Application of various ice accretion simulation approaches in the LOGOS software package

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Abstract. This paper presents results of the ice accretion simulations by the techniques implemented in the LOGOS-Aero module of the LOGOS software package. The results of the Eulerian and the Lagrangian ice accretion simulations are reported for NACA verification problems, which are used to test the software package Lewice. The approaches implemented in the LOGOS-Aero enable simulations of the aircraft icing conditions and the predictions of the shapes and locations of ice deposits on computational models.

1. Introduction

At present, numerical simulations make it possible to compute flows over various types of a complex-shape aircraft. Implemented techniques and algorithms are used to analyze various parameters, like strength and aerodynamic performance of an aircraft under different flight conditions, and to predict the design performance of new types of machinery. Optimization of performance by numerical simulations integrated into the design activities saves the time and costs of design, reduces the scope of experimental research and flight testing, and simplifies the process of aircraft modification in the design phase [1–3]. Among the certification requirements stated in Appendices O to the European (CS25) [4] and US (FAR25) airworthiness standards are sections 25.1093 “Air intake system icing protection” and 25.1419 “Ice protection”. In Russia, the certification is based on the Aviation Regulations, Part 25, “Airworthiness Standards for Transport-Category Airplanes” [5]. The today certification regulations for an aircraft and other flight vehicles for flights under the icing conditions provide for aerodynamic model testing in the wind tunnels and flight testing of a real aircraft with ice deposit simulators [6, 7]. The procedure of the aircraft certification accepts results of the aircraft ice deposit shape predictions provided that these are further confirmed by experimental studies. Shapes and dimensions of ice deposits are determined for natural icing conditions during a flight, for flights behind water splashing tankers [6, 8], and for blowing of aircraft components in special wind tunnels [8] to simulate the ice accretion.

The software package LOGOS [1–3] offers various techniques, including algorithms to simulate the ice accretion on an aircraft. In this paper, we present the results of using various ice accretion simulation approaches implemented in the LOGOS for test simulations of the Lewice verification problems [9].

2. Ice accretion simulation approaches and methods implemented in LOGOS

The LOGOS employs three approaches to simulate the water droplets motion [1–3]:

- the Lagrangian multi-phase approach, which represents droplets as discrete particles;
• the Eulerian multi-phase approach, which represents the water phase as continuum;
• the hybrid approach, which simulates the liquid phase by the Eulerian approach, while the Lagrangian approach is used to simulate the formation and spreading of films on solid surfaces.

In the Lagrangian approach, mathematical modeling of two-phase flows is based on the numerical solution of the major conservation equations for the gaseous and the condensed phases. The condensed phase in this case is treated in the framework of the quasi-particle method. This method provides for the solution of differential equations of path, momentum, energy, and mass for an ensemble of quasi-particles, being a group of non-interacting individual particles (droplets) with identical physical properties. The simulation of flows over large-size bodies by the Lagrangian multi-phase approach is still a challenging problem.

The Eulerian approach [4] assumes that the relationship between the gas and the droplet flows is one-way (the liquid phase has no effect on the gas flow), in which case all the droplets are uniformly distributed across the domain. This model ignores such processes as vaporization or condensation of droplets. The Eulerian multi-phase approach is less expensive.

In the LOGOS, three computational techniques are used to simulate the ice accretion:
• one-step technique;
• multi-step technique; and
• unsteady technique.

The one-step computational technique is used to calculate steady gas flow parameters and new shapes of surfaces exposed to the ice accretion using a grid morphing procedure.

The multi-step computational technique includes separate steps to implement the following solution procedure:
• steady gas flow calculations in the domain, including calculations of tangential stresses at the interface with solid walls and gas/wall heat fluxes;
• calculations of a steady motion of droplets in the Eulerian approximation based on the gas flow calculation results;
• calculations of the thickness of the liquid film and ice over the time given;
• updating the surface shapes exposed to the ice accretion and remeshing.

Each successive step uses a grid changed as a result of ice accretion at the previous step. The calculation ends at a specified total time of the ice accretion.

When the unsteady approach is used, calculations of the gas flow, the motion of droplets and the ice accretion are performed within a single time step without calculating the steady solutions. In this case, sources of mass, momentum, and energy of droplets and liquid films can be communicated to a gas flow solver to couple the solvers. Figure 1 shows flow charts of the calculations in the LOGOS.
3. Verification of implemented models

The ice accretion simulation techniques implemented in the LOGOS were tested and verified on different problems. This paper presents the results of the ice accretion simulations for the NACA23014m airfoil from the verification basis Lewice [9] and compares them with experimental data. Figure 2 shows a grid constructed around the NACA23014m airfoil by the LOGOS and used in the test calculations.

Figure 1. Flow charts of calculations in the LOGOS.

Figure 2. The computational geometry near the airfoil.
The computational grid is structured and consists of ~19 thousand cells. The ice accretion simulation of this airfoil was performed for the conditions given in table 1.

Table 1. The ice accretion simulation conditions.

| No. | Airfoil designation | Chord, m | Exp. ID | V, m/s | Ttot, K | T, K | α,° | LWC, kg/m³ | MVD, m | Time, min |
|-----|---------------------|----------|---------|--------|---------|------|------|------------|--------|-----------|
| 1   | NACA23013(m)        | 1.745    | 219     | 87.2   | 255.37  | 251.3| 0    | 8.2e-4     | 160e-6 | 3         |
| 2   | NACA23013(m)        | 1.745    | 251     | 87.2   | 270.93  | 266.85| 0    | 8.2e-4     | 160e-6 | 21.2      |
| 3   | NACA23013(m)        | 1.745    | 123r8. | 88.5   | 272.04  | 267.85| 5    | 8e-4       | 20e-6  | 10        |

where V is the flight velocity; 
Ttot is the total air temperature; 
T is the Outside Air Temperature, static air temperature; 
α is the angle of attack; 
LWC is the Liquid Water Content in the flow; 
MVD is the Median Volumetric Diameter of droplets; 
Time is the ice accretion time.

Figures 3 through 5 below present the results of the ice accretion simulations for the conditions summarized in table 1.

Figure 3. Comparison of the ice accretion results for the first setup.
Figure 4. Comparison of the ice accretion results for the second setup.

Figure 5. Comparison of the ice accretion results for the third setup.

Figure 6 below shows the results of the ice accretion on the airfoil as a function of simulation time (setup 2, the Eulerian multi-phase approach).
Figure 6. The ice accretion on the NACA23014 (mod) airfoil as a function of simulation time (setup 2, the Eulerian multi-phase approach).

Figure 7 below shows the results of the ice accretion on the airfoil as a function of simulation time (setup 2, the Lagrangian particles).

Figure 7. The ice accretion on the NACA23014 (mod) airfoil as a function of simulation time (setup 2, the Lagrangian particles).

Figure 8 below shows the results of the ice accretion on the airfoil as a function of the number of simulation steps (setup 2, the Eulerian multi-phase approach).
Figure 8. The ice accretion on the NACA23014 (mod) airfoil as a function of the number of simulation steps (setup 2, the Eulerian multi-phase approach).

Figure 9 below shows the results of the ice accretion on the airfoil as a function of the number of simulation steps (setup 2, the Lagrangian particles).

Figure 9. The ice accretion on the NACA23014 (mod) airfoil as a function of the number of simulation steps (setup 2, the Lagrangian particles).
The graphs show that the results calculated by the LOGOS qualitatively agree with the experimental data and the Lewice simulations [9]. The graphs also demonstrate that the shape of ice deposits is resolved in greater detail if the number of steps is increased.

4. Conclusion
The module of compressible flow simulations in the LOGOS offers algorithms and models used for the aircraft ice accretion simulations. The implemented techniques enable the ice accretion simulations to predict the shapes of ice deposits on various types of an aircraft. This paper presents the flow charts of calculations by this technique in the LOGOS [1–3]. The performance of the LOGOS software components employing the Lagrangian and the Eulerian multi-phase flow simulation approaches is demonstrated on the test simulations of some NACA problems [9] intended for the verification of the Lewice software package.

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