Dynamics of the aircraft in a vortex wake

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Abstract. This paper considers the aerodynamics and the dynamics of an aircraft on various modes when the aircraft enters a strongly swirling flow. This is the case when an aircraft purposefully enters the jet-vortex wake of another aircraft in the course of in-flight refuelling, when an aircraft is flying in the trail of an aircraft carrier during landing, or when an aircraft accidentally enters other aircrafts’ vortex wakes. These situations, according to pilots' evaluation, are the most dangerous and the most difficult modes for piloting. That is why their real time modelling on flight simulators has taken on particular importance. This article provides the algorithms and methodology of mathematical modelling of aerodynamic forces and moments which act upon an aircraft in vortex wakes.

1. Introduction
An aircraft sometimes happens to enter a swirling air flow during the flight. This work contains numerical studies of how a vortex wake behind an aircraft and a disturbed air flow from an aircraft carrier affects the aircraft's aerodynamic characteristics. This article also contains the algorithms and methodology for creating mathematical models of aerodynamic forces and moments which act upon an aircraft in a vortex wake, which enable modelling an aircraft's dynamics on a flight simulator online.

In order to determine additional aerodynamic forces and moments acting on an aircraft which are induced by a vortex wake, it is necessary to find the distribution of fluid dynamics parameters across the whole area of the flow. At the same time, a dangerous wake can be up to 20-30 kilometers (13-20 miles) long for the cases of wakes behind heavy aircrafts, so the solution domain has to be divided into the near wake and the far wake areas.

In the near wake, the parameters of flows in vortex wakes are calculated on the basis of solving 3D steady Reynolds-averaged Navier-Stokes equations. The distribution of fluid-dynamic parameters thus obtained is used for determining the vorticity distribution, the inflow temperature and the velocity on the boundary for further calculation of the far wake. In this domain, the unsteady-state two-dimensional Reynolds-averaged Navier-Stokes equations are solved.

After the flow fields have been determined, it is necessary to create real time mathematical models of the forces and moments which act upon an aircraft given its space and angular position in the vortex wake.

Determining additional forces and moments acting upon an aircraft in a jet-vortex wake is based on calculating the configuration flow using the panel method with symmetrizing the singularities.

In real time modelling of an aircraft's dynamics it is necessary to reduce the computing time to 0.01 seconds, which is determined by the integration step of the equations describing the aircraft's flight on
a flight simulator. An approach based on approximating the obtained aerodynamic vaulting with the help of artificial neural networks was used to solve the task. Meanwhile, preliminary calculations of additional forces and moments for a large number of options for the space and angular position of an aircraft in a vortex wake were conducted. Then 6 neural networks whose vector contained the information about the space and angular position of an aircraft, and whose output was the increment of aerodynamic forces and moments caused by the vortex wake were trained.

2. Modelling the effect of vortex wake disturbances

A strongly swirling flow which an aircraft enters is caused by another aircraft. The solution to this problem consists of solving several sub-tasks: determining the characteristics of the flow near the aircraft generating the vortex wake, the wake's parameters and, finally, calculating the forces and moments which act upon an aircraft entering the area of a vortex wake from a tanker aircraft.

Several computational methods from aerodynamics have been used to determine the flow fields in the wake following the generator aircraft. In that case the flow range has been divided into three sub-ranges. The representation of dividing the area behind the tanker aircraft IL-78 into sub-areas of a near field, a near wake and a far wake is given in fig. 1. The border between the near field and the near wake is the initial cross-section for calculating the near wake, then, the far wake.

The velocity field in the near field behind the aircraft was computed using steady Reynolds-averaged Navier-Stokes equations (RANS) for the case of gas, compressed at the temperature which corresponds to the altitude of a cruise or refuelling. The expected angle of attack of an aircraft is determined basing on the necessity to perform a horizontal flight with a given mass and a given velocity at a given altitude. The aircraft is supposed to be flying with zero sideslip.

![Image of dividing solution domain](image_url)

**Figure 1.** The representation of dividing solution domain.

The flow fields and temperatures in the near wake have been calculated using the JVWAKE [2] code, which is based on solving two-dimensional unsteady-state Reynolds-averaged Navier-Stokes equations. In this software, the diffusion of an aircraft's vortex wake was calculated with the help of invariant modelling method developed at Princeton University [3-4] and modified by the authors for calculating the characteristics of a wake [2]. The modification involves the models of closure for Reynold's equations, which, as has been proved several times, lead to a stronger diffusion in the wakes' cores than in the experimental investigations.

Starting from the output cross-section of the computational domain and until the wake dies out, the flow fields are calculated using a simplified procedure. All the vorticity behind an aircraft is considered to be concentrated in two vortices, whose coordinates in the output cross-section coincide
with the coordinates of the mass centres of the right and the left halves of the vortex system. The vortices descend according to a non-standard analogy:

$$\frac{dy}{dx} = \frac{\Gamma}{2\pi bu_\infty},$$

here $b$ is the distance between the vortices, $u_\infty$ - is the velocity and $\Gamma$ is the circulation of vortices, which fades according to the following empirical law:

$$\Gamma = \Gamma_0 \exp\left(-\frac{0.8qx}{bu_\infty}\right).$$

Here $q$ is the atmospheric turbulence.

The vortices do not descend uniformly because they fade. The larger the distance from the wing, the lower the velocity with which the vortices descend. That is why the vortex wake is distorted. Curved vortex lines are replaced with a system of broken wake segments from which the velocities are calculated according to Bio-Savara formulas. These are also calculated in the point for which the velocity to be calculated was outside the computational domain of a near wake.

3. Modelling the effect of disturbances caused by an aircraft carrier wake

The aircraft's motion in a vortex wake following an aircraft carrier is considered. This section contains the solutions to a number of problems which are concerned with modelling a turbulent wind above the water surface, with determining the characteristics of the flow near and behind the ship, as well as with determining the forces and moments which act on a landing or taking off aircraft. The field of velocities near the ship is determined by the velocity and the direction of a gradient wind, which depends on the state of the atmosphere and the ship's velocity. The air flow fields near the ship have been calculated using CFD methods. The solutions to the boundary-value problem for Reynolds-averaged Navier-Stokes equations have been used. The picture of the flow thus obtained at zero angle of the apparent wind with the velocity of 15m/sec is shown in fig. 2. The left part of the figure shows the space pattern of vorticity isolines behind the ship. The streamlines of the flow behind the antenna tower are shown in the lower right corner of the figure.

![Figure 2. The flow in wake following an aircraft carrier.](image)
4. Determining the additional forces and moments caused by a vortex wake

Determining the additional forces and moments which act upon an aircraft in a vortex wake is based on calculating the airflow using a panel method and is performed according to the following algorithm:

1. Aerodynamic forces and moments which act on an aircraft in a body axis coordinate system are singled out from a uniform flow with the help of the panel method;
2. Using the flow fields obtained through calculations in the wake following a generator aircraft or an aircraft carrier velocities in the control points of the aircraft's panels are determined using interpolation;
3. The airflow is calculated considering additional velocities, and aerodynamic forces and moments are calculated;
4. Additional forces and moments are calculated through subtracting the values obtained at step 3 from the values obtained at step 1;

This work uses the modification of a panel code PANSYM [5] where hydrodynamic characteristics on the lifting surfaces (wings, aircraft's empennage and the flap systems) are symmetrized in order to calculate the full configuration of the aircraft to be refuelled. The software has proven useful for solving a wide range of applied problems. In this method the aircraft's surface is modelled using a series of tetragonal panels with the sources and vortices distributed along them. Non-structural elements like the body are modelled using the panels with a piecewise-constant distribution of the sources and the outflows. The surface of the wings’ lifting surfaces, the empennage and the flap systems are modelled using panels with piecewise-linear distribution of the vorticity along a chord and a piecewise-constant distribution of the sources and the outflows. The principle of symmetrizing the characteristics of an element's upper and lower surfaces is used for modelling the lifting elements. In this case the characteristics on the respective panels of the upper and the lower surfaces are equally intensive. A typical configuration of an aircraft in a panel representation is shown in fig. 3.

![Figure 3. Computational model for the panel method.](image)

5. Creating on-line mathematical models on the basis of artificial neural networks

In order to create a system modelling the impact on an aircraft and the vortex wake from a generator aircraft or an aircraft carrier on-line, it is necessary to:

1. Conduct computational research of the airflow of an object generating the vortex wake and form a numerical array of gas-dynamic parameters of flow fields in the wake;
2. Determine the additional forces and moments acting on an aircraft in a vortex wake;
create real time software modules which can determine the increment of forces and moments during flight simulator modelling.

Computing the airflow and obtaining numerical arrays of gas-dynamic parameters of the flows require considerable amounts of time and modern industrial CFD packages. In order to create on-line software modules on the basis of the data obtained it is necessary to employ fast approximation methods.

While using this information to model an aircraft dynamics in a vortex wake on a flight simulator in real time it is necessary to reduce the time required to determine aerodynamic characteristics to 0.01 seconds, which is determined by the time integration step of the equations describing the aircraft’s motion. To solve this task, an approach based on approximating the obtained array of aerodynamic characteristics with the help of artificial neural networks has been used. Under this approach a considerable number of options of the angular and space positions of an aircraft relative to the wake generator object were calculated in advance. Following that, 6 neural networks with the input vector containing the information about the aircraft’s position (three coordinates and three angles), and with the output being the increment of aerodynamic forces and moments caused by the wake were trained. A comparison between the approximation accuracy and the computational result has shown that the accuracy of determining aerodynamic characteristics is adequate. Artificial neural networks that have been trained beforehand with the help of computational data serve as aerodynamic software modules for the simulator’s mathematical support under this approach. This procedure has enabled to reduce the time required to calculate an aircraft’s aerodynamic characteristics in one point dramatically (to 0.0001 - 0.0002 sec) with only a slight decrease in accuracy. Multilayer perceptron-type neural networks with two hidden layers have been used. There were 11 neurons on the first layer and 5 on the second one. In total, 6 neural networks have been trained for approximating the increments of three coefficients of aerodynamic forces and three coefficients of aerodynamic moments. In order to form a set of patterns which were used for teaching and testing the neural networks, about 200000 calculations for each aircraft type, using random values of its position in the wake, have been carried out. The ranges of the computational parameters of the given set of patterns correspond to the area where an aircraft could be located.

After training neural networks the accuracy of determining the increments to forces and moments caused by an aircraft’s position in a vortex wake as compared to the computational characteristics obtained with the help of the panel software was evaluated.

Figure 4. Visualising a vortex wake using a flight simulator.

Then basing on the array of weighting coefficients of neural networks the functions were formed in an algorithmic language C++ with the help of special software. The execution speed of the functions
was evaluated on a PC with an Intel (R) Core (TM) processor 17-3820 CPU, 3.60 GHz, with an installed memory (RAM) of 8.00 GB in a 64-bit operating system Windows. It took about 0.0001 sec CPU to calculate the increments of three coefficients of forces and three coefficients of moments in one point on the flight trajectory. The developed mathematical software enables one to model the dynamics of an aircraft when it enters vortex wakes on a flight simulator and to visualize dangerous areas, which is an important part in training air staff. A flight simulator visualization of the calculated distribution of vorticity behind an IL-78 aircraft is shown in fig. 4.

6. Conclusion
The work presents the results of theoretical research of vortex wakes in a turbulent atmosphere. Mathematical models of an aircraft flying in the area of a strong vortex wake influence, which are applicable to modelling an aircraft's dynamics in real time have been created. The technique of visualizing dangerous vortex wake areas on a flight simulator has been improved. The software based on the suggested mathematical models has been implemented on flight simulators in TsAGI, the Department of Aerodynamics and Flight Engineering at Moscow Institute of Physics and Technology (State University), Russian Aircraft Corporation «MiG» and Beriev Aircraft Company, [1].

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7. References
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