Ways to ensure lightning resistance of aviation carbon fiber polymer composite structures containing adhesive compounds

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Abstract. This work advances solutions to the problem of insufficient electrical conductivity of adhesive material, the adhesive layer, and, ultimately, the entire adhesive connection. Sufficient electrical conductivity is necessary to ensure the survivability of composite structures under lightning strike conditions. Along the way, solutions to the problem of unhindered flow of static electricity charges which can occur when aircraft not in flight and has catastrophic consequences when interaction occurs in the presence of aviation fuel is proffered.

1. Introduction
In the aviation industry, structural carbon fiber plastics are being increasingly used instead of aluminum and titanium alloys, which provides a significant reduction in the weight of the airframe of aircraft. At the same time, structural carbon plastics have specific properties that affect the lightning protection of aircraft structures. This is mainly due to the fact that structural carbon plastics are weak conductors (their resistance is 3 – 4 orders of magnitude higher than that of metals) [1-4]. In this regard, unprotected carbon fiber structures may be damaged by lightning, which is unacceptable for resource and operational requirements. To exclude these damages or reduce their probability, specialized design techniques are used (for example, the use of tires, jumpers, specialized nets, various types of foils embedded in the structure of composites) and/or materials science solutions (modification of polymer matrices of carbon fiber plastics in order to increase conductivity). The development of advanced composite structures involves strategies to increase the degree of their integrality. This can be achieved by reducing the number of mechanical fasteners and use high-strength adhesive joints [5, 6]. In the light of the constant growth of the use of polymer composite materials in the aviation industry, and the need to ensure lightning protection composite structures, this work attempts to proffer solutions from the point of view of security, taking into account the requirement for optimal weight efficiency in designs.

2. Problem analysis and research methods
According to statistics, there are several possible areas of lightning damage to aircraft: “A”, “B” and “C” (figure 1). The most susceptible to lightning strikes are the end sections of aircraft (“A”): the nose, wingtips, Elevator and stabilizer, antennas, engine nacelles. Due to the fact that the impact of lightning on the surface of the aircraft is not the same, the entire surface of the glider is conditionally divided into three zones. Zone A (zone of direct lightning discharges) is the surface of the aircraft for which there is a high probability of initial (direct) lightning discharges and which are affected by currents with
maximum parameters (I=200 kA, Q = 200 C). Zone B (zone of shifting or beveled discharges) is the surface of the aircraft for which there is a high probability of moving discharges from zone 1. The intensity of lightning currents in this zone is slightly lower than in zone A (I=200 kA, Q = 20 C) [3, 4]. Zone C - surfaces of aircraft that are not included in zones A or B.

Figure 1. Schematic representation of lightning strike zones and their location.

Regulatory documentation introduces the term "metallization" - connecting elements and assemblies of an aircraft with reliable conductive connections to bring all elements to the same electrical potential. According to the industry standard for metallization of structural elements and assemblies, shielding coatings of wires and harnesses of aircraft (helicopters), for reliability and compliance with lightning protection, it is necessary to measure the transition resistances between aircraft parts.

When considering the design and technical solution of metallization, in order to create a single potential of the connected parts, additional considerations are taken into account:
- the need to form holes, which complicates the production process, weakens the design;
- additional weight of bolts, contact washers and nuts;
- additional weight of ring or other types of terminals and conductor elements of the required cross-sections connecting them.

In [4], a method for improving the lightning resistance properties of aviation carbon fiber polymer composite structures with adhesive joints is developed and investigated. These adhesive connections are made with the minimum required electrical conductivity. Electrical conductivity is achieved by modifying the adhesive composition with carbon nanoparticles. Work is underway to determine the optimal concentration of nanoparticles and select the method of distribution of the modifier in the volume. Samples of carbon fiber with a light-protection coating are being developed and connected
using high-strength conductive adhesive joints. Figure 2 shows a schematic diagram of a plausible arrangement that will allow to work out this solution (2a) and an experimental test set-up (2b).

![Schematic diagram of tests](image)

**Figure 2.** Schematic diagram of tests: 1 - conductive coating; 2 - carbon fiber plate; 3 - adhesive layer; 4 - wired leads; 5 - electrical test clips; 6 - power supply clips; 7 - Ω-meter; (a) - side view, (b) - top view.

The purpose of this experiment is to make a conductive adhesive joint and measure its electrical conductivity, and confirm that is within the specified limits. The electrical resistance of the glued parts must not be worse than prescribed by the regulatory documentation, including the earlier-mentioned standard [4].

Meeting these requirements will provide an indicator of lightning protection of the structure, as well as the flow of static electricity charges.

A surface linear control was performed, in which the infinite resistance of the glue without nanotubes was revealed. The installed resistance shows that this adhesive is a good dielectric. It is planned to introduce various concentrations of Tuball nanotubes to study the effect on resistances. A sharp decrease in resistance is expected, which should lead to better conductivity.

3. Results and discussion

Polymer dielectrics, primarily polar (paraelectrics), almost always contain groups and molecules of low-molecular additives and impurities that are capable of spontaneous ionization. Ion clusters in an electric field are capable of undergoing deformation (induced polarization), and free ions are capable of transfer, i.e. to ionic current or ionic conductivity.

The electrical properties of polymer dielectrics due to the processes of polarization or ion transfer are usually determined at low field strength. At high voltage, complex processes of electrical breakdown of dielectrics are possible, associated with the occurrence of strong currents due to the breakdown of electron clouds and the course of various thermochemical transformations of polymers. Breakdown voltage characterizes the electrical strength of polymer dielectrics. The conductivity of polymer compositions is not enough to remove a large charge in a short time. To estimate the conductivity of the modified composition, the percolation theory is a geometric type of phase transition, since at a critical fraction of removal the network breaks into significantly smaller connected clusters. The phenomena described by the flow theory belong to the so-called "critical phenomena". These phenomena are characterized by a "critical point" at which certain properties change dramatically. In our case, the electrical resistance at a certain value of the filler concentration in the matrix begins to rapidly decrease or increase the conductivity. It is believed that the filler particles form infinitely conductive chains-clusters in the matrix. Percolation theory provides a description of structures and processes directly near the percolation transition, and away from it, such structures and processes are described quite well by classical methods with an approximation of the effective medium [2, 7, 8].
Experimental measurement of the volumetric resistivity in conventional units of the experimental compositions of the epoxy and polyester base was carried out, depending on the concentration of the Tuball “Matrix 201” modifier (table 1).

Table 1. The results of measurement of the volumetric resistivity.

| The concentration of particles, % mass | Specific volume resistivity, $\Omega \cdot \text{sm}$ |
|---------------------------------------|-----------------------------------------------|
|                                       | Experimental epoxy DER 351 | Experimental polyester bind. Aropol M 105 |
| 0.01                                  | $1 \cdot 10^6$               | $1 \cdot 10^8$                          |
| 0.02                                  | -                             | $1 \cdot 10^7$                          |
| 0.03                                  | -                             | $1 \cdot 10^6$                          |
| 0.04                                  | -                             | $1 \cdot 10^6$                          |
| 0.05                                  | $1 \cdot 10^5$               | -                                         |
| 0.055                                 | -                             | $1 \cdot 10^4$                          |
| 0.07                                  | -                             | $1 \cdot 10^3$                          |
| 0.10                                  | $1 \cdot 10^4$               | $1 \cdot 10^2$                          |

The manufacturer of nanotubes stated that the average diameter detected by the Raman spectroscopy method is $1.6 \pm 0.6$ nm. At the same time, they have an average length of about 5 microns (atomic-force microscope method) (figure 3). The results of some comparisons of different types of single-wall and multi-wall carbon nanoparticles are presented in figure 4.

Figure 3. Some geometrical parameters of Tuball [9].

Figure 4. Some comparisons of different types of carbon nanoparticles: a - Tuball, single-wall; b - multi-wall Fh IWS (scale 200 µm).

And some results of some comparisons of electrical properties of different types of carbon nanoparticles given on figure 5.
These indicators differ favorably from microparticles, nanofibers, particles of conductive carbon black, etc. At the moment, experiments are being conducted with samples of VK-50 composition [14-16] made in the scientific and production company "Techpolikom" (Russia). Apparently, the optimal concentration index, taking into account the possible percolation threshold, will lie in the range of 0.1 - 0.8 % by weight for this type of modifier. This is subject to refinement on a specific type of polymer by experiment.

4. Conclusion
In the ongoing work made:
- the problems of lightning protection of structures when replacing metal parts and aggregates with composite ones are considered;
- the main requirements of industry standards are outlined and the design solutions used to ensure lightning protection of structures are considered;
- the search for an effective solution to ensure lightning protection of carbon fiber parts and aggregates connected using adhesive joints was carried out and the way of its implementation was determined. Trends in improving the electrical properties of the conductivity of polymer compositions using a nanomodifier are revealed. Taking into account the percolation threshold, the optimal nanomodifier content is expected to be in the range of 0.1 - 0.8 % by weight. This value will be clarified in further work and will be thoroughly studied.

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