Numerical analysis of the influence of the lower hull angle of a round skirtless air cushion vehicle

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Abstract. Ever since 1716, when the first concept of building a vehicle to operate with an air cushion was presented, the world remained fascinated by this concept. This article presents a study on important parameters of the flow into the inner cavity of a simple plenum hull, the first configuration of the air cushion vehicle. In order to achieve this, six constructive models were chosen, the only major difference being the angle of inclination at the bottom of the hull. The paper presents the specific mathematical model adapted for this type of configuration, the imposed constructive dimensions, the steps of numerical analysis and results. An important step of this analysis is the estimation of the total weight of each prototype according to the lower hull angle. The estimate was performed using Catia software and the actual analysis was completed using Matlab.

1. Introduction

Air cushion vehicle represent a unique type of transportation due to the fact that these vehicles can operate across a variety of surfaces in a relatively short time. The main factor that makes this movement possible is the air cushion.

For current constructive models, this air cushion is generated between the running surfaces and the flexible skirt of the vehicle. This was not always the case, because the flexible skirt appeared after an initial concept of this vehicle.

Two main types of air cushion vehicle have been featured over the years, open plenum chamber and peripheral jet. The major difference between the two concepts is the buoyancy tank, [1].

The open plenum chamber was the first configuration of this kind of vehicle. An example of such a vehicle is the first experimental model made by Chinese, named Craft ‘33’, [2]. The open plenum chamber configuration has two alternatives: simple plenum (figure 1a) and skirted plenum (figure 1b). Both concepts are represented in figure 1, where: 1 – air source, 2 – hull, 3 – running surface and 4 – flexible skirt, [3].

The purpose of this paper is to study the important parameters describing the flow of fluid only for the simple plenum constructive configuration.

A literature study on these types of vehicles, reveals that most article mention a Swedish philosopher Emanuel Swedenborg, being considered the first person to present a vehicle concept based on an air cushion. His idea was published in Daedalus Hyperboreus, [4], and presented in figure 2, [5].
This concept was described as an elliptical shape made of a wooden frame covered with sailcloth. In the middle there was a cabin in which the crew used two paddles to introduce air under the hull. The main problem of this vehicle was the inability to create the air cushion due to the limitation of human effort, [5].

2. Description of the mathematical model of the simple plenum configuration

The emergence of this concept in academic space, triggered scientific research in the area. Scientists developed mathematical relationships to calculate the governing parameters for this vehicle concept, relationships that are still valid today.

In terms of mathematical modeling describing the flow of a fluid into the inner cavity for such an air cushion vehicle configuration, many researchers were concerned with theoretical issues of this flow, the most important work being carried out by Cocksedge [6], Dukkipati [7] or Wong [8].

The proposed mathematical model is adapted to the examples presented by the authors mentioned above, where the important fluid flow parameters for this configuration are described.

The first step establishes the simplifying assumptions:

- body forces generated at speed will not be considered
- to define a mathematical equation describing the fluid exit velocity, the air is considered to be at rest in the air cushion
- to define a mathematical equation describing the discharge coefficient for the exit flow, it is considered the case of a long wall and ideal fluid flow.

The second step is the description of the mathematical equations. Figure 3 shows a sectional view of this configuration that specifies the parameters to be used in mathematical modeling.

Figure 1. Open plenum chamber configuration (adapted from [3])

Figure 2. The concept proposed by Emanuel Swedenborg
The main fluid flow parameters that describe the mathematical equations (adapted from [8])

The most important parameters describing this configuration are: the lift force ($L_f$) that can be expressed using equation (1), where: $T_f$ – fan thrust [N], $p_c \cdot A_c$ – cushion lift [N], $L_b$ – body forces generated at speed [N] and clearance height ($h_c$) that can be expressed by the equation (2), where: $Q_f$ – the flow through the fan [m$^3$/s], $D_c$ – discharge coefficient for the exit flow [-], $S$ – the peripheral length of the cushion [m] and $v_e$ – exit velocity [m/s].

$$L_f = T_f + p_c \cdot A_c + L_b$$  \hspace{2cm} (1)

$$h_c = Q_f \left( D_c \cdot S \cdot v_e \right)^{-1}$$  \hspace{2cm} (2)

As far as the calculation of the discharge coefficient is concerned, it can be determined by using equations (3) and (4). Regarding the equation (3), this was obtained using five values for $\theta$ (i.e. 0°, 45°, 90°, 135° and 180°), that were used for a polynomial approximation for experimental graphs. Regarding the equation (4), this is a theoretical expression that yields lower numerical values when compared to equation (3), due to the fact that the air velocity is neglected.

$$D_{c1} = 0.5 + 0.4 \cdot 10^{-3} + 0.109 \cdot \theta^2 \cdot 10^{-4} - 0.494 \cdot \theta^3 \cdot 10^{-7} + 0.345 \cdot \theta^4 \cdot 10^{-9}$$  \hspace{2cm} (3)

$$D_{c2} = \frac{1}{2} \left[ \frac{\sin \theta}{\left( \frac{\pi + 2}{\pi - 2} \right) \left( 1 + \cos \theta \right) - \sin \theta \cdot \cos \theta} \right]$$  \hspace{2cm} (4)

To determine the pressure of the air cushion ($p_c$), equation (5) is used, where: $G$ – the hull weight of the air cushion vehicle [N] and $A_c$ – air cushion area [m$^2$].

$$p_c = \frac{G}{A_c}$$  \hspace{2cm} (5)

Considering the second assumption and using Bernoulli’s theorem, equation (6) shows the exit velocity ($v_e$) under the peripheral gap, where: $p_c$ – cushion pressure [N/m$^2$] and $\rho_{air}$ – mass density of air [kg/m$^3$].

$$v_e = \left( \frac{2 \cdot p_c}{\rho_{air}} \right)^{1/2}$$  \hspace{2cm} (6)
Applying the expression of continuity of mass, equation (7) is obtained by which the fan thrust ($T_f$) can be determined, where: $A_e$ – the outlet area of the fluid [m$^2$] and $A_i$ – the inlet area of the fluid [m$^2$].

$$T_f = \frac{2 \cdot p_e \cdot A_e^2}{A_i}$$  (7)

The last two important parameters of this mathematical model are nozzle power ($P_N$), computed using equation (8) and the augmentation factor ($K_a$), equation (9):

$$P_N = p_e \cdot \left(\frac{2 \cdot p_e}{p_{air}}\right)^{1/2} \cdot h_c \cdot S \cdot D_e$$  (8)

$$K_a = \frac{A_e}{2 \cdot h_c \cdot S \cdot D_e}$$  (9)

Using equations (1), (7) and taking into account the first assumption, yields equation (10) which represents lift force:

$$L_f = \frac{2 \cdot p_e \cdot A_e^2}{A_i} + A_e \cdot p_e$$  (10)

3. **The dimensional characteristics of the constructive model proposed for the study**

In order to be able to apply the mathematical relationship described above, it is imperative to impose dimensional characteristics. Therefore, in figure 4 are presented the main dimensions of the proposed model of study.

As mentioned earlier, this study refers to six constructive forms in which the only difference is the angle of inclination of the hull which can have $\theta_1=30^\circ$, $\theta_2=36^\circ$, $\theta_3=42^\circ$, $\theta_4=48^\circ$, $\theta_5=54^\circ$ and $\theta_6=60^\circ$ values. In terms of clearance height, usually the range in which it can vary is between 200 to 600 millimeters [9]. For the configuration presented in this article, these values are very high and for this study a value of 50 millimeters has been adopted.

![Figure 4. Main dimensions of the proposed model](image)

4. **Diagram of steps taken to perform numerical analysis**

For the actual numerical analysis, the diagram presented in figure 5 was used. Analysing this diagram, the constructive dimensions and the imposed initial parameters, one can notice that the only unknown is the weight of the prototype. In the following it will be presented the weight analysis of the prototype for all six proposed cases, in which different types of material are used. The analysis was performed using Catia software.
5. Weight analysis of the proposed design model for different types of material

Studying the literature on these types of vehicles, one can notice that several authors have used certain materials in various studies on the hull of an air cushion vehicle. These materials are: plywood [10][11][12][13], sandwiching polystyrene sheets between plywood sheets [14], styrofoam with balsa wood [15], Aluminum [16], Al 6061-T6 [17], fiber reinforced epoxy composite (60% S – glass fibre and 40% epoxy resin) [18][19] or Dyneema epoxy composite material [20]. It should be noted that these materials were considered hypothetical only where numerical calculation and/or numerical simulation were made or even used in the actual construction of an air cushion vehicle.

Two important factors that are considered when selecting the hull material of an air cushion vehicle are as follows: the structure should have a relatively light weight and must provide a higher strength. For air cushion vehicles that are also used on water, the corrosion resistance of the material must also be considered, due to the long period in which the hull is in salty water.

Taking into consideration the materials presented above, table 1 presents the main materials used for the hull weight analysis of the chosen prototype where new types of materials can be observed.

![Figure 6. Isometric view of hull made of aluminum for θ₁=30°](image)

![Figure 7. Isometric view partially sectioned for wooden hull with θ₁=30°](image)

To perform this weight prototype analysis for the various materials presented in table 1, the Catia software was used due to the complexity of this structural shape. The 3D models of all six constructive designs were created and figure 6 shows an isometric view of the hull having the aluminum material. In order to have a picture of the interior of this hull, figure 7 shows a partially sectioned view of the hull made of wood.
Table 1. The final materials chosen for the study of weight

| No. of case | Type of material                                      | Density [kg/m³] |
|-------------|------------------------------------------------------|-----------------|
| 1           | Aircraft plywood [21]                                | 580 - 650       |
| 2           | Marine plywood [22]                                  | 450 - 720       |
| 3           | Bendy plywood [23]                                   | 400             |
| 4           | Aluminum / Al 6061 – T6 [24]                         | 2700            |
| 5           | Balsa wood [20]                                      | 160             |
| 6           | Fiber reinforced epoxy composite (60 % S-glass fibre and 40 % epoxy resin) [18][19] | 2490 – S-glass fibre 1200 – epoxy resin |
| 7           | Dyneema epoxy composite material [20]                | 970             |

Due to the realization of these 3D models, it was easy to determine the volume, thus resulting in the mass of each prototype in part for each of the previously mentioned materials. Table 2 lists these values where the centre of gravity coordinates is also included.

To analyse the materials used, figures 8, 9 and 10, respectively, show the variation of the mass in relation to the surface for the three types of plywood. Referring to figure 8 and 9, this analysis is performed for two densities, practically the extremes of the density range.

Table 2. The constructive features of the models proposed for the study

| No. | θ [°] | Volume [m³] | Center of Gravity |
|-----|-------|-------------|-------------------|
|     |       | x [mm]      | y [mm]            | z [mm] |
| 1   | 30    | 0.01265     | -4.242e-014       | -2.616e-013 | 169.553 |
| 2   | 36    | 0.01231     | 3.001e-013        | 5.808e-014  | 173.172 |
| 3   | 42    | 0.01208     | -1.481e-014       | 7.848e-013  | 175.900 |
| 4   | 48    | 0.01190     | -1.603e-013       | 1.252e-013  | 177.987 |
| 5   | 54    | 0.01177     | 7.445e-013        | -2.709e-013 | 179.593 |
| 6   | 60    | 0.01167     | 2.656e-013        | 8.861e-013  | 180.824 |

Also, figure 11 shows the variation in mass depending on the surface of the prototype for aluminum and balsa wood and in figure 12 shows the variation in mass in relation to the surface of the prototype for the two composite materials, namely: fiber reinforced epoxy composite and dyneema epoxy composite.

Figure 8. Variation of mass according to the surface of the prototype for aircraft plywood
Figure 9. Variation of mass according to the surface of the prototype for marine plywood

Figure 10. Variation of mass according to the surface of the prototype for bendy plywood

Figure 11. Variation of mass according to the surface of the prototype for balsa wood and aluminium
Figure 12. Variation of mass according to the surface of the prototype for the two types of composite materials

6. Numerical calculation

Using the mathematical model described above, a numerical analysis was performed for all required angles. It should be noted that for aircraft plywood and marine plywood materials, the calculations were made with the lowest density. Regarding the parameters: discharge coefficient and augmentation factor, their numerical values are presented in table 3. For the $\theta_1=30^\circ$ and $\theta_6=60^\circ$, figure 13 shows the variation of the fan flow in relation to the lift force, figure 14 shows the variation of the nozzle power in relation to the lift force and figure 15 shows the variation of cushion pressure in relation to the lift force.

Table 3. Numerical values of discharge coefficient and augmentation factor

| $\theta$ [$^\circ$] | $D_{c1}$ [-] | $D_{c2}$ [-] | $K_{a1}$ [-] | $K_{a2}$ [-] |
|-------------------|-------------|-------------|-------------|-------------|
| 30                | 0.5208      | 0.4077      | 4.8775      | 6.2304      |
| 36                | 0.5268      | 0.3695      | 4.8216      | 6.8737      |
| 42                | 0.5334      | 0.3038      | 4.7615      | 8.3605      |
| 48                | 0.5407      | 0.1957      | 4.6978      | 15.900      |
| 54                | 0.5485      | -0.4150     | 4.6305      | -6.1209     |
| 60                | 0.5570      | 2.5059      | 4.5598      | 1.0136      |

Figure 13. Variation of the fan flow in relation to the lift force for $\theta_1=30^\circ$ and $\theta_6=60^\circ$
Conclusions
The purpose of this article was to perform a numerical analysis using a theoretical model that describes simple plenum configuration and applying this model for a constructive form to obtain numerical results that can be interpreted and may provide an image of the important parameters that characterize this configuration.

Regarding the types of materials used, three types of plywood were used for comparison, i.e. aircraft plywood, marine plywood and bendy plywood. These materials have a relatively low density and can be used to construct such a hull.

Analyzing the values presented in table 2 and considering that the main dimension that varies is the value of the lower hull angle for all six prototypes, it can be inferred that the $\theta$ angle has a major influence on the constructive features. Therefore, it can be noticed that as the value of $\theta$ angle increases, the weight of each prototype gradually decreases. Calculations show that for each material, the mass of the prototype with $\theta_1=60^\circ$ is less than 7.74% of the prototype mass with $\theta_1=30^\circ$.

Performing an analysis of material types, it can be noticed that for aircraft plywood the difference is 0.5684 kg, for the marine plywood the difference is 0.441 kg, for the bendy plywood the difference is 0.392 kg, for the aluminum the difference is 2.646 kg, for the balsa wood the difference is 0.1568 kg, for the fiber reinforced epoxy composite the difference is 1.9345 kg and for the dyneema epoxy composite the difference is 0.9506 kg. It should be noted that the numerical study did not take into account the weight of the air source.
A thorough literature review performed by the authors of this paper revealed that similar studies have not been performed or published. This analysis is particularly important in the design stage of such a vehicle because it estimates the weight of the prototype. Using the graphs presented in this article, it is possible to estimate with some approximation depending on the surface, the weight of the model that is to be built / studied.

Another important observation is that the discharge coefficient calculated with polynomial equation is larger than the one calculated using the theoretical expression.

Given that aluminum has the highest density of all materials used for this numerical analysis, it follows that the highest numerical value obtained are for this material.

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