ON THE CALCULATION OF AERODYNAMIC CHARACTERISTICS OF HIGH-SPEED GROUND VEHICLES ON THE BASE OF THREE-DIMENSIONAL NAVIER-STOKES EQUATIONS

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Abstract

Non-stationary averaged three-dimensional Navier-Stokes equations are applied to the aerodynamic calculation of high-speed ground–effect transport vehicles. The approach used is realized within the framework of applied program package developed by the authors. Each stage of the aerodynamical calculation is analyzed: initial statement of problem, writing the assumed equation in a curvilinear non-orthogonal coordinate system, closing the equation system with the use of turbulent viscosity models, computational grid generation, development of algorithm and algorithmic language, testing and verifying the programs and techniques, carrying out of the calculation and data analysis.

1. Introduction

To improve technical and economical properties of high-speed MAGLEV vehicles the following interrelated aerodynamic problems should be solved: the choice of vehicle geometry and configuration, air flow drag reduction, the use of aerodynamical effects to produce the additional lift. Vehicle drag reduction is a paramount importance because a basic power of the magnetic engines is consumed in drag overcoming.

The state-of-art and outlook in the development of propulsive-levitated systems of high-speed magnetic transport, where superconductivity is applied are analyzed in [1, 2]. Numerical and experimental simulation of flow around the parts of lifting systems in ground proximity are considered in [3-5], where discrete vortex method, Navier-Stokes equations, implicit and explicit approximately factorized schemes, constructed on the base of first, second and high order differential approximations are used. The results of two-dimensional flow around a profile in ground proximity are also given.

In the paper each stage of the aerodynamical calculation is analyzed: initial statement of problem, writing the assumed equation in a curvilinear non-orthogonal coordinate system, closing the equation system with the use of turbulent viscosity models, computational grid generation, development of algorithm and algorithmic language, testing and verifying the programs and techniques, carrying out of the calculation and data analysis.

In spatial flow calculations averaged Navier-Stokes equations are used. To close the equation system algebraic, one- and two-parametric models of turbulent viscosity are implemented. The grid is generated using the transfinite interpolation method.

2. Statement of problem

2.1. Assumed equations

Assumed non-stationary Navier-Stokes equations relative to the arbitrary curvi-linear coordinate system $\xi.\ \eta,\ \zeta$ in the approximation of a thin layer for three-dimensional flows can be written as

$$\frac{\partial \hat{q}}{\partial \tau}+\frac{\partial \hat{E}}{\partial \xi}+\frac{\partial \hat{F}}{\partial \eta}+\frac{\partial \hat{G}}{\partial \zeta}=\frac{1}{\mathrm{Re}}\left(\frac{\partial \hat{R}}{\partial \xi}+\frac{\partial \hat{S}}{\partial \eta}+\frac{\partial \hat{T}}{\partial \zeta}\right) \quad (1).$$

Here $\hat{q},\ \hat{E},\ \hat{F},\ \hat{G},\ \hat{R},\ \hat{T},\ \hat{S}$ – five-component vectors, which have the form

$$\hat{q}=\frac{q}{J},\ \hat{E}=\frac{1}{J}\left(\xi_x E+\xi_y F+\xi_z G\right),\ \hat{F}=\frac{1}{J}\left(\eta_x E+\eta_y F+\eta_z G\right),$$

$$\hat{G}=\frac{1}{J}\left(\zeta_x E+\zeta_y F+\zeta_z G\right),$$

$$q=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ e\end{bmatrix},\ E=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ \rho uw\\ (e+p)u\end{bmatrix},\ F=\begin{bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ \rho vw\\ (e+p)v\end{bmatrix},\ G=\begin{bmatrix}\rho w\\ \rho uw\\ \rho vw\\ \rho w^2+p\\ (e+p)w\end{bmatrix}, \quad (2)$$

$\hat{R}$, $\hat{T}$ и $\hat{S}$ - vectors, containing viscous terms in the directions ξ, η, ζ,

$$\hat{S}\ =\ J^{-1}\begin{bmatrix}0\\ \mu W u_\zeta+\frac{\mu}{3}A_2\,\zeta_x\\ \mu W v_\zeta+\frac{\mu}{3}A_2\,\zeta_y\\ \mu W w_\zeta+\frac{\mu}{3}A_2\,\zeta_z\\ W\left[\frac{\mu}{2}A_3+\frac{k}{(\gamma-1)\mathrm{Pr}}\left(a^2\right)\right]+\frac{\mu}{3}A_4\,A_2\end{bmatrix}, \quad (3)$$

where $A_1=\zeta_x^2+\zeta_y^2+\zeta_z^2$, $A_2=\zeta_x\,u_\zeta+\zeta_y v_\zeta+\zeta_z\,w_\zeta$, $A_3=u^2+v^2+w^2$, $W=\zeta_x\,u+\zeta_y v+\zeta_z w$.

Vectors $\hat{R}$ and $\hat{T}$ are written in the same manner.

The following nomenclature is used in the equations: *u, v, w* -velocity vector components in the directions *x, y, z*; ρ, p, e -density, pressure and total energy, respectively. The equation of state is added to the equation system:

$$\mathrm{p}=\mathrm{p}(\varepsilon,\rho), \quad (4)$$

where ε - internal energy which is determined by the relation

$$\varepsilon=\frac{e}{\rho}-\frac{1}{2}\left(u^2+v^2+w^2\right). \quad (5).$$

Equations (1) are written in a conservative form and if differential equations are replaced by difference ones, the latters will have properties of mass, momentum and energy conservation at each computational point.
Metric coefficients are determined from the relations for x_ξ, y_ξ, z_ξ received with the rule of complex function differentiation:

$$\xi_x = J(y_\eta z_\zeta - y_\zeta z_\eta), \quad \xi_y = -J(x_\eta z_\zeta - x_\zeta z_\eta), \quad \xi_z = J(x_\eta y_\zeta - x_\zeta y_\eta),$$
$$\eta_x = -J(y_\xi z_\zeta - y_\zeta z_\xi), \quad \eta_y = J(x_\xi z_\zeta - x_\zeta z_\xi), \quad \eta_z = -J(x_\xi y_\zeta - x_\zeta y_\xi),$$
$$\zeta_x = J(y_\xi z_\eta - y_\eta z_\xi), \quad \zeta_y = -J(x_\xi z_\eta - x_\eta z_\xi), \quad \zeta_z = J(x_\xi y_\eta - x_\eta y_\xi)$$

$J = \dfrac{\partial(\xi,\eta,\zeta)}{\partial(x,y,z,)} = \begin{bmatrix} \xi_x & \xi_y & \xi_z \\ \eta_x & \eta_y & \eta_z \\ \zeta_x & \zeta_y & \zeta_z \end{bmatrix}$ - is Jacobian of coordinate transformation.

2.2. Turbulence model

Mathematical simulation of turbulence remains one of the week fields in the present-day computational fluid dynamics, especially at the background of general progress in numerical methods, computer power, grid generation and flow visualization methods.
The cause/effect mechanism of turbulent instability still remains hypotetical. Turbulent viscosity models, which are based on the empirical data-bases, obtained as a rule for the free shear flows, do not take into account external pressure gradient, surface curvature and other important parameters properly. At the same time approaches based on the large-scale turbulence and direct numerical simulation of turbulence give an extremely high cost of design work.
The applied program package developed includes algebraic, one- and two-parameter models of turbulent viscosity for Reynold-averaged Navier-Stokes equations. Among numerous algebraic closure methods Boldvin-Lomax, Sebetchi-Smith and Soversheny models demonstrate good behavior. Among one-parametric models Glushko-Rubesin and Spalart-Allamaras ones should be highlighted. To close Navier-Stokes equations with two additional turbulent transport equations k-e model by Johns-Launder and its modification k-w model by Menter show high reliability.

2.3. Initial and boundary conditions

On the body surface the conditions of attachment and thermally insulation are set. On the outer boundary undisturbed mainstream parameters are ensured using the Riemann invariants. On other boundaries symmetry and non-reflection or zero-gradient conditions are set depending on a body in consideration.

2.4. Numerical methods

In using the block grids of a regular type it is worthwhile to apply finite-difference methods in combination with finite-volume ones. Then discrete analog of the Navier-Stokes equation system (1) is written for a finite volume with half-integer indexes in a space (ξ,η,ζ) and the algebraic equation system obtained has the form of finite-difference relations.
On the base of long-term practice in a viscous flow simulation [4] the choice has been done in the favor of methods which imply flow vector splitting with TVD-limiters. In the work implicit second order Van-Leer and Roe with Harten MinMod limiter schemes were applied with the use of Gauss-Zeidel iterative procedure at each time step.

3. Verification of techniques and programs

Testing the algorithms and programs developed is a necessary stage of any numerical separated flow investigation. Comparison of twelve numerical methods for solving the Navier-Stokes two-dimensional compressible separated flow equations has been accomplished [4]. On the base of Eiler equations verification of the solution technique for the inviscid transonic flow around a NACA-0012 profile at M_∞=0.8 and an angle of attack α=1.25^o (fig.2) has been conducted. The problems of viscous supersonic flow around a cylinder, cone at angle of attack and sphere/cylinder body have been also tested [4].

The main regularities in a separated flow development for the cylinder can be seen on characteristic isolines given in figure 3 (M_∞=3.0; $\mathrm{Re}=10^5$). Forebody shock wave, flow separation, shock waves from separation and reattachment and also base flow can be clearly seen in the figures. The flow pattern is in a good agreement with known Tepler pictures.

Pressure distribution on a cylinder surface obtain with the use of Eiler equations, is given in the figure 3 by dusted points.

Verification of the applied program package for three-dimensional Navier-Stokes equations solution was accomplished by the simulation of laminar separation on a leeward surface of a hemisphere/cylinder body (fig.6-8). Calculation was carried out at M_∞=1.2, Re=$2\cdot10^5$, α=19^o. Pressure distribution in a symmetry plane is in a good agreement with known experimental and computational data. Velocity vectors give illustration of the separation on a leeward side as a result of interaction of the flows past a cylinder at angle of attack.

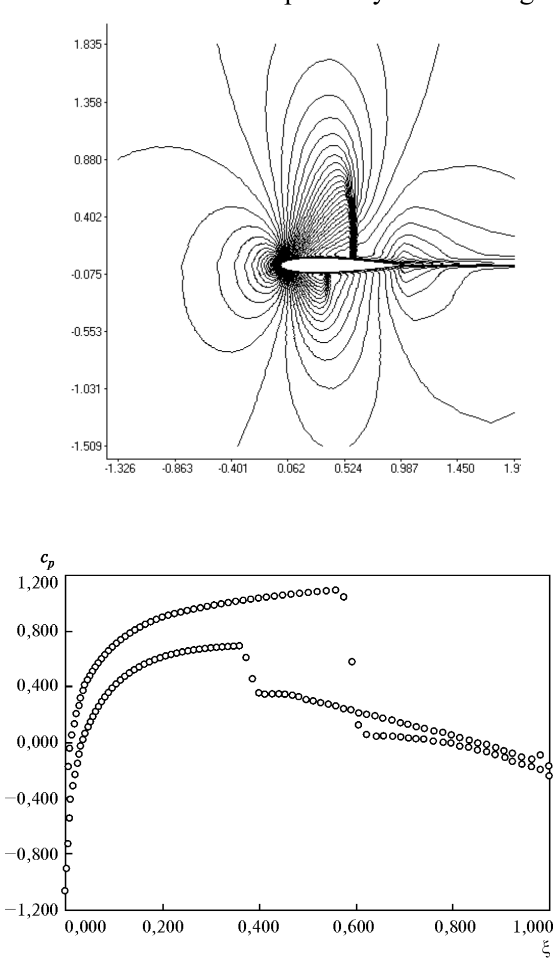


Fig. 1. Mach number contours in the computational domain and pressure distribution on the profile surface

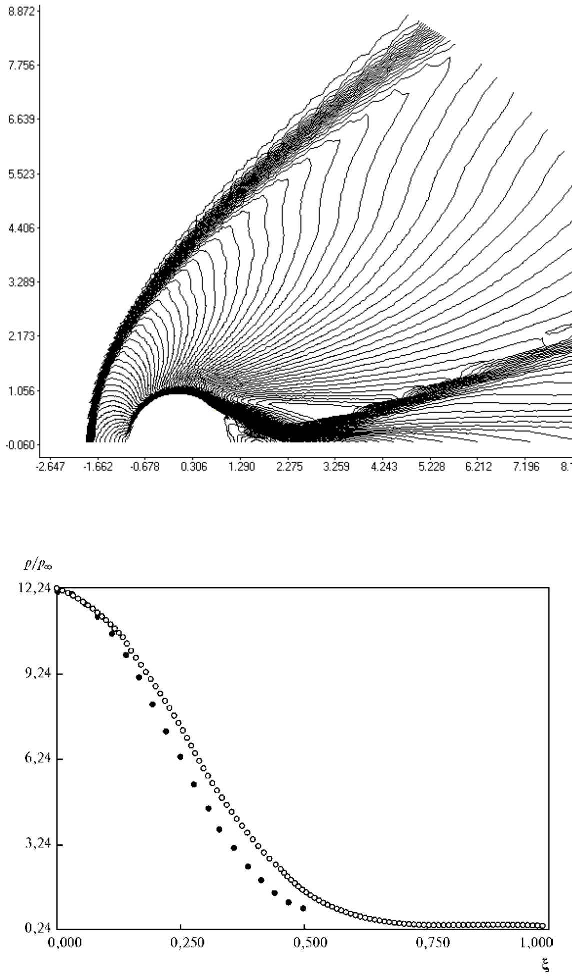


Fig.2. Mach number contours in the computational domain and pressure distribution on the cylinder surface

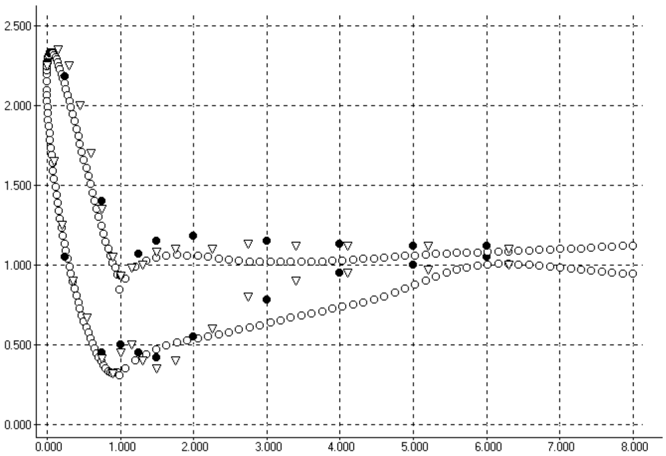


Fig.3. Pressure distribution in the symmetry plane on the surface of sphere/cylinder body
o -calculation of the present paper;
∇, ● -calculation and experiment data

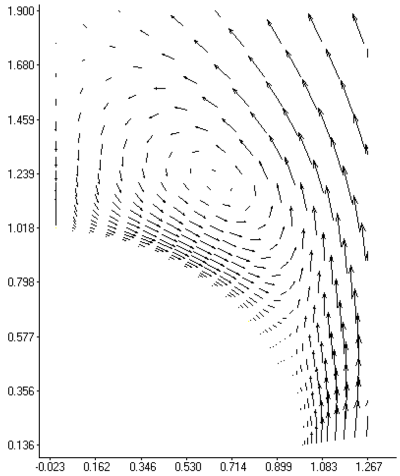


Fig 4. Velocity vector in the crossflow section

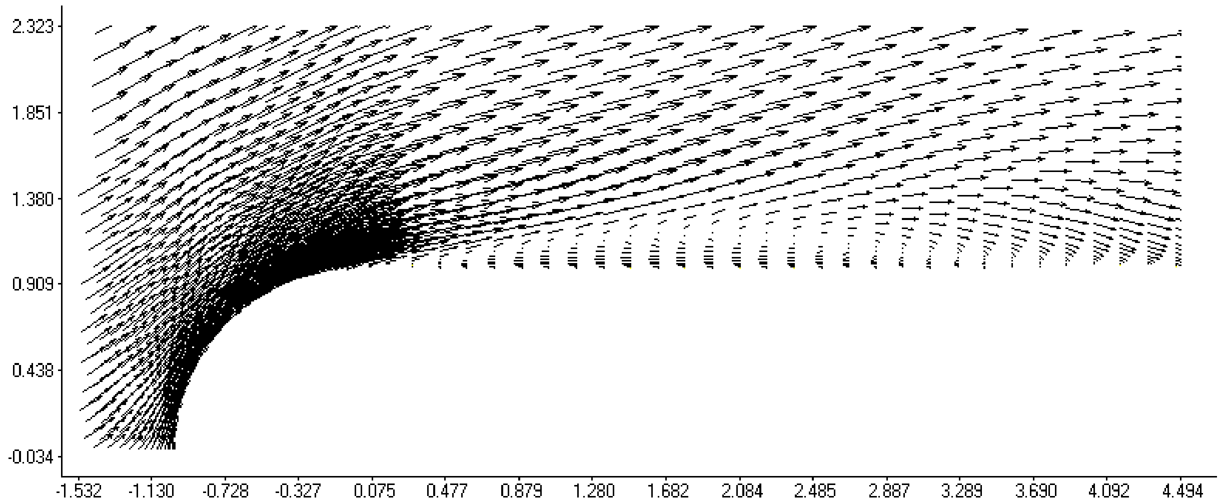


Fig.5.Velocity vector distributions in a symmetry plane on the leeward side

4. Configuration schemes of bodies in stream

Analysis of the existing MAGLEV-configurations has shown that form MLX–01 is aerodynamically optimal for magnet levitated transport as the relation between overall dimensions has been chosen more successfuly. Besides, the nose of MLX-01 is a classic aero-wedge that results in drag coefficient reduction. That is why MLX-01 configuration was chosen as a base for aerodynamical calculation of high speed ground-effect transport. For several years Institute of Transport Systems and Technologies of the Ukrainian Academy of Sciences (Transmag) together with Dniepropetrovsk National University and Kharkov Institute of Aviation are carrying out theoretical and experimental investigation of the aircraft-type configurations for Maglev cars [1-3]. When such a mean is moving in ground proximity the pressure on its bottom and on lower surface of its wing is increased. As a result an air cushion and additional lift effecting the wing and the vehicle as a whole is produced. It gives possibility to use less powerful magnets, to reduce electric power expenditure, to increase stability and safety of travel. Fig.6 shows Transmag-type configurations.

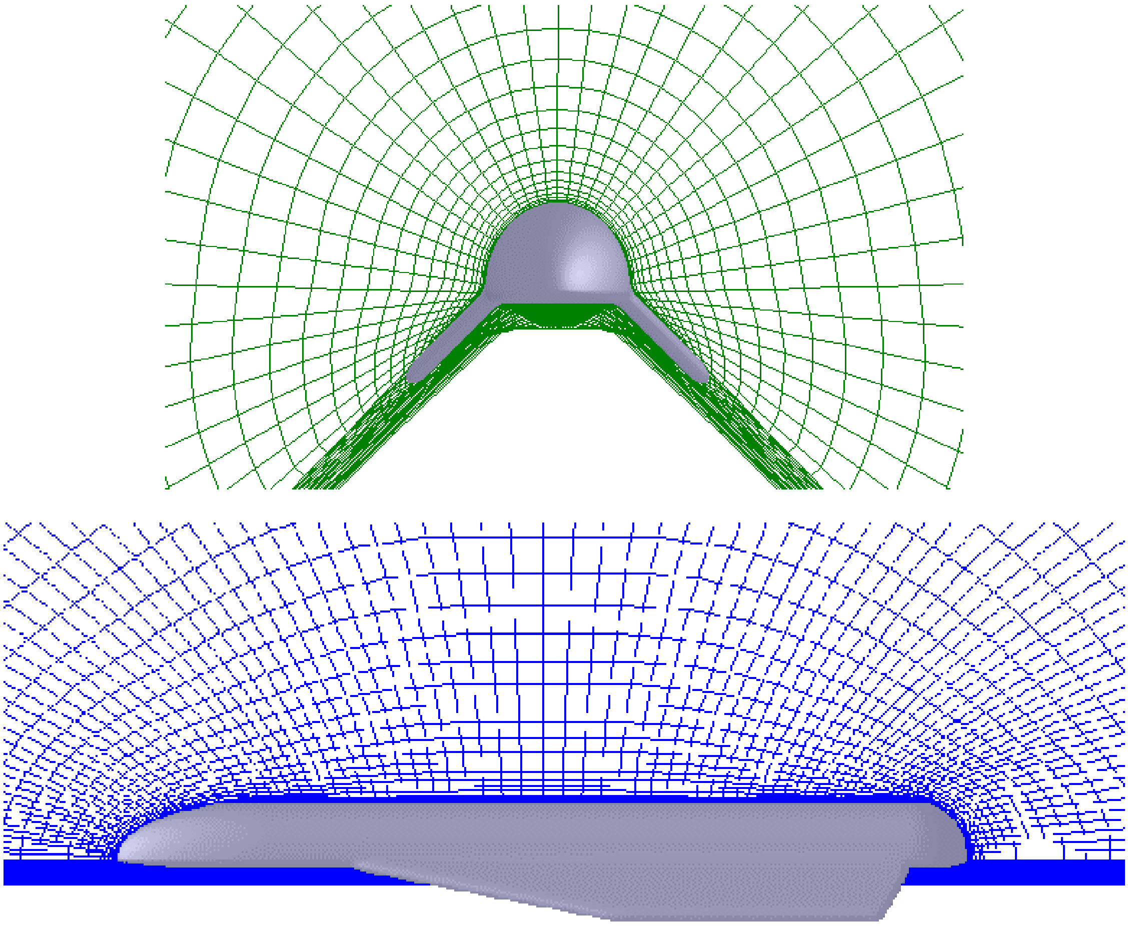


Fig.6. Configuration scheme and computational grids next to the vehicle of Transmag-type

5. High speed ground effect vehicle calculation results

As a result of solving the Navier-Stokes equation pressure fields and velocity vector cartesian components, pressure and friction coefficient distributions on the surface profile of the vehicle and also relationships of aerodynamic coefficients: drag and lift coefficients, pitching moment related to ground distance and angle of attack. Relative profile thickness is 0.07 for Transmag-type and 0.12 for MLX-type car. Aerodynamic coefficients of different angle of attack and ground distance are given in fig. 7-11.

The main factors which determine flow pattern and aerodynamic characteristics of high speed ground vehicle are track structure distance and incidence of a fuselage and wings. Numerical calculations have shown that isobars distribution at changing the angle of attack is not qualitatively equivalent to the change of vehicle height above the ground. In the first case the lift rise is due to the change of pressure above and underneath the profile. Bearing strength of the transport mean is increase due to the change in pressure distribution. Attention is given to the non-linear growth of pitching moment when is the aerodynamical gap is decreased. Large magnitude of aerodynamic moment can cause increasing in the vibration of the vehicle.

In the second case increase in angle of attack results in stagnation the flow on the bottom, increased lift, positive ground effect that is in agreement with available numerical and experimental data [3].
Aircraft-type configuration with zero angle of attack on the fuselage and positive wing incidence can provide the use of ground effect. Given in fig. 11 isobars on the car show redistribution of pressure with account of ground effect in three-dimensional case. Though presence of wings gives some increase in the drag, increased lift gives an overall gain. On the base of numerical data analysis the conclusion can be done about the presence of flow regimes when total compensation of vertical magnetlevitating forces is reached.

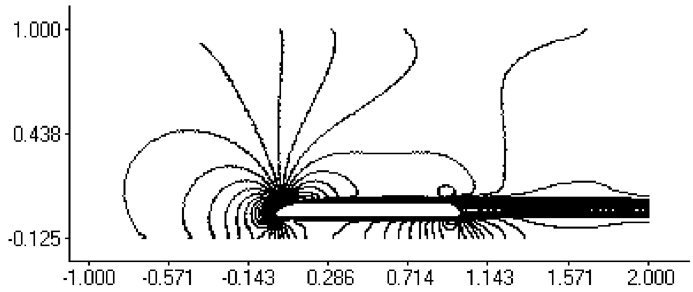
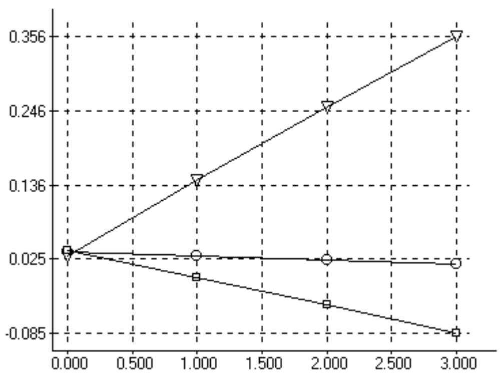


Fig.7. Mach number contours distribution the profile Transmag-type vehicle moving in ground proximity

Cx, Cy



α

Fig.8. Effect of height from the truck structure on the aerodynamic coefficients

Cx, Cy

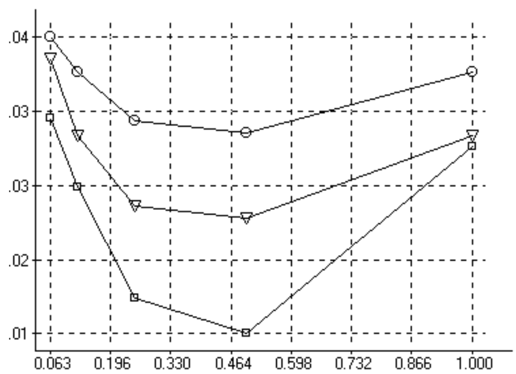


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Fig.9. Effect of angle of attack to the truck structure on the aerodynamic coefficients

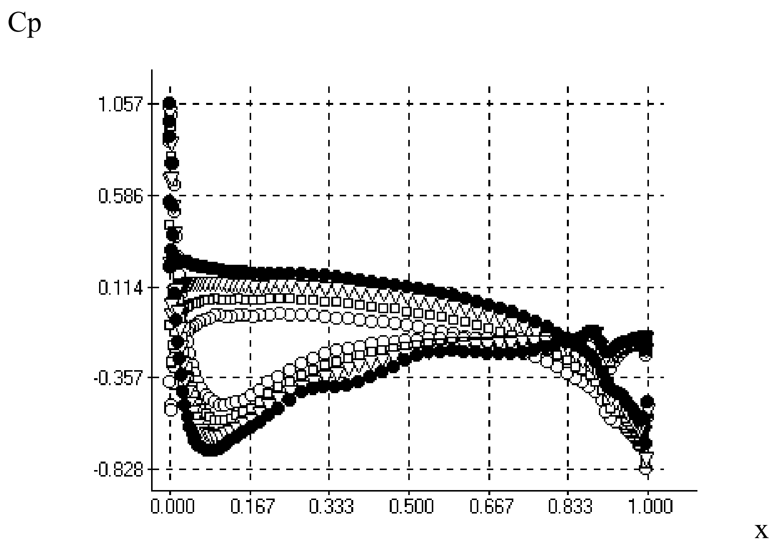

Fig.10. Pressure distribution in plane of symmetry on the surface of the vehicle

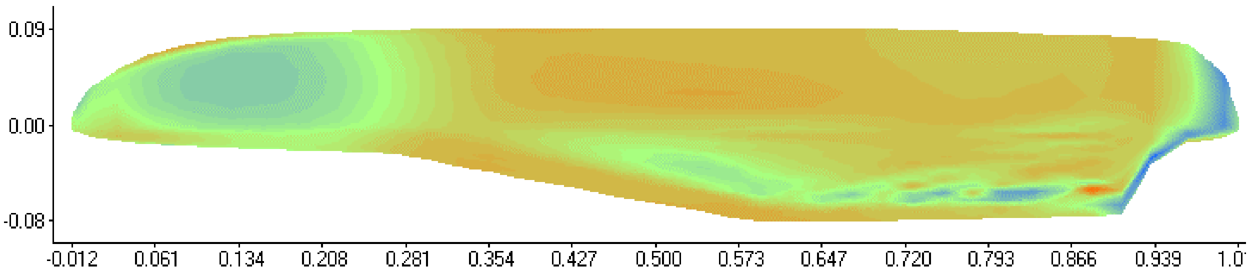

Fig.11. Pressure distribution on the surface of the vehicle on the base of Navier-Stokes equations calculation

6. Conclusions

1. Techniques, algorithms and program tools for two- and three-dimensional calculations of vehicle moving in ground proximity are developed.
2. Verification and testing the techniques, algorithms and program tools are accomplished on the problems of flow around a cylinder and airfoils for different flow regimes.
3. Structured/unstructured grid generation methods are developed for two- and three-dimensional calculations of Maglev components.
4. Aerodynamic characteristics of cylinder, aerodynamical profile, hemisphere/cylinder body, the high speed vehicles in ground proximity have obtained. Regularities of change in drag coefficients, lift and pitching moment related to the ground distance and angle of attack are established.
5. The results obtained can be used to choose the proper form of the vehicle, to investigate its dynamics, stability and crosswind influences, to analyze its surface loading, to estimate the effect of mainstream on the components of the cooling system of power equipment and ventilation.

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