The application of virtual prototyping methods to determine the dynamic parameters of mobile robot

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Abstract: The paper presents methods used to determine the parameters necessary to build a mathematical model of an underwater robot with a crawler drive. The parameters present in the dynamics equation will be determined by means of advanced mechatronic design tools, including: CAD/CAE software and MES modules. The virtual prototyping process is described as well as the various possible uses (design adaptability) depending on the optional accessories added to the vehicle. A mathematical model is presented to show the kinematics and dynamics of the underwater crawler robot, essential for the design stage.

Keywords: Mechatronics; kinematics; dynamics; designing; tracked robot dynamics; virtual prototyping

1 Introduction

The demand for reliable robotic units for the underwater inspection of pipeline installations and reservoirs still remains relatively high due to the time and cost saving potentials guaranteed by this type of solution, especially given the requirement of protecting installations from emergency failures. A major problem present in the design and construction process related to underwater robot systems is the necessary integration of mechanical, electronic and IT systems [1, 2] to achieve the objective of increased performance and assured autonomous operation of the robot. The physical model and description of the kinetics of the object are key elements in the mechatronic design process. They facilitate the use of simulations and are necessary to design control systems. The description and modelling of crawler drives are complicated tasks that are impacted by various time-variable factors. Such issues as designing and building robots to inspect pipelines and various tanks are subject to numerous publications [3–7]. Also modelling of the kinetics of inspection robots of this type is subject to numerous scientific works [8–12]. The majority of these publications contain mathematical models of the analysed robots; however, the methods of determining the parameters necessary to provide a full description of their dynamics and perform simulations are not taken into account. The current mechatronic design method and advanced computer tools make it possible to design and virtually prototype structural elements as well as match the necessary electronic components. Such an approach is presented in [13] and [14]. Thanks to the created virtual models, it is possible to perform the simulations necessary to describe the kinetics of a device thus designed. The basis for determining various important object parameters is a precise CAD model of the intended mechatronic device. Such a model must include all object components, their dimensions and the materials of which they are made. The inspection robot presented in the article was fully designed using CAD software.

The advanced inspection robot designed and built by the authors (Fig. 1) facilitates the monitoring and analysis of the technical condition of flat surfaces, ventilation ducts and pipes (both dry and liquid-filled). The design is modular so it may be reconfigured in response to actual needs.

The movement capability in water up to depths of 30 m (Fig. 2) means that the description of this robot must include the impact of hydrodynamic resistance forces, buoyancy forces, etc.

Moreover, it is necessary to know the mass of the individual elements, mass moments of inertia and other factors present in the dynamics equations. Such issues as the
derivation of the kinematics equation describing the dynamics of the robot are presented in [8–10].

2 Kinematic model of the robot

The description a crawler track in a real environment with uneven ground and changeable conditions is very complex. The detailed mathematical description of movement of individual crawler track points is so compound that it is necessary to apply simplified models. Elastomer tracks with treads could be modeled as a non-stretch tape wound about a determined shape by a drive sprocket, an idler and an undeformable ground [15–17]. The presented kinematic model of the robot describes a plane motion and operation on inclined surfaces. The velocity of the point C (Fig. 3b), placed in the axis of symmetry of the crawler [15–19] may be expressed as

\[ V_C = \sqrt{x_C^2 + y_C^2 + z_C^2}. \] (1)

The equations for particular velocity components were derived taking into consideration slip of the tracks and an assumption that the principal direction of motion is the y axis, and the angle of turn \( \beta \) is positive towards the x axis (Fig. 3a)

\[
\begin{align*}
\dot{x}_C &= \frac{r\dot{\alpha}_1(1 - s_1) + r\dot{\alpha}_2(1 - s_2)\sin\beta}{2}, \\
\dot{y}_C &= \frac{r\dot{\alpha}_1(1 - s_1) + r\dot{\alpha}_2(1 - s_2)\cos\beta\cos\gamma}{2}, \\
\dot{z}_C &= \frac{r\dot{\alpha}_2(1 - s_2) - r\dot{\alpha}_1(1 - s_1)\sin\gamma}{H}, \\
\dot{\beta} &= \frac{r\dot{\alpha}_2(1 - s_2) - r\dot{\alpha}_1(1 - s_1)}{H},
\end{align*}
\] (2)

The velocities of the points \( V_F \) and \( V_G \), located in the centers of + tracks may be expressed as

\[
\begin{align*}
V_F^2 &= \dot{x}_F^2 + \dot{y}_F^2 + \dot{z}_F^2, & V_G^2 &= \dot{x}_G^2 + \dot{y}_G^2 + \dot{z}_G^2, \\
\dot{x}_F &= \dot{x}_C - 0, & 5H\dot{\beta}\sin\beta, \\
\dot{y}_F &= \dot{y}_C - 0, & 5H\dot{\beta}\cos\beta, \\
\dot{z}_F &= \dot{z}_C, \\
\dot{x}_G &= \dot{x}_C + 0, & 5H\dot{\beta}\sin\beta, \\
\dot{y}_G &= \dot{y}_C + 0, & 5H\dot{\beta}\cos\beta, \\
\dot{z}_G &= \dot{z}_C. 
\end{align*}
\] (4)

The created kinematic model will be used in determination of dynamical equations of motion.
It has to be assumed that the kinetic energy of the robot $E$ is the sum of energies of particular components

$$E = E_R + E_{M1} + E_{M2}, \quad (8)$$

where $E_R$ is the kinetic energy of the robot frame, $E_{M1}$ – kinetic energy of the left track drive module, $E_{M2}$ – kinetic energy of the right track drive module.

The kinetic energy of the robot frame is the sum of energies $E_{R1}$ and $E_{R2}$, resultant from translational and rotational motion with respect to the instantaneous center of rotation $O$

$$E_R = E_{R1} + E_{R2} = \frac{1}{2} m_R V_C^2 + \frac{1}{2} I_R \dot{\beta}^2, \quad (9)$$

where $m_R$ is the mass of the robot frame, $I_R$ – moment of inertia of the robot frame, $\dot{\beta}$ – angular velocity of the robot frame with respect to the instantaneous center of rotation.

By introducing equation (9) into (1), the kinetic energy of the robot frame was obtained

$$E_R = \frac{1}{2} m_R \left( \dot{x}_C^2 + \dot{y}_C^2 + \dot{z}_C^2 \right) + \frac{1}{2} I_R \dot{\beta}^2. \quad (10)$$

The kinetic energy of the track drive module was determined by making use of the following formula

$$E_M = E_{K1} + E_{K2} + E_{K3} + E_O, \quad (11)$$

where $E_{K1}$ is the kinetic energy of track drive sprocket 1, $E_{K2}$ – kinetic energy of idler 2, $E_{K3}$ – kinetic energy of idler 3, $E_O$ – kinetic energy of the track module housing.

The kinetic energy of the sprocket and idlers in the track module can be expressed as a sum of kinetic energies of translational motion, rotational motion about the particular axis of rotation and rotational motion about the instantaneous center of rotation [20–22]. The moments of...
inertia were determined for the particular models of the sprocket and idlers that were modeled in a CAD software, according to the datasheet from the Inuktron company [23].

\[ E_{K1} = \frac{1}{2} m_{K1} V_0^2 + \frac{1}{2} I_{x1} \dot{\alpha}_{x1}^2 + \frac{1}{2} I_{z1} \dot{\beta}_1^2, \]  
\( E_{K2} = \frac{1}{2} m_{K2} V_0^2 + \frac{1}{2} I_{x2} \dot{\alpha}_{x2}^2 + \frac{1}{2} I_{z2} \dot{\beta}_2^2, \]
\[ E_{K3} = \frac{1}{2} m_{K3} V_0^2 + \frac{1}{2} I_{x3} \dot{\alpha}_{x3}^2 + \frac{1}{2} I_{z3} \dot{\beta}_3^2, \]

where \( m_{Ki} \) is the mass of the \( i \)-th wheel, \( I_{xi} \) – moment of inertia with respect to the \( i \)-th axis of rotation \( x \), \( I_{zi} \) – moment of inertia of the \( i \)-th wheel with respect to the axis \( z \) about which the wheel changes its orientation with the angular velocity \( \dot{\beta}_i \), \( \dot{\alpha}_{ki} \) – angular velocity of the \( i \)-th wheel, \( V_A, V_B, V_E \) – velocities of characteristic points presented in Fig. 4.

The kinetic energy of the track module housing is the sum of energies of the motor, gear transmission and the track

\[ E_0 = \frac{1}{2} m_o V_o^2 + \frac{1}{2} I_{x0} \dot{\alpha}_{x0}^2 + \frac{1}{2} I_{z0} \dot{\beta}_0^2, \]

where \( m_o \) is the mass of the track module housing, \( I_{x0} \) – moment of inertia of the elements in rotational motion, \( I_{z0} \) – moment of inertia of the housing with respect to the instantaneous center of rotation.

The total kinetic energy of one track drive module is denoted as follows

\[ E_M = \frac{1}{2} m_{K1} V_A^2 + \frac{1}{2} I_{x1} \dot{\alpha}_{x1}^2 + \frac{1}{2} I_{z1} \dot{\beta}_1^2 + \frac{1}{2} m_{K2} V_B^2 + \frac{1}{2} I_{x2} \dot{\alpha}_{x2}^2 + \frac{1}{2} I_{z2} \dot{\beta}_2^2 + \frac{1}{2} m_{K3} V_E^2 + \frac{1}{2} I_{x3} \dot{\alpha}_{x3}^2 + \frac{1}{2} I_{z3} \dot{\beta}_3^2 + \frac{1}{2} m_o V_0^2 + \frac{1}{2} I_{x0} \dot{\alpha}_{x0}^2 + \frac{1}{2} I_{z0} \dot{\beta}_0^2, \]

with the assumption that

\[ V_A = V_B = V_E = V_0 = V, \]

and

\[ E_M = \frac{1}{2} V^2 (m_{K1} + m_{K2} + m_{K3} + m_o) + \frac{1}{2} I_{x1} \dot{\alpha}_{x1}^2 + \frac{1}{2} I_{x2} \dot{\alpha}_{x2}^2 + \frac{1}{2} I_{x3} \dot{\alpha}_{x3}^2 + \frac{1}{2} I_{x0} \dot{\alpha}_{x0}^2 + \frac{1}{2} I_{z1} \dot{\beta}_1^2 + \frac{1}{2} I_{z2} \dot{\beta}_2^2 + \frac{1}{2} I_{z3} \dot{\beta}_3^2 + \frac{1}{2} I_{z0} \dot{\beta}_0^2 (I_{z1} + I_{z2} + I_{z3} + I_{z0}). \]

When taking into account the relations between angular velocities and radii of the sprocket and idlers

\[ \alpha_{ki} r_1 = \alpha_{ki} r_2 = \alpha_{ki} r_3 = \alpha_i r, \]
\[ \dot{\alpha}_{ki} r_1 = \dot{\alpha}_{ki} r_2 = \dot{\alpha}_{ki} r_3 = \dot{\alpha}_i r. \]

Thus, using the following substitution

\[ m = m_{K1} + m_{K2} + m_{K3} + m_o, \]

\[ I_x = I_{x1} + I_{x2} \left( \frac{r_1}{r_2} \right)^2 + I_{x3} \left( \frac{r_1}{r_2} \right)^2 + I_{x0}, \]
\[ I_z = I_{z1} + I_{z2} + I_{z3} + I_{z0}. \]

The total kinetic energy for the track drive module is derived

\[ E_M = \frac{1}{2} m V^2 + \frac{1}{2} I_x \dot{\alpha}_i^2 + \frac{1}{2} I_z \dot{\beta}_i^2. \]

Previously, only one track drive module was investigated and particular properties were denoted without an index. However, in a more detailed analysis, the energy of the left and right track drive module is used (according to the notation in Fig. 2a)

\[ E_{M1} = \frac{1}{2} m V_1^2 + \frac{1}{2} I_x \dot{\alpha}_1^2 + \frac{1}{2} I_z \dot{\beta}_1^2, \]
\[ E_{M2} = \frac{1}{2} m V_2^2 + \frac{1}{2} I_x \dot{\alpha}_2^2 + \frac{1}{2} I_z \dot{\beta}_2^2. \]

After substitution of velocities denoted in (4), (5), (6), the following formulas are obtained

\[ E_{M1} = \frac{1}{2} m \left( \left( \dot{x}_c - \dot{\beta}_H \sin \beta \right)^2 + \left( \dot{y}_c - \dot{\beta}_H \cos \beta \right)^2 \right) + \dot{\alpha}_1^2 + \frac{1}{2} I_x \dot{\alpha}_1^2 + \frac{1}{2} I_z \dot{\beta}_1^2, \]
\[ E_{M2} = \frac{1}{2} m \left( \left( \dot{x}_c + \dot{\beta}_H \sin \beta \right)^2 + \left( \dot{y}_c + \dot{\beta}_H \cos \beta \right)^2 \right) + \dot{\alpha}_2^2 + \frac{1}{2} I_x \dot{\alpha}_2^2 + \frac{1}{2} I_z \dot{\beta}_2^2. \]

The total kinetic energy of the robot described in (8) was derived by making use of equations (10) and (21)

\[ E = \frac{1}{2} m \left( \dot{x}_c^2 + \dot{y}_c^2 + \dot{z}_c^2 \right) + \frac{1}{2} I_x \dot{\alpha}_1^2 + \frac{1}{2} I_x \dot{\alpha}_2^2 \]
\[ + \frac{1}{2} I_x \dot{\alpha}_3^2 + \frac{1}{2} I_x \dot{\alpha}_4^2 + \frac{1}{2} I_x \dot{\alpha}_5^2 + \frac{1}{2} I_x \dot{\alpha}_6^2 + \frac{1}{2} I_z \dot{\beta}_1^2 + \frac{1}{2} I_z \dot{\beta}_2^2 + \frac{1}{2} I_z \dot{\beta}_3^2 + \frac{1}{2} I_z \dot{\beta}_4^2 + \frac{1}{2} I_z \dot{\beta}_5^2 + \frac{1}{2} I_z \dot{\beta}_6^2. \]

In order to determine the dynamic equations of motion, Maggi’s formalism is employed

\[ \sum_{i=1}^{n} C_{ij} \left( \frac{\partial E}{\partial q_j} - \frac{\partial E}{\partial \dot{q}_j} \right) = \theta_i, \]

\[ \dot{q}_i = \sum_{j=1}^{s} C_{ij} \dot{e}_j + G_j, \]

where \( n \) denotes the number of independent parameters expressed by generalized coordinates \( q_i \) \( (i = 1, \ldots, n) \)
where according to Maggi’s formalism

\[ \dot{e} = \begin{bmatrix} \dot{\alpha}_1 \\ \dot{\alpha}_2 \end{bmatrix}^T, \quad G_j = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T. \]
According to this assumption, six generalized velocities were denoted by multiplication of the matrix $C_{ij}$ that consists of nonholonomic constraints with two kinematic parameters $\dot{a}_1, \dot{a}_2$

\[
\begin{bmatrix}
\dot{x}_c \\
\dot{y}_c \\
\dot{z}_c \\
\dot{\beta} \\
\dot{\alpha}_1 \\
\dot{\alpha}_2
\end{bmatrix} = 
\begin{bmatrix}
\frac{1}{2} r (1 - s_1) \sin \beta \\
\frac{1}{2} r (1 - s_1) \cos \beta \cos \gamma \\
\frac{1}{2} r (1 - s_1) \sin \gamma \\
\frac{1}{2} r (1 - s_1) \sin \beta \\
1 \\
0
\end{bmatrix}
\begin{bmatrix}
\frac{1}{2} r (1 - s_2) \sin \beta \\
\frac{1}{2} r (1 - s_2) \cos \beta \cos \gamma \\
\frac{1}{2} r (1 - s_2) \sin \gamma \\
\frac{1}{2} r (1 - s_2) \sin \beta \\
0 \\
1
\end{bmatrix}
\begin{bmatrix}
\dot{a}_1 \\
\dot{a}_2
\end{bmatrix}.
\]

(25)

The generalized forces and moments are denoted as follows

\[
\theta_i = \begin{bmatrix}
M_{\theta 1} + (-0, 5P_u - 0, 5F_D - 0, 5G \sin \gamma + 0, 5W_{\ell 1}) r (1 - s_1) + \frac{M_P r (1 - s_1)}{H} \\
M_{\theta 2} + (-0, 5P_u - 0, 5F_D - 0, 5G \sin \gamma + 0, 5W_{\ell 2}) r (1 - s_2) - \frac{M_P r (1 - s_2)}{H}
\end{bmatrix}.
\]

(26)

The final form of the dynamic equations of motion based on Maggi’s formalism are presented as follows

\[
M_{s 1} = \frac{a_4 \dot{a}_1 + a_2 \dot{a}_1^2 + a_1 \dot{a}_2 + a_1 \dot{a}_2^2 - a_5}{\eta^i}, \quad M_{s 2} = \frac{b_4 \dot{a}_1 + b_2 \dot{a}_1^2 + b_1 \dot{a}_2 + b_1 \dot{a}_2^2 - b_5}{\eta^i},
\]

(27)

where

\[
\begin{align*}
a_1 &= \frac{r^3 (1 - s_2)^2 \cos (\beta) (m_R + 2m) (1 - s_1) \sin (\beta)}{4H} - \frac{r^3 (1 - s_2)^2 \sin (\beta) \cos (\gamma)^2 (m_R + 2m) (1 - s_1) \cos (\beta)}{4H}, \\
a_2 &= \frac{r^3 (1 - s_1)^3 \cos (\beta) (m_R + 2m) \sin (\beta)}{4H} + \frac{r^3 (1 - s_2)^3 \sin (\beta) \cos (\gamma)^2 (m_R + 2m) \cos (\beta)}{4H}, \\
a_3 &= \frac{1}{4} r^2 (1 - s_2) \sin (\beta^2) (m_R + 2m) (1 - s_1) + \frac{1}{4} r^2 (1 - s_2) \cos (\beta)^2 \cos (\gamma)^2 (m_R + 2m) (1 - s_1) \\
&\quad + \frac{1}{4} r^2 (1 - s_2) \sin (\gamma)^2 (m_R + 2m) (1 - s_1) - \frac{r^2 (1 - s_2) (I_R + 2I_z + 2mH^2) (1 - s_1)}{H^2}, \\
a_4 &= \frac{1}{4} r^2 (1 - s_1)^2 \sin (\beta) (m_R + 2m) + \frac{1}{4} r^2 (1 - s_1)^2 \cos (\beta)^2 \cos (\gamma)^2 (m_R + 2m) \\
&\quad + \frac{1}{4} r^2 (1 - s_1)^2 \sin (\gamma)^2 (m_R + 2m) + \frac{r^2 (1 - s_1)^2 (I_R + 2I_z + 2mH^2)}{H^2} + I_x, \\
a_5 &= r (1 - s_1) [0, 5F_w \sin (\gamma) - W_{\ell 1} - 0, 5P_u - 0, 5F_D - 0, 5G \sin (\gamma)] + \frac{M_P r (1 - s_1)}{H}, \\
b_1 &= \frac{r^3 (1 - s_2)^3 \cos (\beta) (m_R + 2m) \sin (\beta)}{4H} - \frac{r^3 (1 - s_2)^3 \sin (\beta) \cos (\gamma)^2 (m_R + 2m) \cos (\beta)}{4H}, \\
b_2 &= \frac{r^3 (1 - s_1)^2 \cos (\beta) (m_R + 2m) (1 - s_2) \sin (\beta)}{4H} - \frac{r^3 (1 - s_1)^2 \sin (\beta) \cos (\gamma)^2 (m_R + 2m) (1 - s_2) \cos (\beta)}{4H}, \\
b_3 &= \frac{1}{4} r^2 (1 - s_2)^2 \sin (\beta) (m_R + 2m) + \frac{1}{4} r^2 (1 - s_2)^2 \cos (\beta)^2 \cos (\gamma)^2 (m_R + 2m) \\
&\quad + \frac{1}{4} r^2 (1 - s_2)^2 \sin (\gamma)^2 (m_R + 2m) + \frac{r^2 (1 - s_2)^2 (I_R + 2I_z + 2mH^2)}{H^2} + I_x, \\
b_4 &= \frac{1}{4} r^2 (1 - s_1)^2 \sin (\beta) (m_R + 2m) (1 - s_1) + \frac{1}{4} r^2 (1 - s_1)^2 \cos (\beta)^2 \cos (\gamma)^2 (m_R + 2m) (1 - s_1) \\
&\quad + \frac{1}{4} r^2 (1 - s_1)^2 \sin (\gamma)^2 (m_R + 2m) (1 - s_1) - \frac{r^2 (1 - s_1) (I_R + 2I_z + 2mH^2) (1 - s_1)}{H^2}, \\
b_5 &= r (1 - s_2) [0, 5F_w \sin (\gamma) - W_{\ell 2} - 0, 5P_u - 0, 5F_D - 0, 5G \sin (\gamma)] - \frac{M_P r (1 - s_2)}{H},
\end{align*}
\]

where $W_{\ell 1}$ – rolling friction force, $P_u$ – pull force, $F_w$ – buoyant force, $F_D$ – hydrostatic resistance force, $M_{s 1}$ – torque on the shaft drive motors, $M_P$ – moment of transverse resistance.

Dynamic equations of motion (27) may be used to solve simple and inverse dynamics problems, however care must be taken when calculating values of the forces, particularly the rolling friction force $W_{\ell 1}$ as various surfaces on which the robot operates would introduce significant variations in its value. The type fluid in which the robot moves has also strong influence on the forces, especially $F_D$ and $M_P$. 
The force $F_D$ present in equations (27), i.e. the (concentrated) hydrodynamic resistance force, is presented by the dependence:

$$\frac{d}{dt} \left( \frac{\partial E}{\partial \beta} \right) = I_\beta \ddot{\beta} + 2I_\beta \dot{\beta} + 2m \ddot{\beta} H^2. \quad (28)$$

where: $C_D$ – hydrodynamic resistance factor; $\rho$ – medium density; $V_C$ – robot (weight centre) point C velocity; $A$ – surface of the robot frontal cross-section;

An important role in the description of robot movement under water is also played by the force $F_w$, present in equations (27), i.e. the buoyancy force defined by the expression:

$$\frac{\partial E}{\partial x_C} = 0. \quad (29)$$

where: $g$ – gravitational acceleration; $\rho$ – medium density; $U$ – robot volume.

Methods of determining certain factors for equations (27), (28) and (29) are presented below.

4 Determining parameters necessary to describe the dynamics using mechatronic design tools

The mechatronic approach to design required taking into account the changes (particularly changes in shapes) introduced during the individual design stages which had an influence on the values of forces $F_D$ and $F_w$. Modifications of the design during the CAD model stage also influenced some elements of equations (27), such as the weight of the elements, volume and mass moments of inertia. Thus the SolidWorks software and its Flow Simulation module was used to determine these forces.

SolidWorks Flow Simulation is a program used to simulate the flow of liquids and conduct thermal analyses, and is embedded in the SolidWorks software. It eliminates the necessity to change designs when the flows of various liquids are calculated, which saves time and costs considerably. The Flow Simulation module was used to perform simulations for the robot with its crawler drive. A simulation is a complex task, consisting of numerous stages. The basic simulation parameters had to be defined for the previously built precise CAD model. It was necessary to select water as a liquid flowing around the robot and assume the liquid pressure as well as velocity. It was necessary to define the CFG grid for all the examined robot elements, which can be seen in Fig. 5.

After defining the basic simulation parameters, the values to be obtained must be defined. As regards the movement simulation of a robot with a crawler drive, the following parameters were useful: velocity of the liquid flowing around the robot, hydrodynamic force impacting the model and hydrodynamic resistance factor $C_D$ (Fig. 6).

The resistance factor $C_D$, which is vital in simulations, was not automatically calculated by the program, but had to be defined using the equation in Fig. 6.

The area of the body projection on a plane (factor $C_D$) perpendicular to the velocity vector necessary to be determined was defined for all robot configurations in the Flow Simulation system.
### Table 1: Factors values obtained in the simulations.

<table>
<thead>
<tr>
<th>Robot configuration</th>
<th>Factor value $C_D$</th>
<th>Area of the body projection on a plane perpendicular to the velocity vector $m^2$</th>
<th>Robot volume $m^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_D = 0.44$</td>
<td>$A = 0.0251$</td>
<td>$V = 0.001993$</td>
</tr>
<tr>
<td></td>
<td>$C_D = 0.51$</td>
<td>$A = 0.0247$</td>
<td>$V = 0.001986$</td>
</tr>
<tr>
<td></td>
<td>$C_D = 0.56$</td>
<td>$A = 0.0151$</td>
<td>$V = 0.001782$</td>
</tr>
<tr>
<td></td>
<td>$C_D = 0.59$</td>
<td>$A = 0.0267$</td>
<td>$V = 0.002002$</td>
</tr>
<tr>
<td></td>
<td>$C_D = 0.68$</td>
<td>$A = 0.0305$</td>
<td>$V = 0.002155$</td>
</tr>
</tbody>
</table>
The simulations resulted in determining the factors (Table 1) necessary for equations (28) and (29) for the robot in various configurations.

Analyses of the data provided in Table 1 show that the lowest hydrodynamic resistance factor is ensured by the configuration for pipes 300 mm in diameter and the highest factor is obtained by the configuration with a battery compartment.

The results of the simulations included the distribution of liquid velocity values and the trajectories of flow around various robot configurations (Fig. 7).

Such factors as weight, surface areas, volumes and mass moments of inertia of individual robot elements were determined on the basis of the CAD models with assumed materials from which they would be made (Fig. 8).

Simulations of liquid flow around the different robot configurations were performed at various pressures both for open water reservoir and various diameter pipe conditions. The tool shown in Fig. 8 was used to determine the necessary weight and volume parameters for all elements of an underwater inspection robot.

5 Summary

The paper presents methods of determining the parameters necessary to build a mathematical model of a mechatronic device of the inspection robot type by means of CAD/CAE and CFG software. An extensive mathematical model is presented which defines the kinematics and dynamics of the underwater crawler robot in a 3D coordinate system. The suggested methods are based on the precise CAD model of the designed device. Thanks to this approach, it is possible to describe the object dynamics and introduce necessary structural changes as early as during the design stage. The presented methods and tools facilitated determination of the hydrodynamic resistance factor for various robot configurations, precise robot volume and weight, frontal cross-sectional area and mass moments of inertia. In-depth knowledge of these parameters was necessary to perform simulation of robot behaviour in water and to design its control system.

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