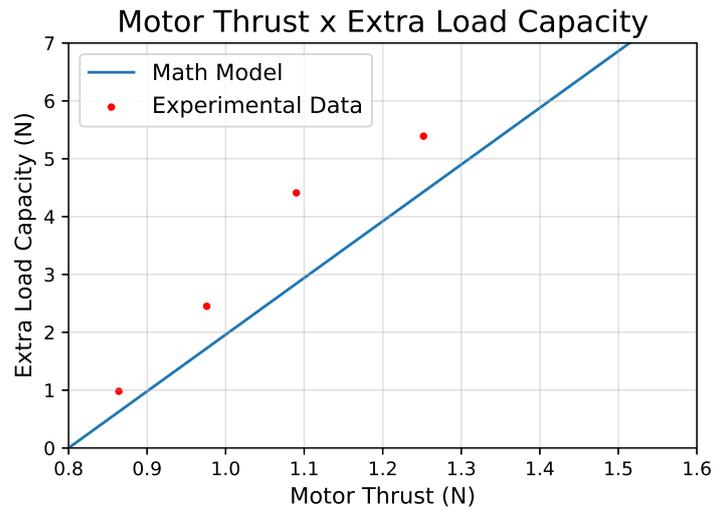
Figure 13. Supported Weight of Hovercraft Prototype's air cushion increasing its Motor Thrust.
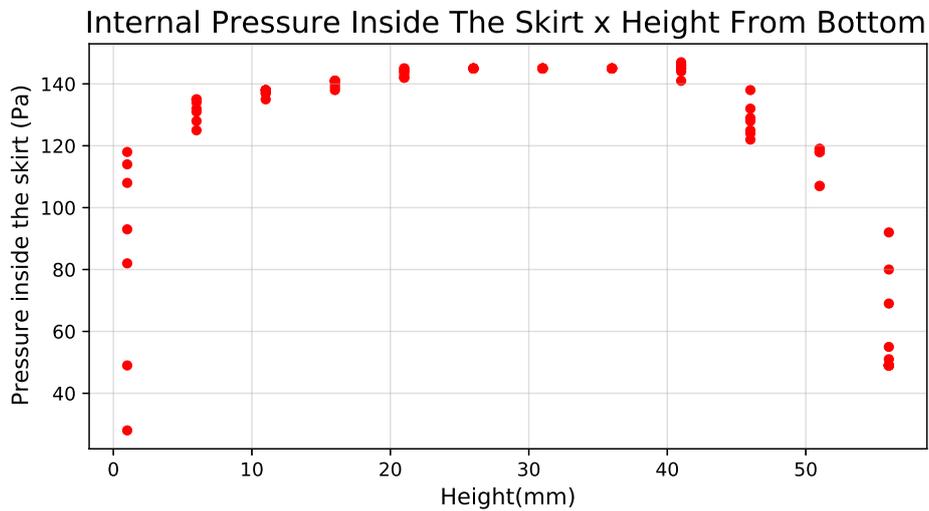

Figure 14. Experimental data pressure of Hovercraft Prototype's air cushion according to its distance from the ground.
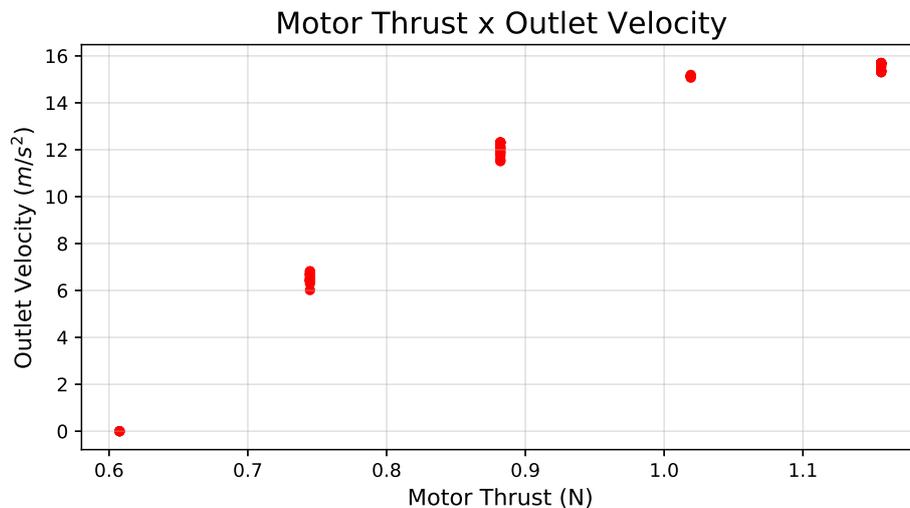

Figure 15. Experimental data velocity of Hovercraft Prototype's air cushion increasing its Motor Thrust.

4. Conclusions

In this work the Hovercraft Prototype's air cushion lift system performance characterized through the mathematical model proposed based on Bernoulli's principle and the experimental pressure data using the Pitot tube showed that the

pressures variations acquired experimentally varies not in a linear way as the proposed mathematical model, because of the limitations of the real system due to battery. Althought their variations are nearly numerically.

As proposed mathematically the maximum lift force of the air cushion is about 14,32 N, which imposes a limit to the weight of the entire prototype of 1,43 kg, which becomes below, finally it weights 0,8 kg. From the Fig. 8 it seen that the Hovercraft Prototype starts to lift when its air cushion reach a pressure of 90 Pa.

From the experimental pressure data it is also possible to validate the CFD simulations finally, as observed in the pressure map at Fig. 9 it presents a pressure diferece of about 150 Pa from the inside of the air cushion to the outlet, which is near to the maximum experimental data of 140 Pa.

The experimental extra load capacity graph presented in Figure 13 shows that its maximum is about 550 grams, while mathematically it achieves a value of 645 grams, probably because some losses in the real system.

The experimental data pressures also gives us a soft parabolic curve of the pressure inside the skirt as presented in Fig. 14 varying the height from the ground of the Pitot tube, which maximum pressure variation between two points of acquisition is nearly 50 Pa.

As it is possible to calculate the air velocity at outlet through the Pitot Equation Eq.11, it opens the possibility to compare it with the values obtained in the velocity map at Fig.10 from the CFD simulations and validate it, finally it presents values of 17,33 m/s in the outlet which are very near to experimental data of 16 m/s.

Being validated by the experimental data, the CFD 3D simulations finally shows us the behavior of the pressure, velocity and the air flow both inside the air cushion and in the boundaries of the system.

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