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Creating a 3D Model of a Hovercraft for Research into Structural Shape Optimization and Material Design of Structural Parts

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The article describes the creation of a mathematical 3D model of the original hovercraft structure, which will be further used for research into modifying the shapes and materials of the structure to ensure better driving conditions. Proposals for new materials for individual parts of the hovercraft structure will be addressed in order to reduce the weight of the hovercraft and thereby ensure a higher possible speed of movement, reduce fuel consumption and ensure the necessary mechanical properties of individual segments. The mathematical model of the simplified hovercraft model was created in the Cradle and Adams simulation programs. The paper is presented by analyzing the hovercraft properties in order to obtain sets of advantages and disadvantages of the hovercraft. The following is a description of the creation of a geometric 3D model of the hovercraft, which is built using Autodesk Inventor. The article further describes the transformation of the 3D model into a simulation model that can be used for co-simulation of movement in the Adams and Cradle computer simulation systems. The simulations will be the first step towards modifying the structure of a real rescue UAV prototype with improved maneuverability, stability and the ability to traverse terrain with surfaces unsuitable for hovering.

Keywords: Hovercraft, Mathematical model, Simulation, Multibody system, Airflow, Rapid design

1 Introduction

A hovercraft is a means of transport (Fig. 1) that moves on a cushion of air just above the surface of solid ground, just above the water, eis or snow surface. The air cushion is created by a flow of air that is forced under the hovercraft by an airscrew or blowers through openings in the bottom of the hull. The development of new hovercraft designs, improving the quality of their handling characteristics or reducing their fuel consumption and noise level, is nowadays a frequently addressed issue [1].

Hovercraft can eliminate the disadvantages of amphibious vehicles or drones [2] and offer great potential for their use in flood rescue operations or in transporting the injured people in inaccessible terrain [3].

Research and development is currently being carried out worldwide mainly using multi-body and CFD programs (e.g. Adams, Cradle, Fluent) [4] or using FEM computational methods (Ansys, MATLAB) [5]. The level of knowledge in this area has been ascertained by studying a number of papers dealing with the design of hovercraft in various fields [6]. A research of them was carried out. The aim of the search was to identify new elements of hovercraft design and especially the flaws of hovercraft in order to determine the direction of our future research. In the publication [7], the main advantages and disadvantages of hovercraft were presented. Hovercraft are capable of travelling at high speeds of up to 110 $km.h^{-1}$ on water and up to 150 $km.h^{-1}$ on land. They can operate in a variety of terrains including water, mud, ice, snow and sand. Hovercraft create minimal pressure on the ground or water. Hovercraft are suitable for sensitive environments such as wetlands. Hovercrafts glide on a cushion of air therefore they offers less friction and resistance compared to conventional boats, resulting in lower fuel consumption. Hovercraft have excellent manoeuvrability and can turn on the spot, making them ideal for search and rescue operations, military operations and border control. However, hovercrafts also have their disadvantages. They are generally noisy, which can disturb wildlife and people in the area. Hovercraft usually have a limited carrying capacity, so they are not suitable for large-scale transport of people and cargo. They are affected by adverse weather conditions such as high winds and waves, which can limit their ability to operate effectively. Hovercraft requires regular maintenance of cushion, engine and propulsion systems, resulting in relatively high maintenance costs. Hovercraft can stir up sediments and disturb aquatic habitats, potentially harming fish and other wildlife. In a article titled Development of a Working Hovercraft Model, the design and development of a prototype hovercraft with complete basic hovercraft functions was described. The hovercraft design process was recognized as very similar to that of ships and aircraft. In-depth research was carried out to determine the components of the hovercraft system, their basic functions and in particular the principle of operation. To determine the size of the components, a detailed design analysis was carried out in full compliance with the relevant standard requirements applicable to the air cushion model. Test performance was performed and the prototype was found to meet the design expectations and provide a 0.5 inch air cushion. The test result showed an efficiency of 69 % for the design. Further research is recommended to improve the determination of the efficiency of the craft [8].

Fig. 1 *Hovercraft of small dimensions – model Hovercraft 425 [author]*

In the article [9], the hydraulic drive of a hovercraft was investigated. A unified mathematical model of the force section of the hydraulic drive and the fan supplying air to the air cushion section was developed. The rotation speed of the ventilator and the height of the hovercraft above the reference level were analyzed using a hydraulic drive with volumetric control in the highest efficiency zone. The regulation was proposed to be done by a directional change of the pump operating volume. The air cushion height was characterized by the hovercraft's field capability and power costs. In addition, the air cushion height was linked to hovercraft pressure and airflow in the air cushion sections. The setting of the air cushion elevation enabled a general assessment of the hovercraft. Ensuring the zone of highest fan efficiency was linked to the condition of stable operation of the fan as well as the hovercraft. In the paper, the calculation schemes of the hydraulic actuator were presented and acceptable transitional characteristics of the system were obtained when the pump pad inclination angle was changed. The simulation allowed to analyze the energy efficiency of the system essential in the implementation of optimal operating modes.

In a paper [10], the authors addressed the problem of trajectory tracking control of hovercraft with asymmetric time-varying multiple state restrictions in the presence of unmodeled dynamics and external disturbances. Using a vector mathematical model of the hovercraft with four degrees of freedom, an extended state observer was used to provide an estimate of the concentrated disturbance. Additionally, control laws for the virtual impact velocity and angular roll rate were obtained by using an ordinary Lyapunov barrier function of logarithmic type to stabilize the attitude and roll errors. Moreover, compared with the traditional Lyapunov function of symmetric integral barrier, a new asymmetric integral barrier Lyapunov function was introduced into the design process to solve the asymmetric state constraint problems. The impact velocity and the angular rate of rotation to the inside barrier were analyzed, thus guaranteeing the safe rotational motion or performance required at high speed. The effectiveness of the proposed control scheme was addressed using numerical simulations.

Most types of hovercraft suffer from a lack of poor manoeuvrability, low specific mass power, loss of buoyancy and hence ability to move on excessively rough terrain, poor manoeuvrability, lack of effective braking and direction reversal capability, poor hull waterproofing and buoyancy, the absence of an emergency back-up propulsion system on water, poor distribution of airflows under the fuselage, poor safety and efficiency of the rotor, propeller blades, and air intake and protective ring around the propeller, incorrect length of the rectifying segments of the flexible circumferential air cuff, and improper top and bottom segment attachment. The quality of the segment materials will also need to be addressed, as they are currently poorly resistant to abrasion and have poor security for winter operation. Other options for improving the use of hovercraft for rescue operations may include modifying the composition of special equipment for rescue service purposes, implementing the possibility of unmanned aerial vehicle support by means of finding a suitable route when moving to the intervention site.

Two main disadvantages in the operation of small hovercraft have been selected by the research team in this part of the research and their elimination becomes the first objective. The main disadvantages of small hovercraft selected by the research team to be addressed are:

- The possible loss of buoyancy and thus the ability to move on too rugged terrain,
- Lack of possibility of unmanned deployment of the hovercraft in a rescue operation.

For a greater range of possibilities in the deployment of small hovercraft in rescue operations, it would be very beneficial to eliminate these two disadvantages.

The aim and content of this article and the articles that will follow is to describe the process that will lead to the elimination of the two selected disadvantages. This path starts with the construction of a simulation model that will be used to test the suitability of the new hovercraft design. These disadvantages of small hovercraft can be eliminated by changes in their design. The fastest way to test the effects of proposed design changes is by performing mathematical computer simulations.

Therefore, a mathematical simulation model of the hovercraft was built, which is close in design to the Hovercraft 425 model, which experts consider to be one of the most successful types of hovercraft and which are currently produced and sold for the purposes of rescue services. However, the new model incorporates several design changes that should improve the performance of the newly designed hovercraft. The mathematical model of the hovercraft is built for the Cradle and Adams simulation software. The mathematical model of the hovercraft has been built using the results of the research carried out. The basis for the construction of the mathematical model for the simulation systems Cradle and Adams was a 3D model that was created in Autodesk Inventor.

2 Construction of the 3D model of the hovercraft

3D modeling is the process of creating digital three-dimensional objects or scenes using specialized 3D modeling software. This process is widely used in various industries including film, video games, architecture, industrial design and engineering [11]. There are several different methods and techniques for 3D modeling. It is Polygonal modeling, NURBS modeling, Procedural modeling, Parametric modeling, CAD modeling or Autodesk Inventor.

The dimensional and mass parameters of a real and operational hovercraft were used to create the 3D model. The input parameters will be further optimized using simulations. The input parameters for creating the mathematical model of the hovercraft can be seen in Tab. 1.

The HTI 425 Hovercraft on which the simulation model was based is shown in the Fig. 2.

Fig. 2 *Hovercraft model HTI 425 Hovercraft [author]*

Tab. 1 *Main parameters of the hovercraft for the creation of the 3D model*

Parameter	Value	Parameter	Value
Length of the hovercraft	3800 mm	Speed at maximum engine power	5500 min^{-1}
Hovercraft height	1100 mm	Propeller diameter	1010 mm
Hovercraft width	2100 mm	Maximum propeller speed	2969 min^{-1}
Hovercraft weight	212.3 kg	Air flow at 2386 min^{-1}	87720 m^3h^{-1}
Maximum engine power	73.5 kW	Load weight	160 kg

2.1 Conceptual design of the hovercraft model

The construction design of the simulation model was built in Autodesk Inventor. It is a professional 3D CAD (Computer-Aided Design) software that is often used for industrial design, engineering and product development. This software offers a wide range of tools for creating and simulating 3D models. Autodesk Inventor allows the creation of assemblies where individual components can be combined into complex units [12].

The basic element of the system is the Parametric Design module. Its function is based on the ability to create a design for the construction of a new product by allowing the definition of parameters such as dimensions and material characteristics. These parameters can then be easily modified. The system allows quick changes to be made throughout the model. In the design shown in Fig. 3, the dimensions (marked in red) can be seen, and by changing them, a part of the sketch will be changed.

Another very important element in the creation of the hovercraft model was the use of the Visualization module. This tool provided a tool for visualizing the 3D models created, including the ability to add materials, textures, lighting and create photorealistic renders. An example of the possible construction of 3D hovercraft models is shown in Fig. 4.

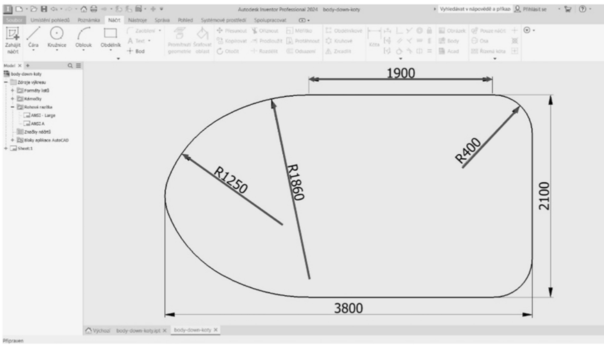

***Fig. 3** Example of parametric modelling of hovercraft shape [author]*

One of the great advantages of the Inventor is the fact that it is possible to combine different components in an assembly and put them together into a single unit [13]. This is useful when modelling real products or mechanisms. It is easy to place and position the separate parts in the assembly due to the possibilities of movements and rotations that can be defined using different tools. The purposeful and simple creation of relations between parts allows to define how the parts should behave in relation to each other. For example, fixing a position, constraining movement or assembling parts together (Fig. 4).

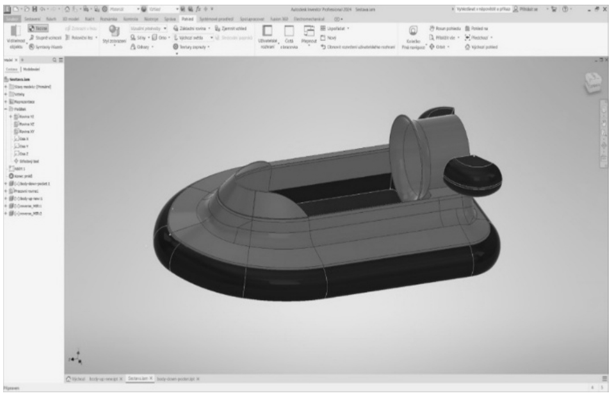

***Fig. 4** Visualisation of the mutual fixation of the position of the flexible cuff, hull and thrust reversers of the hovercraft [author]*

The Interference Check function monitors whether there are any collisions between components in the assembly. This is crucial for accurate design because each component in an assembly can have its own parameters and attributes that can affect the mutual interaction and appearance of the assembly. Assemblies can contain links to individual components, making it easier to manage and update the project [14]. Inventor allows easy creation of drawings and documentation for assemblies. This is important for production and assembly. Autodesk Inventor also allows to create animations that show the movements and behavior of an assembly. This is useful for verifying required features or presenting a designed product. The proposed assemblies can be subjected to simulations and analyses. This allows to verify the required conduct and validate their features.

All these features allow the creation of realistic and detailed models, which is crucial in the design, development and actual construction of new products [15].

2.2 Construction of the hovercraft 3D model

The hovercraft is planned to be used and shaped for rescue purposes, in particular to transport two injured persons in a recumbent position. The main dimensions of the hovercraft are 5 x 2.6 x 2 m. The hovercraft is equipped with a 100 kW internal combustion engine and one propeller. The hovercraft is also powered by thrust reversers for braking and moving backwards. The material of the fuselage and propeller air ring is laminate, optionally composite material. The basic parts of the hovercraft frame, which can be seen in Fig.5, are the upper fuselage half (red), the lower fuselage with floor (white), the rubber air cuff (black), the propeller thrust reversers (blue), the propeller air ring and also the airflow diverter to the fuselage (camouflage colour) and the protective shield protecting the crew from the airflow when the hovercraft is moving forward (transparent brown). All parts of the hovercraft were modelled individually.

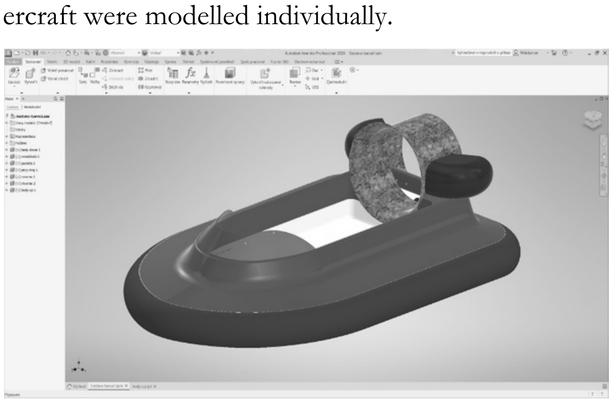

***Fig. 5** Layout of the proposed hovercraft [author]*

It was necessary to divide the parts into parts with regard to the intended future production by negative lamination, or lamination into a negative mould. By designing a 3D model and producing it in a 1:1 scale, e.g. from plastic wood, it is possible to produce moulds for the individual parts of the hovercraft for repeatability of production. Figure 6 shows the breakdown into individual parts just with a view to future production. Once the 3D model of the hovercraft was completed, which accurately describes the geometry of the shapes of the individual parts of the hovercraft, it was possible to proceed to build the simulation model for the Cradle and Adams computer simulation systems.

3 Construction of hovercraft simulation model in Adams and Cradle programs

The goal of the work in building the simulation computational model for the Cradle and Adams simulation systems is to create a full-scale model of a real, but modified, HTI 425 Howercraft model. The simulation model will be defined for both MBS and CFD systems as a free body with 6 degrees of freedom.

3.1 Virtual prototype

The application of theoretical simulations of fluid and gas flow (CFD-Computational Fluid Dynamics) by the Cradle module csFLOW, in conjunction with the computational system for modelling and simulation of coupled mechanical systems (MBS-multibody systems) Adams, offers the possibility to implement the existing experimental experience and to have a virtual insight into the process of "hover". The ideal goal of the computational model is to find input conditions that allow maximum reduction of power consumption, increase of cargo weight and improvement of manoeuvrability. The ideal verified computational model allows to observe the behaviour not only of a real hovercraft but also of a virtually modified model. The individual input conditions can then be changed to optimize the use of the energy source and thus increase efficiency. This computational model can also be called a virtual prototype.

3.2 Geometric model

The geometric shape of the functional surfaces (used to guide the air) is very important in terms of minimising the energy source for propulsion of the hovercraft. It is dependent on and therefore adapted to the selected drive option of the separate ventilator for both traction and thrust.

The actual air supply under the hovercraft is realised by holes in the bottom of the hovercraft. In order to observe the effect of the geometry of the air supply to the space between the ground and the hovercraft, the parameterisation of these openings can be defined. The diameter of the opening, the position of the opening in the longitudinal direction (forward direction), the position of the opening in the transverse direction (direction perpendicular to the forward direction) and the angle of of inclination of the opening from the vertical axis.

The goal of the geometric shape optimization algorithm is to find values of the input parameters (i.e. hole characteristics) that correspond to the desired stroke height and inclination of the hovercraft, considering the instantaneous position of the center of gravity of the hovercraft.

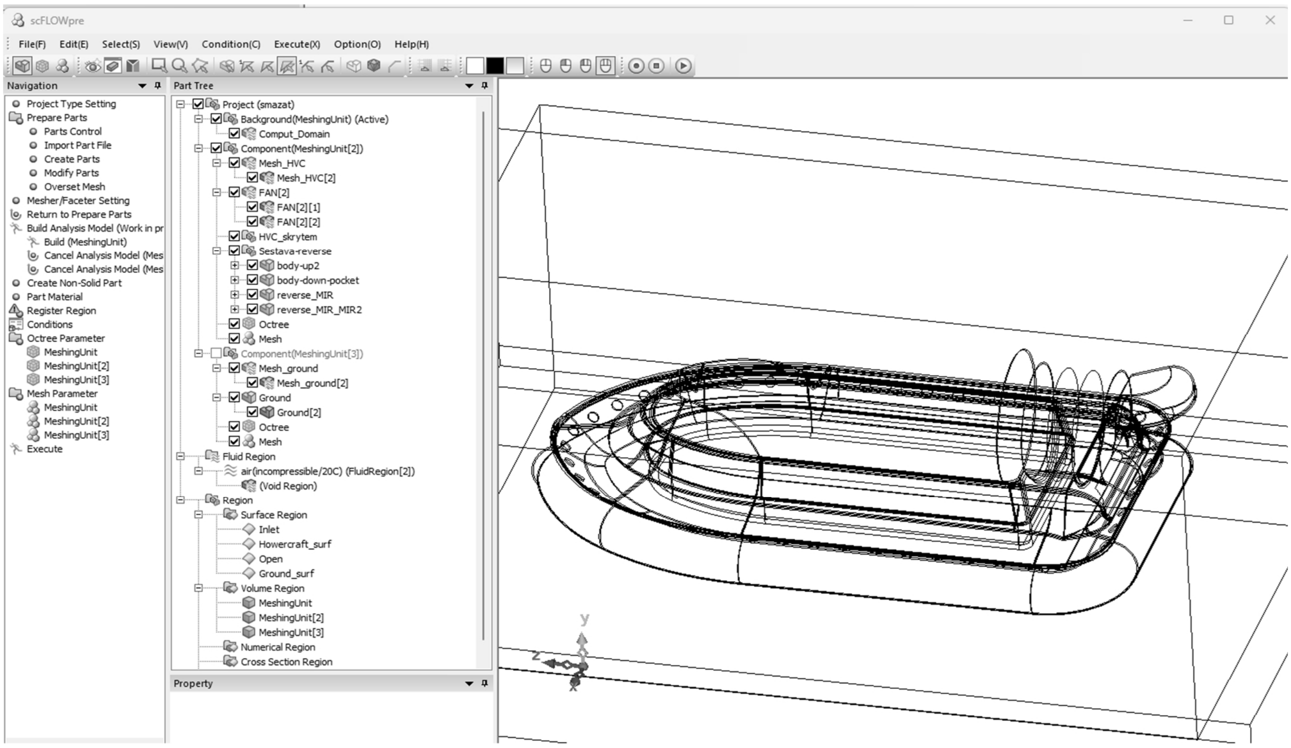

Fig. 6 *Hovercraft geometric model display in Cradle scFLOW [author]*

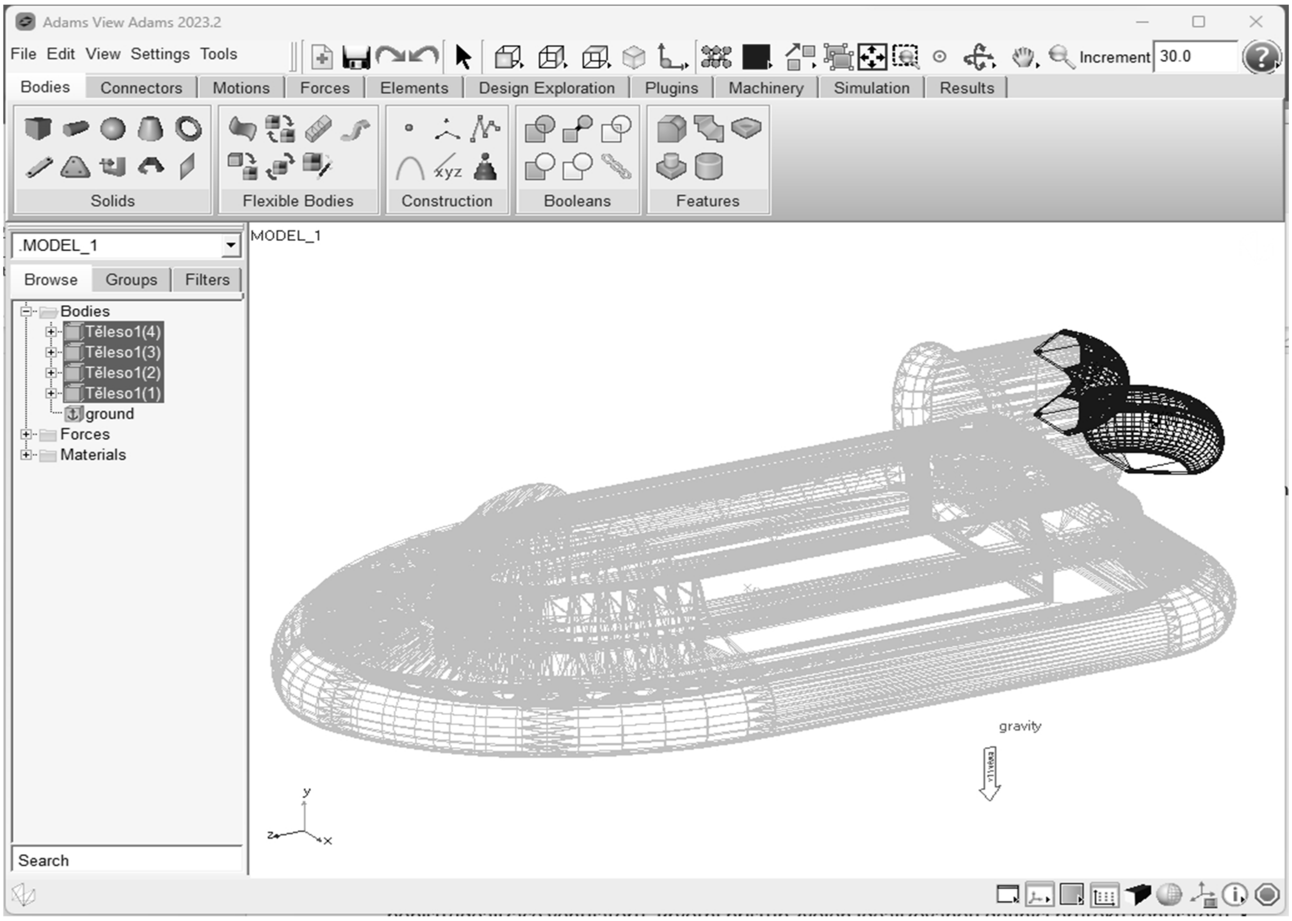

Fig. 7 *Hovercraft geometric model display in Adams [author]*

Another important geometry is thrust reversers. Their position can also be defined parametrically-the angle of rotation of the reverser. The minimum angle corresponds to the position in travel mode, the maximum angle-the closing position-corresponds to the braking mode.

The amount of air supplied under the hovercraft also affects the size of the inlet opening behind the fan. This opening can be parameterised as the area of the air inlet opening under the hovercraft. This aperture separates the air stream coming from the ventilator into the air stream under the hovercraft and the air stream behind the hovercraft. The purpose of the flow behind the hovercraft is to create a motive force for travel, braking or turning.

The motor is modelled in terms of centre of gravity, weight and moments of inertia. In the first stage, the effect of its geometry on the airflow will be neglected.

A representation of the hovercraft geometric model in the Cradle scFLOW and Adams software is shown in Fig. 6 and 7.

As noted in the disadvantages of current hovercraft, the inability to move on rugged terrain, where an air cushion cannot be formed, limits the range of applicability. Therefore, to improve the hovercraft's passability over rough terrain, a geometric model of an additional landing gear to be placed at the bottom of the hovercraft is considered.

3.3 Fundamentals of the computational model function

The hovercraft's propeller blows air into the space under the hovercraft's fuselage, creating pressure. The amount of air Q_1 and the value of pressure p_1 generated by the propeller can be determined from the propeller characteristic measurement report. The atmospheric pressure p_0 is also given in the log. The air velocity v_1 behind the propeller is obtained by calculation using the Navier-Stokes equation and the continuity of flow equation. The calculation can be performed by any suitable numerical method. Using Bernoulli's equation, the airflow velocity v_2, the amount of escaping air Q_2 and the pressure p_2 in the space under the hull can be calculated. Knowing the size of the hull bottom area A and the mass of the hovercraft m, it is then possible to calculate the basic structural elements of the hovercraft using common analytical methods. These are, in particular, the minimum pressure required to ensure a sufficient buoyancy force under the hovercraft or the minimum hull bottom area of the hovercraft. It is also possible to calculate the maximum possible hovercraft mass or the minimum required engine power.

In these calculations it is necessary to bear in mind the fact that a sufficient supply of propeller-driven air under the hull must be ensured. A safety factor must be included in the calculations to eliminate the negative dynamic characteristics of the airflow. For the hovercraft to be stable, the pressure under the hull must be evenly distributed and the air cushion must be sufficiently large. The reason for this is to cover well the increased buoyancy leakage when the hovercraft is tilted over the surface or the buoyancy leakage due to irregularities in the surface relief of the terrain to be traversed.

The calculation part of the simulation program works as follows: first, the value of the volume of supplied air Q_1 pumped by the propeller is read from the propeller characteristic measurement log (Fig. 8). Next, the value of the pressure p_1 generated by the propeller is read.

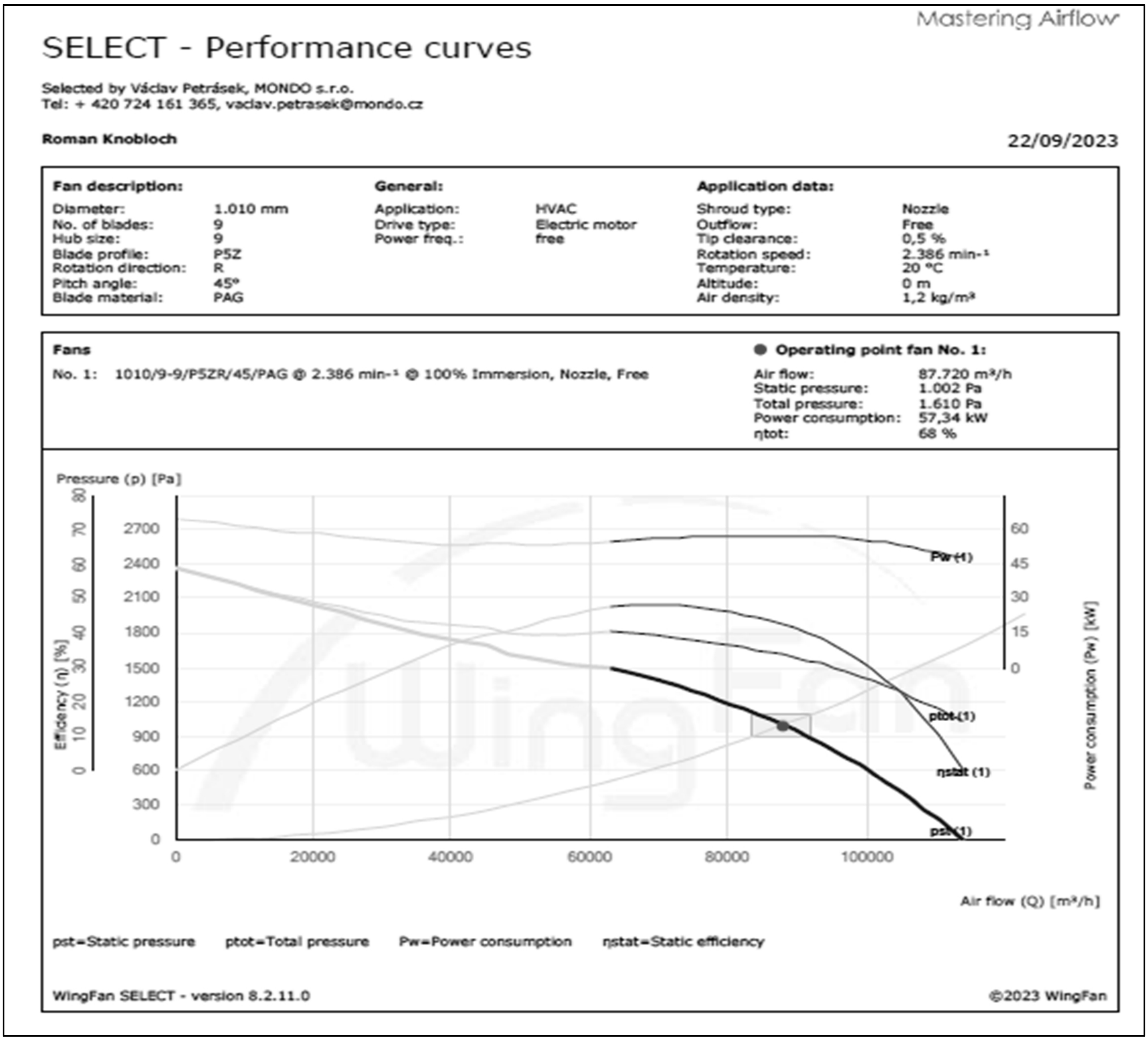

Fig. 8 *The propeller characteristic measurement protocol [author]*

The propeller must provide in air leakage compensation of quantity of air escaping from the space under the hovercraft fuselage Q_2 that maintains the outlet air pressure p_2 in the air cushion below the hovercraft. Therefore:

$$Q_{in} \geq Q_{out} \quad (1)$$

Where:

Q_{in}…Quantity of air delivered by the fan [m^3·h^{-1}],

Q_{out}…Quantity of air escaping from the space under the hovercraft fuselage [m^3·h^{-1}].

At the same time:

$$Q_{out} = v \cdot A_v \quad (2)$$

Where:

v…The velocity of the airflow from the space under the hovercraft [m·s^{-1}],

A_v…The cross-sectional area through which the air escapes from the cushion [m^2].

The velocity of the supplied air flow v_1 can be calculated by solving the Navier- Stokes equation.

In basic vector form, this equation is:

$$\rho\left(\frac{\partial v}{\partial t} + (v \cdot \nabla)v\right) = -\nabla + \mu\nabla^2 v + f \quad (3)$$

Where:

ϱ…The density of air [kg·m^{-3}],

v…The velocity field of air [m·s^{-1}],

t…Time [s],

p…Pressure [Pa],

μ…The dynamic viscosity of air [Pa·s^{-1}],

∇p…The pressure gradient [Pa·m^{-1}],

$\nabla^2 v$…The Laplace velocity operator [m·s^{-2}],

F…The volumetric force acting on the air [N] (in our case the gravitational force and possible turbulent effects).

The resulting solution is a calculation relation for calculating the velocity v_1 of the air flowing behind the propeller:

$$v_1\left(\frac{H}{2}\right) = \frac{H^2}{8\rho L v} \cdot \triangle p \quad (4)$$

Where:

H…The height of the air cushion [m],

L…The length of the hovercraft circumference [m],

ϱ…The air density [kg·m^{-3}],

v…The kinematic viscosity [m^2·s^{-1}],

Δp…The difference between atmospheric and working pressure [Pa].

The velocity of the escaping air stream v_2 and the pressure in the air cushion under the hull p_2 can be calculated using Bernoulli's equation:

$$\frac{1}{2}mv_1^2 + p_1 = \frac{1}{2}mv_2^2 + p_2 \quad (5)$$

Where:

m …The weight of air delivered by the fan [kg],

v_1…Speed of inlet air flow [m·s^{-1}],

p_1…Inlet air pressure [Pa],

v_2…Speed of outlet air flow [m·s^{-1}],

p_2…Outlet air pressure [Pa].

At the same time:

The leakage air volume Q_{out} can be calculated according to the following calculation relation:

$$Q_{out} = C_d \cdot A_{out} \cdot \sqrt{\frac{2\Delta p}{\rho}} \quad (6)$$

Where:

C_d …The dimensionless discharge coefficient [-],

A_{out}…The area where the air escapes [mm^2],

ϱ…The air density [kg·m^{-3}],

Δp…The difference between atmospheric and working pressure [Pa].

This theory allows the design of the hovercraft hull area bounded by the air rubber cuff and the fan power required to ensure the hovercraft's ability to move on the air cushion. For the hovercraft to be able to maintain a certain height above the surface it is moving over, a certain lift force is required to overcome the weight of the hovercraft. This force is directly proportional to the size of the hovercraft's bottom surface area and the value of the air pressure of the air cushion over which the hovercraft is moving. The pressure p_2 in the air cushion is defined as the force acting on the unit area [MPa]:

$$p_2 = \frac{F}{A} \quad (7)$$

Where:

F…The force exerted on the surface [N],

A…The area of the hull bottom on which the pressure is applied [mm^2].

The hull bottom area A is usually composed of a front semicircle of radius r [m], a rear semicircle of the same radius and a rectangular area of the middle part of the bottom with dimensions length a [m] and width b [m]:

$$A = \pi r^2 + a \cdot b \quad (8)$$

The lift force F_L [N] under the hovercraft is generated by forcing air through the propeller into the space created by the bottom of the hovercraft fuselage and the air rubber cuff fitted around the bottom of the hovercraft fuselage. The air creates an air cushion of a certain pressure in this space under the hovercraft, which floats the hovercraft.

The lift force F_L is the result of the air pressure acting on the total area of the hovercraft bottom, framed by the rubber air cuff:

$$F_L = p_2 \cdot A \quad (9)$$

Where:

A…The area of the hull bottom [m],

p_2 …The air pressure in the air cushion under the hovercraft [MPa].

To achieve lift, the lift force F_L must be equal to or greater than the gravitational force G:

$$F_L \geq G \quad (10)$$

For the hovercraft to climb, the pressure difference Δp of the pressure p_2 in the air cushion and the atmospheric pressure p_0 must be applied:

$$\Delta p = p_2 - p_0 \quad (11)$$

Where:

Δp…The pressure difference [Pa],

p_2…The pressure in the air cushion [Pa],

p_0…The atmospheric pressure [Pa].

If this pressure difference Δp is positive, the total lift force F_L can be expressed as:

$$F_L = \Delta p \cdot A = (p_2 - p_0) \cdot A \quad (12)$$

Where:
Δp…The pressure difference [Pa],
p_2…The pressure in the air cushion [Pa],
p_0…The atmospheric pressure [Pa],
A…The area of the hull bottom [m²].

The magnitude of the gravitational force G [N] acting on the hovercraft is:

$$G = m \cdot g \tag{13}$$

Where:
m…The mass of the hovercraft[kg],
g…The gravitation acceleration [kg·m·s⁻²].

When hovering over terrain:

$$\Delta p \cdot A \geq m \cdot g \tag{14}$$

Where:
Δp…Pressure difference [Pa],
A…The area of the hull bottom [m²],
m…The weight of air delivered by the fan [kg],
g…Gravitational acceleration [kg·m·s⁻²].

The equation of motion for the vertical movement of the hovercraft is based on the equilibrium of the lift force F_L and the weight of the hovercraft G:

$$F_L - G = 0 \tag{15}$$

The shape of the equation of motion in the vertical plane is:

$$(p_2 - p_0) \cdot A - m \cdot g = 0 \tag{16}$$

Where:
A…The area of the hovercraft hull bottom [mm],
p_2…The air pressure in the air cushion under the hovercraft [MPa],
p_o…The atmospheric air pressure [MPa],
m…The hovercraft mass [kg],
g…The gravitation acceleration [kg·m·s⁻²].

For motion in the horizontal plane:

To achieve the motion in the horizontal plane, the traction force F_T must be equal to or greater than the aerodynamic drag force F_V:

$$F_T \geq F_v \tag{17}$$

The equation of motion for the movement of the hovercraft in the horizontal plane is based on the balance of the traction force F_T and the force of aerodynamic air resistance F_v:

$$F_v - F_T = 0 \tag{18}$$

$$F_v = \frac{\rho}{2}\, c_x\, S_č\, v^2 \tag{19}$$

$$F_T = \frac{P_m \cdot \eta_v}{v} \tag{20}$$

The shape of the equation of motion in the horizontal plane is:

$$\frac{P_m \cdot \eta_v}{v} - \frac{\rho}{2}\, c_x\, S_C\, v^2 = 0 \tag{21}$$

Where:
P_m…The hovercraft engine power [kW],
η_v…The propeller efficiency [-],
v…The atmospheric air pressure [m·s⁻¹],
ρ…The air density [kg·m⁻³],
c_x…The frontal air resistance coefficient [-],
S_C…The hovercraft frontal area [m²].

The Navier-Stokes equation modified by the continuity of flow equation and the Bernoulli equation are used for the above calculations. These equations need to be transformed into the form of partial differential equations for the solution. It is not possible to use an analytical solution. It was chosen to use the application of theoretical simulations of fluid and gas flow to build a simulation model to solve the hovercraft motion simulation problem. This is based on the finite volume method (CFD). This application is called Cradle and is equipped with the csFLOW module. The cosimulation program is in conjunction with the computational system for modelling and simulation of coupled mechanical systems (MBS) Adams. Two problems can be solved with Cradle.

The first of these tasks is to determine the values of pressures p (x, y, z) and velocities v (x, y, z) as a function of propeller air supply. At the same time, it is possible to calculate the pressure gradient ∇p, which provides the lift force that keeps the hovercraft at a certain height above the ground.

The second problem to be solved may be the calculation of air leakage along the edges of the air rubber cuff. A simplification can be applied for laminar flow that occurs in the gaps between the cuff segments. Here a simplified description of the outflow velocity through the narrow gaps between the cuff segments is used. For turbulent flow, which is caused by air escaping through the free space under the rubber cuff, the equations must be solved numerically. In this way, it is possible to solve the calculations of pressure p_2 and velocity v_2 in the discrete grid space under the hovercraft.

The Cradle and Adams simulations will be used in the future to simulate hovercraft motion over various surface shapes. Currently, the construction of the simulation models of both systems is in the stage of completion and the first control calculations are being performed.

3.4 Contact model

The computational model allows the contact forces between the hovercraft and the terrain to be monitored. The contact is defined in Adams by input parameters: static and dynamic friction coefficient, stiffness and damping. The exchange of information between omputational Fluid Dynamics System (CFD) and Multi Body System (MBS) is implemented by means of cosimulation it the Fig. 9, is controlled by the MSC Cosim software.

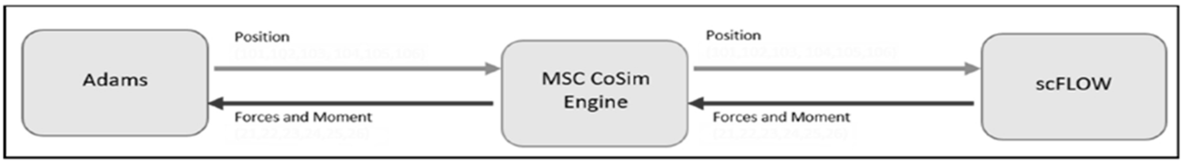

Fig. 9 *MBS and CFD cosimulation scheme [author]*

The contact behavior between the terrain and the pockets is proposed in the simulation model as rigid body versus rigid body. A detailed investigation of the pockets' behavior is not the objective of the simulation model. If it is necessary to describe the real pocket behaviour in the simulation, it would be necessary to define the pockets as compliant and to simulate the deformation due to inflation (possible solution of cosimulation with MKP solver Marc).

The contact body "terrain" is considered as absolutely rigid in the simulation model. In case of simulations on non-rigid ground, it would be necessary to define the material characteristics and thus the contact body type as malleable.

3.5 Boundary conditions model

There are several fan description/idealization options available in Cradle csFLOW as airflow source. The initial approach chosen is an idealized fan flow definition. Two options are available: a 9-blade fan with a flow rate of 24.3 $m^3 \cdot s^{-1}$ and a 12-blade fan with a flow rate of 22.1 $m^3 \cdot s^{-1}$. Depending on the available computational power and the required computational time range, the fan model can be refined by modelling the blades.

The hovercraft is defined in CFD as a free body with 6 degrees of freedom [16-17], the exchange of information (position, forces and moments) is realized by cosimulation with Adams at the center of gravity. Gravity acts on the hovercraft in a direction perpendicular to the terrain level. The total mass of the hovercraft is defined as 372 kg, of which the total weight of the passengers carried is considered to be 160 kg. The assumed source of torque is a Rotax 914 engine of 75-112 kW.

3.5.1 Material model

The material of the entire hovercraft body and components is designed to be EPOXY composite material with glass fibre complemented by carbon and Kevlar canvas in exposed areas.

The material for the pockets (shell) is assumed to be plastic coated fabric.

3.5.2 Stress states model

Stress states can be defined and divided into following processes:

- Lifting the hovercraft in place.
- Forward motion.
- Reversing.
- Stopping.
- Cornering.

These stress states are realized by the defined rotation (position) of the thrust reversers. Currently, when completing the simulation model, the model function is only tested in „Reversing“and „Lifting the hovercraft in place“.

4 Discussion

The simulation model should purposely allow immediate tracking of the height of the centre of gravity lift or measuring reference points from the ground, whose position will correspond to real distance meters. From these reference points, height information will be transmitted to the control unit.

In addition, the actual lift (lift force) dependent on the instantaneous engine power and the amount of air supplied under the hovercraft and the minimum required theoretical lift force dependent on the instantaneous cargo weight will be monitored.

The inclination of the hovercraft is also an important parameter that will be monitored. Specifically, the inclination in both the longitudinal and transverse directions from the horizontal.

In most sport hovercraft, the longitudinal position of the centre of gravity must be changed at take-off, by moving the driver, due to the lack of instantaneous air supply to the front of the hovercraft, and also to create a horizontal component of the lift force. Similarly, in the case of cornering, an acceleration of manoeuvrability is also traced to a shift of the centre of gravity in the lateral direction. Therefore, we will also track the actual center of gravity position and the ideal center of gravity position in our model. Fig. 8 shows the current position of the centre of gravity and coordinates of the connection point MBS with CFD when the hovercraft is fully loaded.

Configuration and verification simulations on the computational model allow verification with the real model behaviour and subsequent pilot simulations identify the behaviour when input parameters are changed. The identification and subsequent parameterization of the input variables will form the basis for the application of the control system, both the virtual model and subsequently the real controller. In the virtual model, the application of control systems using EASY5, Elements or Matlab is proposed.

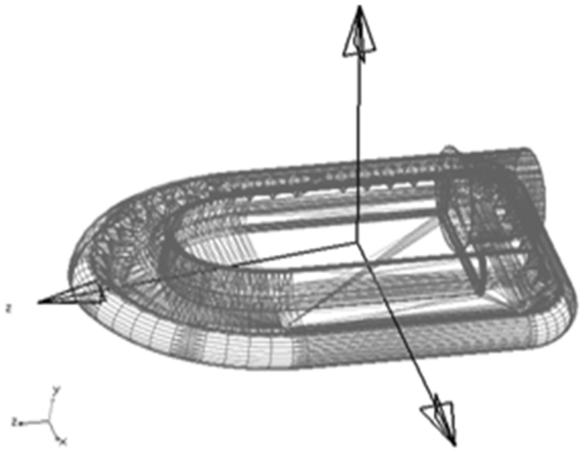

Fig. 10 *Representation of the current centre of gravity position [author]*

5 Conclusion

The paper describes the beginning of the solution of the long-term research objective, which is defined as the determination of the possibilities of eliminating selected disadvantages of small hovercraft. These selected disadvantages that accompany the use of hovercraft are the possible loss of buoyancy and thus the ability to move on excessively rugged terrain and the lack of the ability to deploy the hovercraft unmanned in a rescue operation.

However, this paper mainly describes the laying of the foundations for research into the possibilities of improving hovercraft design, starting with the use of mathematical modelling and simulation of design changes that can have a major positive effect on the behaviour of the hovercraft in regular use.

Future results of the optimization of the hovercraft design parameters by modeling and simulations are planned to be used in the design and production of a new hovercraft in the future. The new hovercraft should be geometrically arranged to have good lateral handling, braking and reversing capability. It should be equipped with an additional landing gear to improve passability in rough terrain. It should be equipped with a 3D camera system and a remote operator control system. Simulations will also be used to find ways to design new materials for individual structural parts of the hovercraft. All of this would then increase the quality and efficiency of the hovercraft when used especially for rescue purposes.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Chalupa Milan, Veverka Josef and Knobloch Roman. The first draft of the manuscript was written by Chalupa Milan commented on previous versions of the manuscript. Conceptualization: Chalupa Milan, Veverka Josef and Cais Jaroslav, Methodology: Švásta Adam, Štěrba Jan and Lattner Michal, Formal analysis and investigation: Krobot Zdeněk, Writing-Original draft preparation: Svoboda Antonín; Writing-review and editing: Svoboda Martin; Funding acquisition: Knobloch Roman, Resources: Balcar Patrik, Supervision: Ponikelský Josef. All authors read and approved the final manuscript.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare no conflict of interest.

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