Research on the Static Electricity Characteristics of Large Airplanes

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Abstract: Large aircraft play a very important role in various fields today. During the execution of tasks, large aircraft will carry charges due to various reasons, and these static charges will pose a hazard to the safety of large aircraft. This paper analyzes the charging and discharging characteristics of large aircraft and studies the changes in the amount of charge and surface potential of large aircraft during flight. This paper uses simulation software to simulate the surface charge distribution of large aircraft, and combines the simulation results with theoretical knowledge to analyze the surface charge distribution of large aircraft. It is concluded that the surface charge density is high at the locations of large surface curvature, as well as the ends of the fuselage and wings. The distribution of equipotential lines of electric field strength on the aircraft is also simulated, and it is concluded that static discharge is more likely to occur in areas with higher charge density. This research has theoretical guiding significance for ensuring the safe flight of large aircraft.

Keywords: Electrostatic distribution, electrostatic protection, finite element simulation.

1 INTRODUCTION

Large aircraft have applications in multiple fields, making it significant to ensure that they successfully carry out their missions[1]. When flying at high altitudes, the metal surfaces of aircraft inevitably accumulate charges due to interactions with various particles in the air. When the accumulated charges reach a certain level, static discharge occurs, and the

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electromagnetic effects of the discharge can cause malfunctions in the aircraft[2] In some cases, accidents that cause casualties and huge economic losses may occur. US scientists have pointed out that over 1% of aviation accidents each year are caused by static electricity interference. Furthermore, static electricity has caused major accidents in many aircraft, including the US Thor-Delta rocket, Minuteman I missile, European Europa-2 rocket, and Hercules - 3 C rocket.

In order to reduce the damage of static electricity to aircraft, people have proposed some methods, including using static discharge brushes to discharge the aircraft and using anti-static materials to protect the aircraft. The study of the distribution characteristics of static charges deposited on aircraft can provide a theoretical basis for these anti-static measures. Therefore, researching the distribution of charges on large aircraft can help reduce the harm caused by static electricity to aircraft, and has important significance for the design of static electricity protection measures, increasing the probability of successful execution of missions by large aircraft[3].

Many scholars have carried out research on static electricity distribution on aircraft. Beach studied the principle of surface charge accumulation during aircraft flight[4]. Nanevicz studied the static charging reasons and discharge currents of large aircraft[5]. Grosshans et al. elaborated and verified the friction electrification model to predict the electrical situation when a helicopter hovers in a dusty environment[6]. Lekas proposed a method to calculate the amount of static electricity generated by the aircraft when flying in sandstorms. Revel et al[7]. proposed a method of locating static discharge components on aircraft surfaces by arranging detectors. Andersen et al. studied the distribution of static electricity discharge in polymer materials and improved the estimation of static electricity breakdown fields in space environments[8]. Yadav et al. introduced the application and development of various aviation nano-composite materials in aircraft anti-static. Yi Ming et al. studied the static distribution characteristics of fixed-wing aircraft and static discharge during landing[9]. Yang Zhenyi et al. studied the suppression effect of the discharge brush on static discharge of the aircraft, and found that increasing the diameter of the discharge brush is the most effective method for discharging the aircraft body charge[10]. Hu et al. conducted theoretical analysis and experimental research on the friction electrification law of aircraft surfaces, and obtained the polarity of the aircraft's friction electrification[11]. Zhang Jing et al. studied the static discharge characteristics and influencing parameters of an aircraft's static discharge brush. Liu Hao et al. studied the static electrification and leakage characteristics and influencing factors of a silicon-based thermal protection material on the surface of an aircraft[12]. Temnikov et al. investigated the characteristics of electrostatic discharge inside and outside the antenna fairing of aircraft[13]. Carmen studied the methods of lightning protection and electrostatic discharge prevention for new aircraft[14].

As can be seen from the previous content, the electrostatic discharge and protection of aircraft have received a lot of attention from many scholars, and many scholars have carried out extensive research work on this topic. However, there is relatively little research specifically focused on the electrostatic characteristics of large aircraft. Therefore, this paper first analyzed the charging current and discharging current of large aircraft, and then used simulation software to simulate and calculate the electrostatic characteristics of large aircraft, studying the distribution of surface electrostatic charges and electric fields. The results of this study can provide a basis for analyzing and evaluating the electrostatic hazards of large aircraft, as well as for the electrostatic protection of aircraft.

2 ANALYSIS OF CHARGING AND DISCHARGING CHARACTERISTICS OF LARGE AIRCRAFT

Aircraft can become charged during flight due to various reasons. Based on the characteristics of large aircraft, there are two main ways for aircraft to acquire charges: frictional charging and Engine charging. The discharge mode of large aircraft is mainly corona discharge.

2.1 Frictional Charging

Large aircraft typically fly at altitudes of around 9 km. The frictional charging current of large aircraft is mainly produced by the friction between the metal skin of the aircraft and ice crystals in the air. An empirical formula commonly used in engineering to calculate the magnitude of the frictional charging current I_P of the aircraft is:

$$I_P = S_m v_m J/600 \tag{1}$$

In the formula, S_m stands for the windward area of large aircraft, v_m stands for the flight speed of large aircraft, J stands for sedimentary electrostatic current density, which needs to be determined in conjunction with the specific flight environment of large aircraft. Taking the windward area of a typical large aircraft as 60m^2 and the flight speed as 204m/s. It can be inferred from the flight altitude that a large aircraft usually flies in cirrus, and J can be taken as 50~100μA/m^2 at this time. By calculation, the frictional electrification current of large aircraft is about 1~2mA.

2.2 Engine Charging

When an aircraft's engines are running, the high-temperature combustion process inside the engines will cause the gas to ionize. The electrons generated by ionization have a higher velocity than the positively charged ions, resulting in different movements between the electrons and the ions. The electrons will scatter into the metal shell of the engine combustion chamber, while the positively charged ions will be rapidly ejected from the engine's nozzle. This will result in the aircraft carrying a negative charge. For large aircraft, the typical value of Engine charging current can be taken as $I_e = 0.175$mA according to research results from SRI.

2.3 Corona Discharge

The main discharge mode of large aircraft is corona discharge. When enough charge accumulates on the aircraft, the electric field strength generated by the charge reaches the breakdown threshold of air, and corona discharge occurs. The formula for calculating the breakdown threshold is as follows[15]:

$$E_C = m_0 E_0 \delta_K (1 + \frac{0.337}{\sqrt{\delta_K r_0}}) \times (1 + \frac{H_S - 11}{100}) \tag{2}$$

In the formula, m_0 is a constant related to the roughness of the discharge site; E_0 is a constant with a value of 29 kV/cm; δ_K is the relative air density; r_0 is the equivalent radius of the discharge portion; H_S is the absolute humidity of the environment at that time.

After corona discharge occurs, scholars believe that there is a relationship between the corona discharge current and the corona discharge voltage as shown in formula (3)[16].

$$I_C = \eta_1 (U_y - U_{ons}) U_y \tag{3}$$

In this formula, the symbol η_1 is a constant whose specific value depends on the pressure in the environment and the relevant properties of the discharge site. The symbol U_y represents the voltage of the aircraft with respect to the ground, and the symbol U_{ons} is the threshold potential at which corona discharge occurs on the aircraft. From the formula, it can be seen that the corona discharge current increases with the increase of the surface potential of the aircraft.

For large aircraft, the typical value of its corona discharge current can be determined by consulting literature, and is on the order of Ma[17].

2.4 Analysis of the Charge Quantity and Surface Potential Variation of Large Aircraft

Based on the analysis of the charging and discharging currents of the aircraft in the previous text, it can be concluded that the change of charge quantity Q on the aircraft during cruise flight can be expressed using formula (4) with respect to time.

$$\frac{dQ}{dt} = I_P + I_e + I_c \tag{4}$$

In the formula, I_P represents the frictional charging current of large aircraft, which is usually generated by the friction between the aircraft surface and ice crystals in the environment, resulting in the surface of the aircraft carrying a negative charge. The symbol I_e represents the engine charging of the aircraft, which also causes the surface of the aircraft to carry a negative charge. Under the combined effect of these two charging currents, the surface of the aircraft will carry a negative charge. When the accumulation of negative charge on the aircraft surface reaches a certain value, corona discharge occurs on the aircraft, resulting in discharge current I_c.

For aircraft with specific shapes, there is a linear relationship between its charge quantity and its voltage with respect to the ground, as shown in formula (5).

$$Q = U_y C \tag{5}$$

In the formula, C represents the capacitance of the aircraft to the ground. Combining the changes in the charge quantity of the aircraft with the relationship between the charge and voltage on the aircraft, it can be seen that at the beginning of corona discharge, the charge quantity on the aircraft is small, and the voltage of the aircraft to the ground is also small, resulting in a small discharge current. The charge quantity on the aircraft continues to rise under the influence of the charging current. As the charge quantity on the aircraft increases, the voltage of the aircraft to the ground increases, and the discharge current of the aircraft continues to increase until the magnitude of the charging current is equal to that of the discharge current. At this point, the charge quantity and ground voltage of the aircraft both reach their maximum values.

3 SIMULATION CALCULATION OF ELECTROSTATIC CHARACTERISTICS OF LARGE AIRCRAFT

From the above analysis, it can be inferred that the surface potential of a large aircraft is negative. During the flight of the aircraft, the surface potential will gradually increase until it reaches equilibrium. Previous studies by scholars have shown that the typical potential of a large aircraft can reach -40kV[18].

This article uses simulation software to take the E-3 aircraft as a typical large aircraft and simulate the charge and electric field distribution of the aircraft during flight in order to study the electrostatic characteristics of large aircraft.

Modern aircraft are sprayed with conductive paint on their surface to reduce the hazards of electrostatic discharge, ensuring good electrical continuity on the surface of the aircraft. Therefore, the entire surface of the aircraft can be regarded as a conductor. When analyzing the charged state of a large aircraft, the surface of the aircraft can be analyzed as an equipotential body. Due to the difference in materials used to construct the radar cover and fuselage of the aircraft, there is a significant difference in the values of the dielectric constant between these two parts. Considering that the materials used to construct the radar cover and fuselage of a typical large aircraft are fiberglass and aluminum alloy, respectively, the relative dielectric constant of the radar cover material is set to 4 and the relative dielectric constant of the fuselage material is set to 81. Based on the previous analysis, the potential value of the surface of the aircraft is set to -40kV. The numerical simulation result of the charged state of the aircraft is shown in Figure 1.

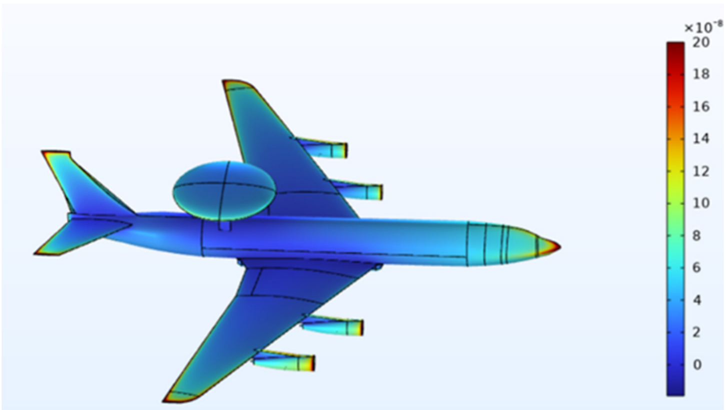

Figure 1: Distribution of surface charge density on large aircraft.

The red area in Figure 1 represents a very large surface charge density, while the surface charge density in the yellow area is slightly lower than that in the red area. The blue-green area has the lowest surface charge density. Figure 1 provides a clear observation of the distribution of the aircraft's charge under the absence of external environmental factors.

According to the distribution of the surface charge density of the aircraft, the amount of charge carried by the aircraft can be calculated, and it is found to be 51.2μC. Table 1 lists the charge amount of typical aircrafts[19]. It can be seen that the simulation results are within the same order of magnitude as the experimental results, indicating that the simulation results have certain reference value.

Table 1: Charge Amount of Typical Aircrafts.

types of aircraft	BO 727	DC 9	Caravelle	Piper
charge amount (μC)	-720	-580	-110	-13

The distribution of surface charge density on the aircraft is observed by selecting specific positions on the aircraft. As shown in Figure 2, 14 points are selected from the aircraft's dorsal surface in the plane of symmetry. The distribution of the surface charge density at these 14 points is shown in Figure 3.

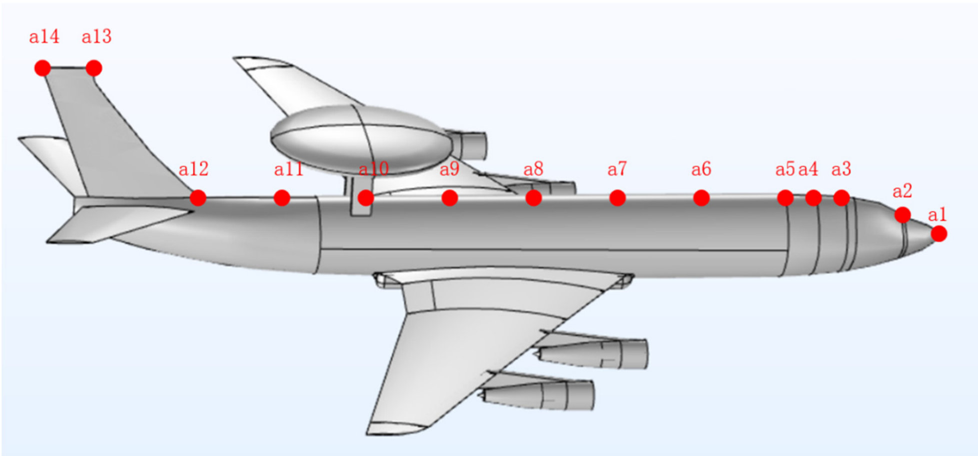

Figure 2: Locations for Measuring Surface Charge Density.

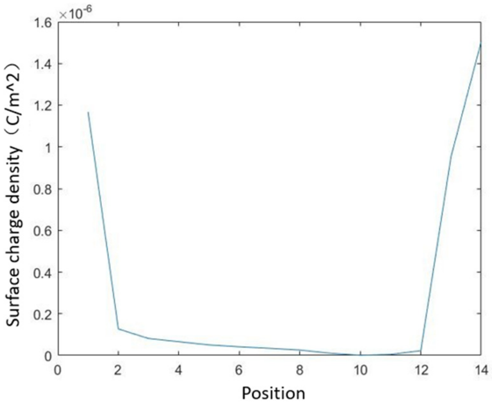

Figure 3: Surface Charge Density at Different Positions.

Through simulation calculations of the surface charge density of large aircraft and the study of the distribution of surface charge density at specific points on the aircraft, it can be found that the charge distribution on the surface of large aircraft has the following characteristics when there are no external environmental factors present. The surface charge density is higher at the wingtips, tailtips, edges facing outward from the engines, and nose tip of the aircraft. And the surface charge density is lower in the middle of the fuselage, near the wing roots, and the part of the fuselage under the radar cover.

The reasons for the above situation are as follows. Firstly, when considering only the effect of the average surface curvature of the large aircraft on the surface charge density under the premise of being unaffected by other factors, it can be assumed that the surface charge density of the conductor increases as the average surface curvature of the aircraft increases. This leads to areas of the aircraft with sharp protrusions, such as the tip of the aircraft's nose, having a significant surface charge density.

The magnitude of the surface charge density at a certain location on the aircraft is not only related to the average surface curvature, but also to the interactions between the charges on the aircraft. This leads to a higher surface charge density near the ends of the fuselage than in the middle. Especially for the part of the fuselage under the radar cover, in addition to the repulsion of charges on the body, the charges on the radar cover also have a significant repulsion effect on the charges in this area, which leads to a lower surface charge density.

Continuing to analyze the distribution of charges on the wings and engines, using the same method as the analysis of the charge density distribution on the fuselage, the positions selected on the aircraft are shown in Figure 4. The charge density at the selected positions is shown in Figure 5.

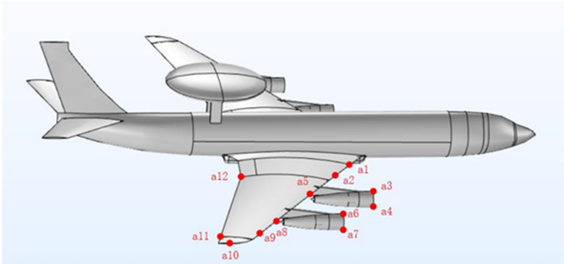

Figure 4: Locations for Measuring Surface Charge Density.

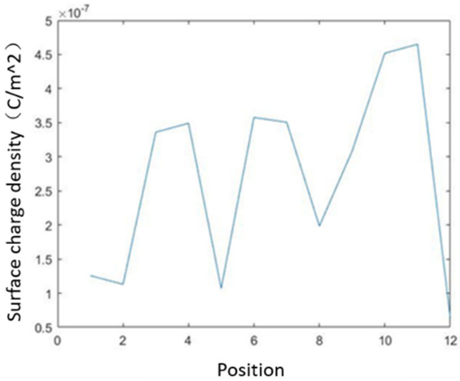

Figure 5: Surface Charge Density at Different Positions.

The values of surface charge density on the wings and engines are higher at the ends of the wings and at locations farther away from the wings on the engines. The surface charge density on the wings closer to the fuselage is lower. The areas of the wings and engines with a higher average surface curvature also tend to have a higher charge density. The distribution of charges on the wings and engines of the aircraft is consistent with the theoretical analysis results of the distribution of surface charge density on the aircraft discussed earlier.

Based on the charge distribution on the surface of the aircraft, the magnitude of the electric field strength of the aircraft can be simulated and calculated. Figure 6 shows the distribution of the magnitude of the electric field strength of the large aircraft.

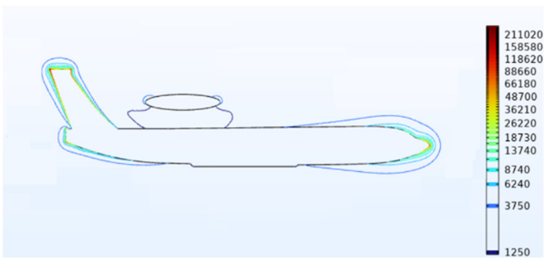

Figure 6: Distribution of magnitude of electric field strength of large aircraft.

The different colored curves in the figure represent different magnitudes of electric field strength. Each curve corresponds to a specific value of electric field strength magnitude, with units of V/m. Simulation results of the electric field strength magnitude show that areas with higher surface charge density also have higher electric field strengths, making them more likely to experience electrostatic discharge. Therefore, attention should be paid to these areas when taking measures to prevent electrostatic discharge.

4 CONCLUSIONS

This paper studied the electrification and discharge characteristics of large aircraft. The main focus was on friction electrification and engine jet electrification in the electrification process of large aircraft, as well as corona discharge in the discharge process of large aircraft. An estimate was made of the approximate range of charging and discharging currents for the aircraft. After analyzing the charging and discharging currents of the aircraft, this paper studied the charge quantity carried by the aircraft and the changes in the surface potential of the aircraft, and obtained the process of reaching the equilibrium of charge quantity and surface potential on the aircraft.

After analyzing the charging and discharging characteristics of large aircraft and the changes in surface potential, this paper simulated the distribution of charges on the surface of the aircraft using simulation software. The paper identified the parts of the large aircraft that are more likely to accumulate charge, including the tips of the aircraft and both ends of the fuselage. The simulation of the electric field strength demonstrated that these parts are more susceptible to electrostatic discharge. Therefore, electrostatic discharge devices should be installed in these areas to ensure flight safety. The research results of this paper have guiding significance for the installation of discharge devices on large aircraft.

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