Technology for aerodynamic wake characteristics measurement behind an aircraft on a rail-guided track

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Abstract. A framework for vehicle wake vortexes experimental investigation on a rail-guided track in sub- and supersonic flows is presented. Basic requirements for measurement system and results treatment are determined based on numerical modeling and wind-tunnel tests.

1. Introduction

Coherent vortex structures in the atmosphere are represented with strong vortexes that are stable enough for their lifetime to be larger than elementary volume rotation period around instant axis. At the same time, their nature is stochastic and unpredictable. Classical examples are vortices behind aircraft (Figure 1a), vortex wakes behind air-carriers (Figure 1b), wind vortex structures in a mountain landscape (Figure 1c).

Figure 1. Coherent vortex structures examples: (a) aircraft vortex wake, (b) aircraft carrier wake, (c) wind vortex structures under mountain landscape.

Entry into the coherent vortex structures can lead to unexpected abrupt bank angle changes, which is especially dangerous at low altitudes, autopilot deactivation, engine cut-out, crew errors, hard
landing out the runway (RW) and others. Passing across the vortex is dangerous in terms of dynamical loadings and structural damage. Vortex wake strength determines the delay between aircraft landing on the same RW and take-off and eventually the overall throughput of an airport. ICAO recommends to set safe distance between two consequent aircraft depending on their classes. However, sometimes accidents occur even if all the recommendations and air traffic controller (ATC) commands are carried out [1].

There are many factors that influence on the evolution and decay of wake vortexes, such as wind in terms of vortex transfer (in particular, wind shear that carries vorticity), stratification (vortex cluster descending against its buoyancy increases vortex dissipation rate), atmospheric turbulence. Due to mutual induction, the vortexes go down, earth influence causes them to spread out and raise themselves. Side wind carries them, keeping the upwind one stay above RW for some time, which is the worst case for flight safety. The influence of random wind gusts leads to long-wave instability onset. Direct numerical simulation in the framework of the boundary-value problem for filtered Navier-Stokes equations (Large Eddy Simulation) with subgrid turbulence model (LES) reproduces small-scale as well as long wave instability development [2].

Current simplified models doesn’t account for these factors or do that inaccurately. Due to that fact the efforts to make vortex safety system based on vortex wake evolution prediction are not likely to be successful. It is required to see or sense wake vortexes in time. The former is possible with lidars, IR-cameras or meteoradars. The latter is possible with onboard system detecting the trajectory deviation from the trajectory of controlled flight in the calm atmosphere. In both cases the problem of image recognition arises, for which machine learning techniques can be employed.

In order to provide data about atmospheric conditions in the area of the runway, missing data have to be generated based on limited amount of information from sensors. For this task, generative artificial neural networks (ANN) can be employed. There is a good progress in system identification and modeling of unknown nonlinear processes using recurrent ANN. As soon as the flow pattern (atmospheric conditions) in the area of interest is known, the decision has to be made on whether to allow takeoff or landing. It is generally quite hard for human operator to make such a decision based on raw flow pattern, thus, decision support is needed. The most important function of that system is to recognize vortexes, determine their size and strength, and to provide relevant information to ATC. For the task of pattern recognition, convolutional neural networks have proved their efficiency and could be successfully used for the task.

In this work, methodological questions of using a rail track for experimental measurement of vortex wake parameters at sub- and supersonic conditions for flight safety purposes are discussed. Experimental data received will be used for the verification and validation of the computer’s codes used for the aircraft vortex wakes simulation.

2. Aircraft vortex wake

Wake formation was demonstrated for A380 aircraft during final approach (flight on glidepath, mass 380 t, velocity 70 m/s, wing span 83 m). Parameters of the atmosphere: temperature 273K, pressure 70121.2 Pa [3]. Angle of attack 13.5 degrees. Core circulation 420.35 m²/s, core radius 3.39 m.

On figure 2 wake parameters in control section 3 seconds after the aircraft crossed it are presented. Three distinct pairs of vortexes can be observed. Contour corresponds to the position of the wake generating aircraft during its traversal through the cross-section.

The modeling is conducted according to [3–7]. The wake is represented by the structure of several pairs of vortexes with opposite directions of rotation. One pair is generated by wingtips, two pairs by the flaps, and one pair is due to the fuselage. External flap vortexes has the same direction as those by the wingtips and could be stronger.

Unexpected wake vortex entering won’t allow the pilot to have a soft landing on RW. Timely notification can alleviate the consequences (figure 3).
In [4–7], the possibility of constructing an early warning system for a pilot when an aircraft subscriber enters the vortex wake from an aircraft—generator based on the use of an on-board air signal system and cross flow air sensors was considered. Num\r\nberically verified algorithm was validated in T-103 TsAGI’s wind-tunnel tests. Near wakes behind two aircraft models were simulated, in which the distinct coherent structures are not present yet. Algorithm generated the alarm signal if the all three pair of sensors reach agreement in center of vorticity prediction in the framework criteria used.

**Figure 2.** Fields of horizontal and vertical velocity components, longitudinal vorticity component and aircraft contour 3 seconds (210 meters) behind the aircraft.

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**Figure 3.** Pilot-in-the-loop simulation the aircraft entering the left vortex behind the preceding aircraft during flight on glidepath.

The results wake vortex scanning behind Il-106 aircraft (figure 4) in TsAGI’s T-103 wind tunnel with elliptic test section axes 4 × 2.33 m, at flow speed \( V = 50 \) m/s are represented in figure 5.

**Figure 4.** Il-106 model and three 6-point cross flow sensors, which act as probe aircraft.

Measured vertical and horizontal velocity components and static pressure fields in the control section are shown on figure 5. Pressure difference in control section that can be used to detect vortex structure core is 20 Pa. Working area boundaries as well as contour of an aircraft generating the wake are also shown. Origin of coordinates is situated in the center of the model (in the intersection of
fuselage construction horizontal line and vertical plane crossing the front mounts of the model support system).

![Figure 5](image)

**Figure 5.** Vertical and horizontal velocity distributions and pressure distribution in control cross-section.

Proposed and verified during numerical modeling and wind tunnel tests algorithm can be proposed for experimental verification in direct motion.

3. **Rocket-powered rail track as a mean for wake vortex experimental modeling in straight motion.**

Validation of onboard real-time expert system for wake vortex detection has to be conducted in straight flow. To do that high-speed track can be employed, including rocket-powered track. Principal trolley sketch is shown on figure 6. The experiment has to be conducted in 2 stages.

In the first stage wing model (8) is set on the car (4) via support system (5). The car is mounted to the rails (10) stopped on them by rail shoes (12). Behind the wing model the comb with pressure and velocity sensors (3) is installed for continuous flow measurements in the near wake. In front of car (4) pressure sensors are installed according to figure 6. Behind the car with the wing model, rocket-powered car (1) with solid fuel rocket engine rigidly connected with it is installed. On rocket-powered car the comb with pressure and velocity sensors (3) is set. Axes of two wake combs mounted on car with model and on car with engine should be aligned.

In the second stage, the rocket engine is turned on and both cars drive along the track. At a certain point A (see figure 7), rocket-powered car is uncoupled and in the second stage car with the model moves freely before full stop. Vortex wake parameters measurement behind the wing model is continuous throughout the experiment.

![Figure 6](image)

**Figure 6.** Rocket-powered car experiments (1) booster car; (2) engine; (3) comb with pressure and velocity sensors; (4) car with a model; (5) support system; (6) visualization system; (7) smoke generator; (8) wing model; (9) camera and/or IR-camera; (10) rail track; (11) car connection; (12) rail shoes.

Civil aircraft flight velocity ranging from 70 to 300 m/s can be realized on 2500 m length track: the acceleration to 300 m/s will take about 750 m, deceleration from 300 m/s to 70 m/s on 1000 m track.
will last for 3-10 seconds, and deceleration from 70 to 0 m/s will take 750 m length. Measured in forward flow vortex characteristics can be employed to validate numerical methods.

4. Conclusion
Technology foundations are proposed for modeling evolution and decay of vortex wake behind an aircraft in forward motion on rocket-powered trolley in short- and long-range vortex wake at sub- and super-sonic speeds. The results of the experiment can be employed for validation of numerical schemes, engineering practices, as well as for onboard vortex detecting and avoidance systems.

One of the possibilities to develop the system is to apply it for flight safety issues, connected to in-flight refueling (automatic refueling system), air carrier landing, close formation flight, mountain terrain airport landing, flight and other operations in mountains landscape and near high rise buildings (in orographic turbulence conditions), clear-sky turbulence detection during cruise flight.

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Figure 7. Graph of the model movement along the rocket track.