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Supercomputer Modeling of Parachute Flight Dynamics

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In this article the authors present parallel implementation of numerical method for computer modeling of dynamics of a parachute with filled canopy. To solve the 3D problem of parachute free motion numerically, authors formulate tied problem of dynamics and aerodynamics where aerodynamic characteristics are found with discrete vortices method on each step of integration in time, and to find motion law the corresponding motion equations have to be solved. The solution of such problems requires high computational resources because it is important to model parachute motion during a long physical time period. Herewith the behavior of vortex wake behind the parachute is important and has to be modeled. In the approach applied by the authors the wake is modeled as a set of flexible vortex elements. So to increase computational efficiency, the authors used methods of low-rank matrix approximations, as well as parallel implementations of algorithms. Short description of numerical method is presented, as well as the examples of numerical modeling.

Keywords: parallel algorithms, numerical simulation methods, fluid dynamics, vortex methods, parachute aerodynamics.

Introduction

Parachute is a complex aeroelastic system the geometrical form of which appears as a result of aerodynamic and elastic forces interaction. That is why the first problem in computer modeling of a parachute is to simulate the overall process of canopy geometry generation in steady flow. For its solution authors developed mathematical model based on simultaneous application of bars method and lumped-mass method to describe canopy deformations [1], and discrete vortices method to model the flow past canopy [2]. Modeling a real parachute flight requires additional development of this model to simulate the dynamics of the parachute.

In this article the authors describe an approach based on solution of the above problem in two steps. On the first step we find the aeroelastic form of canopy in the assumption of steady flow past it using the vortex method and lumped-mass method. During aerodynamic computation the canopy shape and stress-strain behavior characteristics are adjusted on each step of iterational process based on the pressure distribution got from aerodynamic calculation. Then, final canopy shape obtained on first step of algorithm is used to solve the tied problem of aerodynamics and dynamics of parachute flight where canopy is supposed to be stiff.

It is notable that the solution of such problems requires high computational resources because it is important to model parachute motion during a long physical time period. Herewith the behavior of vortex wake behind the parachute is important and has to be modeled. In the approach applied by the authors the wake is modeled as a set of flexible vortex elements. So to increase computational efficiency, the authors used methods of low-rank matrix approximations, as well as parallel implementations of algorithms.

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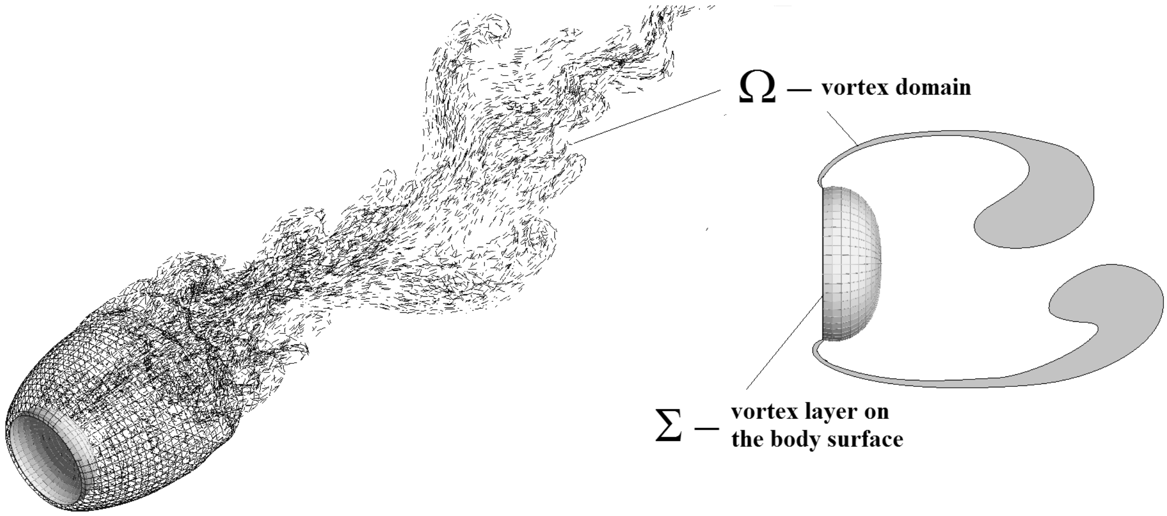


Figure 1. Vortex method

1. About Numerical Method

The authors consider the 3D problem of separated flow past bodies within the model of inviscid non-compressible fluid. The main idea of vortex methods is to utilise integral representation of velocity field $\vec{w}$ through vorticity $\vec{\omega} = rot\vec{w}$. With this it is assumed that vorticity is concentrated locally in bounded domains Ω and thin layer on the body surface Σ (Fig. 2). Then velocity field can be represented as

$$\vec{w} = \vec{w}_\infty + \vec{w}_1 + \vec{w}_2, \quad \vec{w}_1(x,t) = \int_\Omega \vec{\omega}(y,t) \times \vec{V}(x-y)\ dy, \quad \vec{w}_2(x) = \int_\Sigma \vec{\gamma}(y,t) \times \vec{V}(x-y)\ d\sigma_y,$$

where $\vec{V}(x-y) = (y-x)(1/(4\pi|x-y|^3))$, function γ is surface density of vorticity distribution, $\vec{w}_\infty$ – flow velocity on infinity.

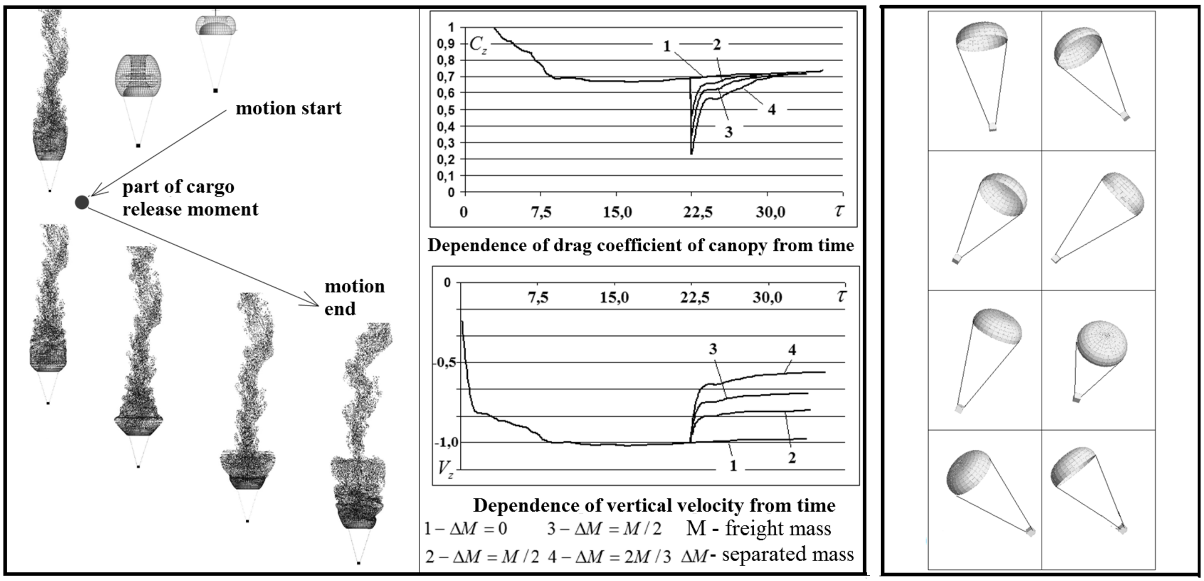
The authors use numerical model (see [2]) where vortex domain Ω is approximated with the system of discrete vortex segments l_i, each of which has the beginning in point x_i^-, and the end in point x_i^+, and has some vortex intensity $\vec{\omega}_i$, $i = 1, ..., N_\Omega$. Body surface Σ is approximated with set of cells σ_i, $i = 1, ..., N$, each cell is bounded with closed vortex line with intensity $g_i = g_i(t)$. Velocity field is approximated with expression:

$$\vec{w}_1(x) \approx \sum_{i=1,N_\Omega} \vec{\omega}_i \left[(x_i^+ - x_i^-) \times \vec{V}(x - x_i)\right], \quad \vec{w}_2(x) \approx \sum_{i=1,N} g_i \int_{\partial\sigma_i} \vec{dl}_y \times \vec{V}(x-y),$$

$x_i = (x_i^- + x_i^+)/2$. Approximation of vorticity transport laws is assured if the following motion equations for the ends of vortex segments are fulfilled in domain Ω:

$$\frac{dx_i^\pm}{dt} = \vec{w}(x_i^\pm, t), i = 1, ..., N_\Omega, \quad \frac{\vec{\omega}_i}{dt} = 0. \qquad (1)$$

In the numerical solution of the problem on each time integration step we assume known the positions of vortex segments in the domain approximating vorticity area and their intensities ω_i. Unknown intensities g_i on the body surface are calculated from the system of linear equations representing non-penetration condition of fluid on body surface, which is checked in collocation



(a) Separation of part of freight (b) Self-rotation

Figure 2. Simulation examples

points $x_i \in \sigma_i$, $i = 1, ..., N$:

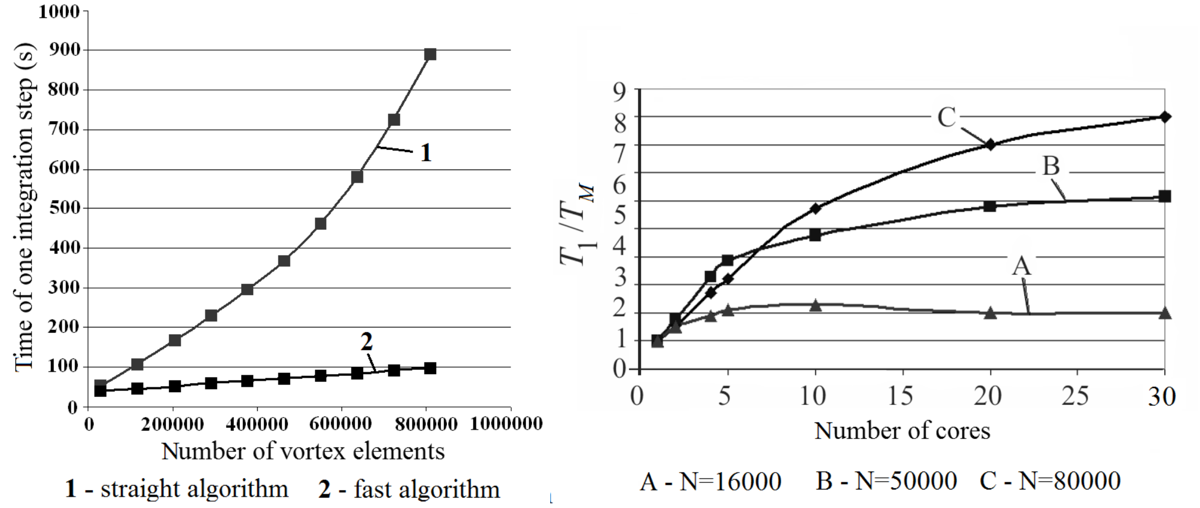
$$\sum_{j=1,N} g_j(\vec{W}_j(x_i)\vec{n}(x_i)) = -(\vec{w}_\infty + \vec{w}_2(x_i))\vec{n}(x_i). \qquad (2)$$

Then we shift the ends of vortex segments approximating vortex domain in accordance to equations (1) – here Euler scheme of the first order by the time is used. Then the process of new vortex elements birth is modelled on body surface and appending of vortex domain by them. These segments appear on predefined separation lines or on the full surface of the body.

In case when body makes free motion, the solid body dynamics equations also have to be written.

2. Computational Examples and Discussion

Considered numerical modeling of vertical flight with separation of part of freight. It is known from practice that at the moment of freight part separation the dramatic decrease of loads on canopy occurs. This leads to the breath effect on canopy and in some cases may lead to canopy collapse. So numerical modeling of the separation of part of freight is the important problem which helps to make right evaluation of freight part that can be securely separated. From the descriptions above it follows that at the moment of part of cargo release the parachute slows down and part of vortex wake that was behind canopy overtakes it. Herewith the dramatic decrease of pressure drop coefficient happens over all canopy surface, and consequently, the decrease of drag coefficient. Figure 2a (left side) shows the shape of vortex structures at different moments of time. On the right the dependency plot of parachute drag coefficient and vertical velocity from measureless time is shown. Let us note that measureless time τ, measureless velocity V and drag coefficient C_x were introduced as $\tau = t\ V_0/D$, $V = V^*/V_0$, $C_x = 2\ F_x/(\rho V_0^2 S)$, where t is physical time, V – physical velocity, D – diameter of filled canopy, V_0 – steady vertical velocity of parachute with cargo, F_x – drag force of air, ρ – air density, S – canopy square. The results obtained in numerical experiments showed good qualitative correspondence with observations.



(a) Comparison of fast and straight algorithms

(b) Acceleration of one time-integration step for various number of cores

Figure 3. Algorithm efficiency

For the parachute with fixed canopy authors made computations to model parachute motion from angled initial position as the next example. The transition to self-rotation mode is shown on the Fig. 2b.

To solve the problem in the example, the authors were to use more than 800000 approximating vortex elements. Figure 3a shows time comparison of one integration step made with fast (methods of low-rank matrix approximations) and straight algorithms. In both cases 128 processors were used, calculations were made on supercomputer Lomonosov in Lomonosov Moscow State University supercomputer center. The supercomputer node utilised in calculations had the following characteristics: 2 x Xeon 5570/2.93 GHz, memory 3 Gb per core. It is notable that straight algorithm gives quadratic dependence of time growth from element number growth, and fast algorithms shows linear time growth (theoretical estimate $O(Nlog^4N)$). Figure 3b shows dependence of vortex structures transformation time (fast algorithm) from the number of processors used in calculations and the number of vortex elements in the wake (M – cores quantity, T_1 – time of one integration step on one core, T_M – time of one integration step on M cores, N – number of vortex elements). Details of parallel algorithm for vortex method are presented in [3, 4].

Conclusion

The numerical method for the solution of tied aerodynamics and dynamics problems in parachute flight was presented. Numerical modelling of the separated flow past the moving parachute canopy was carried out with the vortex method. So the vortex wake was considered as an ensemble of moving vortex particles. The simultaneous application of the low-rank matrix approximation method together with the parallel implementation of the algorithm, made it possible to significantly increase the complexity of problems that can be solved. For example, in calculations on 128 cores, the number of vortex elements reached 10^6. Therefore the results obtained numerically in the considered problems showed good qualitative correspondence with observations.

In practice such approach can be applied to solve the following problems: investigate the behavior of a parachute with fixed thimble vectored from equilibrium state, and to find stable balance positions (it is important, for example, for brake parachute); modeling of development of slight disturbances in steady motion of ballistic parachute; modeling of dynamic of parachute motion with changing freight mass (here the most interesting case is separation of part of cargo during steady parachute descent which may lead to the system rollover).

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