WIND TUNNEL TESTING ON UNDERWATER ROBOTS MODELS

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The paper aims at determining the drag coefficients C_x, for three types of submersible hulls. Determination of considerations of similitude and ratios between similitudes ranges were achieved through the Method of Forces.

Experimental determinations of drag C_x were made in a test area of a wind tunnel, belonging to the Aerodynamic Laboratory of the Technical University of Civil Engineering of Bucharest, in which the specific considerations of similitude were taken. The wind tunnel selected according to the operational requirements is an experimentation installation with open circuit, with short and guided experimental area, limited by solid walls.

By virtue of the experimental results, the best solution was chosen, from the hydrodynamic point of view, for all hulls.

1. INTRODUCTION

In order for the flow around the model (from the laminar and turbulent boundary layer, as well as from the area of detachment of the boundary layer off the surface of the respective body) and the value of the drag coefficient to be considered valid ($C_{x_M} \cong C_{x_N}$), the conditions of similitude should be respected.

According to the second theorem of similitude, in order for the phenomenon of the model M to be similar to the real one, from nature (N), it is well enough for both phenomena to have the same nature, and the criteria of similitude between the homologous proportions to be identical.

For the determination of the similitude criteria specific to research on a mock-up of the movements at low speeds and of the drag forces of an underwater vehicle, one can use three methods: the method of forces, the method of theorem π of the dimensional analysis, or the method of considering a non–dimensional way of the equations describing the studied phenomenon.

This method has been approached because the equations that describe the underwater vehicle movement (displacements, speeds, forces, moments etc.) are extremely complex, and are influenced by a great number of disturbing factors, which can not be always evaluated.

The coefficients and the linear variables, as well as non – linear ones, which occur in the movement equations of the underwater vehicle, demonstrate the complexity of the phenomena that take place all along the route of the underwater immersed robot.

In conclusion, since the theoretical mathematical models are inoperative and the simulations related to them are confusing and non-conclusive, the option of this paper of developing research on the underwater robots movement at determined time intervals (shorter and shorter – time impulses and increments) on the basis of similitude proved to be the only viable solution.

Similitude criteria and the relations between similitude scales through the method of forces are shown below.

In correspondence with the speed movement domain, considered to be optimum for the movement of underwater vehicles (1Nd ÷ 4Nd), we consider this speed as the testing movement speed, specified in the operational requirements of the theme under observation.

2. DETERMINATION OF THE SIMILITUDE CONDITIONS BY THE METHOD OF FORCES

The similitude between the model phenomenon (M) and the prototype (N) implies the following:

- geometrical similitude, which supposes a scale of lengths S_{lc}

$$S_{lc} = \frac{l_{cM}}{l_{cN}} \tag{1}$$

- cinematic similitude, which supposes a scale of lengths S_{lc} and a scale of speeds S_U;

$$S_{lc} = \frac{l_{cM}}{l_{cN}} \quad (2) \qquad \text{or:} \qquad S_U = \frac{U_M}{U_N} \quad (3)$$

- the dynamic similitude, which supposes a unique scale for the determinant forces that come up during the phenomenon of movement of a solid body in a liquid. These forces are: momentum forces F_i, viscosity forces F_v, and pressure forces F_p. Now, the relation between the forces scale can be written:

$$S_{F_i} = S_{F_v} = S_{F_p} \tag{4}$$

Scale of the inertial forces:

$$S_{F_i} = \frac{(F_i)_M}{(F_i)_N} = \frac{(m \cdot a)_M}{(m \cdot a)_N} = \frac{(\rho \cdot l_c^{\,2} \cdot U^2)_M}{(\rho \cdot l_c^{\,2} \cdot U^2)_N} = S_\rho \cdot S_{lc}^2 \cdot S_U^2 \tag{5}$$

Scale of viscosity forces:

$$S_{F_v} = \frac{(F_v)_M}{(F_v)_N} = \frac{(\mu \frac{dU}{dn} \cdot A)_M}{(\mu \frac{dU}{dn} \cdot A)_N} = S_\mu \cdot S_U \cdot S_{lc} \tag{6}$$

Scale of pressure forces:

$$S_{F_p} = \frac{(F_p)_M}{(F_p)_N} = \frac{(p \cdot A)_M}{(p \cdot A)_N} = \frac{(p \cdot l_c^{\,2})_M}{(p \cdot l_c^{\,2})_N} = S_p \cdot S_{lc}^2 \tag{7}$$

From the equality of the inertial forces (5) and the viscosity forces (6) results:

$$S_\rho \cdot S_{lc}^2 \cdot S_U^2 = S_\mu \cdot S_U \cdot S_{lc} \tag{8}$$

from which results:

$$\frac{S_U \cdot S_{lc} \cdot S_\rho}{S_\mu} = 1 \quad (9) \qquad \text{or:} \qquad \frac{S_U \cdot S_{lc}}{S_\nu} = 1 \quad (10)$$

that is:

$$\frac{\dfrac{U_M}{U_N}\cdot\dfrac{l_{cM}}{l_{cN}}}{\dfrac{\nu_M}{\nu_N}}=1 \tag{11}$$

from which results the condition for similitude:

$$\frac{U_M\cdot l_{cM}}{\nu_M}=\frac{U_N\cdot l_{cN}}{\nu_N} \tag{12}$$

From the equality of the inertial forces scales (5) with the pressure forces scale (7) results:

$$S_\rho\cdot S_{lc}^2\cdot S_U^2=S_p\cdot S_{lc}^2 \tag{14}$$

so the relation between scales is:

$$\frac{S_p}{S_\rho\cdot S_U^2}=1 \tag{15}$$

that is:

$$\frac{\dfrac{p_M}{p_N}}{\dfrac{\rho_M}{\rho_N}\cdot\dfrac{U_M^2}{U_N^2}}=1 \tag{16}$$

and the condition for similitude is:

$$\frac{p_M}{\rho_M\cdot U_M^2}=\frac{p_N}{\rho_N\cdot U_N^2} \tag{17}$$

or:

$$Eu_M=Eu_N \tag{18}$$

As a result, through the method of forces the following were highlighted: Reynolds (Re) and Euler (Eu) criteria, the conditions for similitude ($\mathrm{Re}_M=\mathrm{Re}_N$ and $Eu_M=Eu_N$) and the corresponding relations between scales ($S_U\cdot S_{lc}\cdot S_\nu^{-1}=1$ and $S_p\cdot S_\rho^{-1}\cdot S_U^{-2}=1$ respectively). All these should be respected in the process of guiding of the under water vehicle movement. In the above relation between scales, the scales signify: S_{lc} – the scale of the characteristic lengths, S_U – the scale of speeds, S_ρ – scale of densities, S_μ – scale of dynamic viscosity, S_ν – scale of cinematic viscosity, S_p – scale of pressures, S_k – scale of roughness.

Modelling according to the method of similitude implies determination of calculating („interest") proportions on miniature models (made at a certain scale), which keep to the rules of similitude.

The proportions determined on a model can be extended, with acceptable error for the approved proportions of real underwater robots, which develop in their natural environment.

Based on modelling according to the method of similitude in an aerodynamic tunnel, we shall try to determine, experimentally according to the model, the drag coefficients C_x of three real / natural, underwater vehicles, as follow: autonomous underwater vehicle (VSA), the self – propelled underwater vehicle (RSA), and the diver-carrying submersible (SM 358), through research on their respective models, built according to a pre-established scale.

3. DESCRIPTION OF THE WIND TUNNEL "TA 1 – LAIV"

The wind tunnel "TA1" (fig. 1) selected according to the operational requirements is an experimentation installation with open circuit, with short and guided experimental section, limited by solid walls. In this case two walls situated on either side of the vein (destined for visualization) are transparent, thus allowing the watching of the flow around the underwater robots mock-ups. At the base part there is a detachable board, with Ø = 280mm, through which the mock-ups can be introduced, and which during the measuring with the aerodynamic scales, can act as a turntable.

The distribution of speed in the veins upstream of the mock-up is homogeneously uniform. This is due both to the honey comb, position 1 and to the profiled disturbing device with modulation point, position 2, from figure 1, which maintains it. The first one, due to the big contraction ratio leads to the decrease of the turbulence level in the experimental zone. The vein zone (with lateral glass walls – position 9) is in depression, because the battery of ventilators (pos. 9) sweeps the air by the help of the honey comb.

All the area between the battery of ventilators and the smoothing comb is in depression, while the zone beyond the ventilators, up to the sector where there is super pressure, is in repression. The guidance with solid walls of an experimental zone leads to the effect of limited vein. This means that the walls influence the flow around the mock-up, and to the stopping or chocking of the experimental vein zone, if the mock-up dimension amidships is bigger than the experimental vein zone. That is why it is recommended that we should have a cross-section of no more than 5% ÷ max. 10% of the experimental vein's section, in this case $0,3 \times 0,3 = 0,09$ m^2.

The underwater robots vehicles mock-ups take this condition into consideration. If the condition is not respected there appears a strong modification in the flow around the mock-up, as compared to the flow around the real (in full size) underwater robot vehicle (URV), with important consequences for the determination of the drag coefficient C_x.

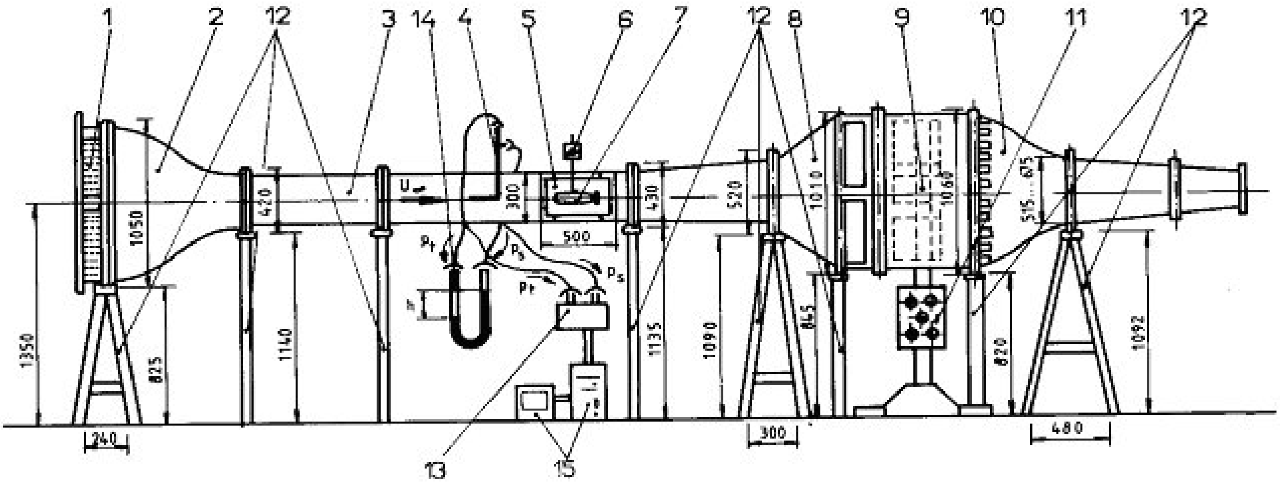


Fig. 1 The wind tunnel "TA1 – LAIV"

1. softening comb, 2. Confessor profiled, 3. experimental zone, 4. tube Pitôt-Prandtl connected to the differential manometer, 5. experimental vein, 6. device for fixing the incidence angle, 7. mock-up, 8. distributor, 9. battery with four axial ventilation, 10. Dispersorr, 11. Electrical panel 12. holders for the positioning on the check table, 13. differential pressure equalizer, 14. differential manometer, 15. equipment for calculation.

The measuring of local speeds and their distribution within the experimental vein (section 300 x 300mm, with lateral glass walls) were made with a Pitôt-Prandtl tube fastened to an initial manometer and to a differential pressure equalizer, of the "AUTO RAN" type, model 600D-011, with domain from 0…1" col. H_2O, which was attached to the acquisition board of the computer for data processing.

The Pitôt-Prandtl tube used in measuring speeds has the following dimensions: diameter *d* = 5 mm, the total pressure set p_t has a diameter of 0,3d, the static pressure set p_s has a diameter of 0,12d, the distance between the two pressure sets is 3d and U_∞ is the local speed upstream of the model.

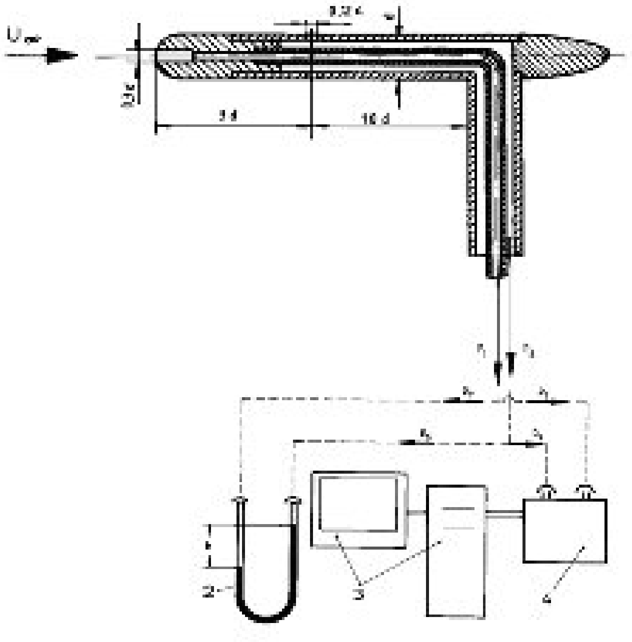


Fig. 2 Equipment for measuring speeds
1. Pitôt-Prandtl tube, 2. differential manometer, with one component,
3. equipment for calculation, 4. differential pressure equalizer.

The local upstream speed, U_∞, can be calculated depending on the dynamic pressure:

$$p_d = \Delta p = p_t - p_s \tag{19}$$

with relation:

$$U_\infty = \sqrt{2 \cdot g \cdot \frac{p_d}{\rho \cdot g}} = \sqrt{2 \cdot g \cdot \frac{\Delta p}{\rho \cdot g}} = \sqrt{2 \cdot g \cdot \frac{p_t - p_s}{\rho \cdot g}} \tag{20}$$

where: $\rho = 1{,}21 \text{kg/m}^3$ – is air density since experimental vein of the wind tunnel;

$$p_t - p_s = \rho_{apă} \cdot g \cdot h \tag{21}$$

h - the difference between the two water columns from the differential manometer (fig.1,2).

The differential manometer was fastened in parallel with the pressure equalizer, in order to allow the permanent bringing to the standards of the pressure equalizer.

After measurements and calculation the speed of the air when experiment is made in the tunnel is:

- for VSA $U_\infty = 20$m/s;
- for RSA $U_\infty = 15$m/s;
- for SM 358 $U_\infty = 20$m/s.

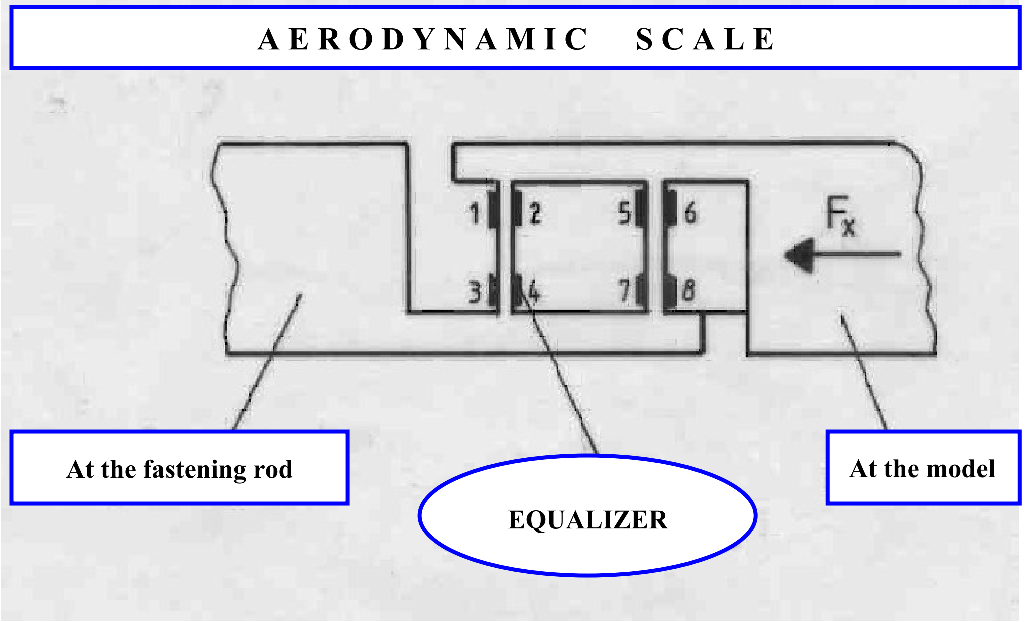
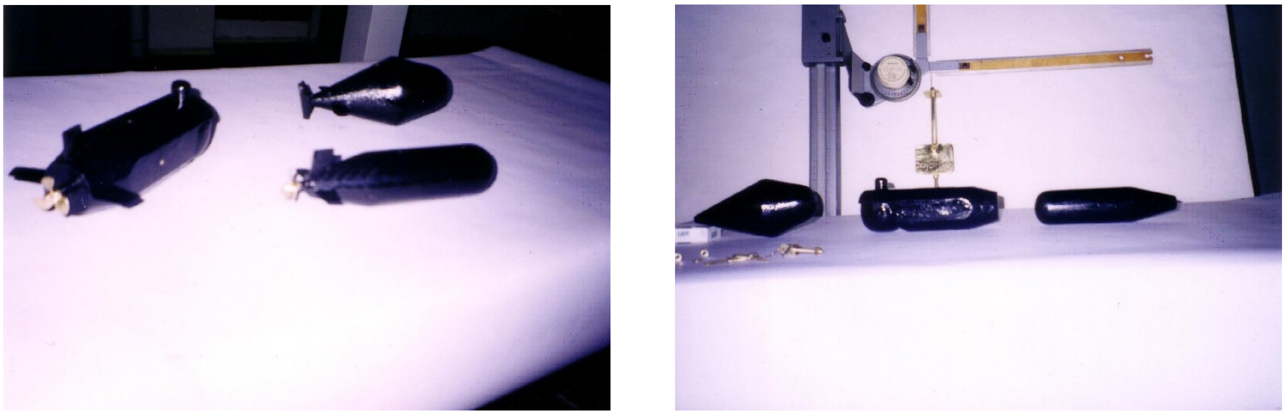


Fig. 3 Simplified scheme of the aerodynamic scale

4. PRESENTATION OF MODELS

The present research work had in view the aerodynamic study of three different forms of submersibles: VSA, RSA and SM 358, for the determination of the flow aspect in the boundary layer around them, and of their of their drag coefficients.

In figures 4a and 4b can be seen the models for three submersibles with and without empennage and propulsion.



a ***b***

Fig. 4 The models for the submersibles (RSA, SM 358, VSA)
a with empennage and propulsion and b without empennage and propulsion

In this chapter the following are presented: the models of underwater robots used for experimental research, of the necessary mock – ups for trials, so that the blocking effect of the experimental vein should be avoided.

After placing the mock-ups in the experimental zone of the wind tunnel “TA 1 - LAIV”, the next step was the measurements and visualization of the tests. In order to know the aspect of the flow, there was a prior visualization of the flow in the boundary layer existing at the surface of the models, through the “method of wires” (fig. 5).

Fig. 5 The flow visualization in the boundary layer through the "method of wires"

In figure 5, it can be observed the monitoring of the phenomena appeared at the VSA model in experimental wind tunnel "TA1- LAIV" vein for the values of incidence angle: $\alpha = 0^0$ (visualization of the flow in the boundary layer existing at the surface of the models).

5. Experimental Results

As a result, through the method of forces the following were highlighted: Reynolds (Re) and Euler (Eu) criteria, the conditions for similitude and the corresponding relations between scales. All these should be respected in the process of guiding of the under water vehicle movement.

Conclusions referring to the modelling of movement at low speeds, of the underwater robots, through the similitude method:

- Through the forces method the geometrical, cinematic and dynamic similitudes are shown, thus resulting the Reynolds similitude criterion, together with the Euler similitude criterion;
- The robots' movement speeds U_N in water being low, there results that the air speed on the models existing in the U_M wind tunnel is enough for achieving the Reynolds similitude;
- By using the π theorem the following were determined: the structural form of the drag expression;

and the similitude criteria that will be taken into account in the modelling process of the underwater robots' movement, aking place in the wind tunnel;

- In conclusion, once the similitude of Rynolds and Euler criteria , as well as the relative rugosity are achieved, the drag coefficient determined on model $(C_x)_M$ is equal with the drag coefficient for the real scale underwater robot $(C_x)_N$.

All the conditions for the correct and efficient experiments were fulfilled in the wind tunnel - these are:

- the homogenuous and uniform distribution of speeds in the pilot plant (experimental vein)
- cutting out the effects of limited vein or clogging vein;
- the achievement of the parallelism between models and flow currents;
- the inclination angle between the air current and model;

- safe fastening of the models in the desired position, for trials, so as the experiments in the wind tunnel be accurate in what the flow in a limited space is concerned, for all the three tested models – with and without empennage and propulsion, for all the pre-established angles.

For the measurement of the speeds within the experimental zone the following have been used: a pitot – Prandtl tube fastened to a pressure differential pick-up, wired up to the computer's acquisition board, for the storage and processing of data. For the determination of the drag coefficients C_x a tensiometric transducer was used. After the measurements, the calculuses for the drag coefficients of each model, for α = 0^0.were done. Using the same algorithm we can determine the drag coefficients for each angle of incidence.

Experiemntal results obtained in tunnel TA1

- for the three modfels *without empennage and propulsion*			***- for the three models*** *with empennage and propulsion*		
The following values of the drag were obtained :					
For VSA	**-**	***C_x = 0,485;***	***for VSA***	**-**	***C_x = 0,506;***
For RSA	**-**	***C_x=0, 571;***	***for RSA***	**-**	***C_x = 0,590;***
For SM 358	**-**	***C_x = 0,534.***	***for SM 358***	**-**	***C_x = 0,536.***

- The drag coefficients obtained through measurements on models are the same for test engines at real scale, because the testing of models in relation with Reynolds number was successful.
- Having the drag coefficients $(C_x)_M$ already determined experimentally on models, the drag forces will be calculated on the real robot, $(F_x)_N$, for all the analysed hulls, by using the relation:

$$(F_x)_N = (C_x)_N \frac{\rho_N \cdot U_{\infty N}^2}{2} \cdot (A_C)_N \tag{22}$$

- For the calculation of these forces it is necessary to choose or impose a certain water density in which the robot moves, as well as its speed and the area of the middle of the ship A_{CN} of the real robot.

The measurements resulting in the experimental drag coefficient C_x**,** helps to the correct sizing of the underwater robots propulsion systems.

6. CONCLUSIONS. THE ANALYSIS OF THE RESULTS OBTAINED THROUGH EXPERIMENTAL AND NUMERICAL PHYSICAL MODELING

Through the analysis of the experimentally and theoretically determined C_x drag coefficients, there results that: for the three models under observation, the values of all coefficients are bigger for the robots with empennage and propeller than of those without them. This is natural if we observe the extension of the lateral surfaces and the flow perturbations round the hulls. A change in the distribution of the local pressure of the lateral surface of the hull, as well as a growth of the drag coefficients $C_{x,f}$ resulted from friction, for the RSA and SM 358 is noticed. Implicitly, there is a corresponding growth of the total coefficient values of the drag C_x.

The coefficients C_x for the VSA have the smallest value, since the model has a better cut hull. In this case both the values of pressure coefficients $C_{x,p}$ and those of friction coefficients $C_{x,f}$ are the lowest compared to the corresponding values of the other models.

In conclusion, among the three models under observation the model selected for the VSA is the best, if drag is taken into account.

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LIST OF ACRONYMS USED

AUR = autonomus underwater robot;
AUV = autonomus underwater vehicle;
ROV = remotely operated vehicle;
T-R = translation-rotation;
UR = underwater robot;
URS = underwater robotic systems;
URV = underwater robot vehicle;
UUV = unmanned underwater vehicle.

SYMBOLS USED

C_G = the load centre;
C_p = local pressure coefficient;
C_x = total drag coefficient expressed either by the dead flat part of the ship (the largest part of the UR), and marked with $C_{x(D^{2},}$ or with volume representing the cube of 2/3 and marked with $C_{x(V^{2/3})}$;
$C_{x,f}$ = the drag coefficient based on the friction of the limit layer or drag coefficient of friction;
$C_{x,p}$ = the drag coefficient based on the action of pressure forces or shape forces;
$(C_x)_M$ = the aerodynamic drag coefficient of the robot model;
$(C_x)_N$ = the aerodynamic drag coefficient of the robot prototype;
F_i= momentum forces;
F_p= pressure forces;
F_v= viscosity forces;
F_x= drag forces;
(M) = model phenomenon;
(N) = phenomenon from nature, prototype, the real one;
S_k = scale of roughness;
S_{lc} = the scale of the characteristic lengths;
S_p = scale of pressures;
S_ρ = scale of densities;
S_U = the scale of speeds;
S_v = scale of cinematic viscosity;
S_μ = scale of dynamic viscosity;
U_M = the models movement speeds;
U_N = the robots’ movement speeds;
U_∞ = the local upstream speed.