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Composite Thickness Design of the Leading-edge Skin for Bird-strike Protection and Airworthiness Interpretation

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Abstract

The main airworthiness authorities in the world have studied and formulated a series of measures for bird strikes, in this paper. The contents of airworthiness clauses for the birdstrike of domestic and foreign transport aircraft are analyzed. The formula of bird strike penetration speed and the ultimate impact load of bird strike are added to the airworthiness compliance process, and the leading-edge skin's thickness is estimated for preliminary design. This provides a good starting point for future structure design.

Keywords: Airworthiness clause; Airworthiness compliance; Composite thickness of the leading-edge skin; Bird strike.

1. Introduction

Since the invention of the airplane in 1903, human beings have realized the dream of flying for thousands of years. However, while enjoying the fun and convenience of flying, human beings have to bear the disastrous consequences of airplane accidents. Bird strike is a widespread and destructive aircraft accident. It refers to the flight accident caused by the collision of aircraft (air-vehicles, etc.) with birds flying in the sky. Once it happens, it will cause immediate damage of structural components, directly threaten the lives and safety of aircrews and passengers, and lead to significant economic loss, which will result in the replacement and maintenance of aircraft structural components or flight delays, and even bring about catastrophic accidents of aircraft damage and death.

According to the literature, from the 1960s to the 1980s, the number of destructive bird strikes by the U.S. Air Force increased rapidly from several times a year to more than 360 times a year and reached 1894 times a year. Since the 1990s, the number of bird strikes on American civil aircraft has increased from 1759 times a year to 7666 times a year. It can be seen from the above data that, as time passes, bird strike has become increasingly prevalent and has become a major threat to human aviation safety. Therefore, bird strike has become an important consideration of aircraft design.Aircraft collisions with birds (bird strikes) at airports have always been a part of aviation.

In this century, the statistical data of all parts of the world show that the engine accounts for about 44%, the wing accounts for about 31%, the windshield accounts for about 13%, the nose accounts for about 8%, and the fuselage accounts for about 4%. As bird impact incidents happen frequently, reducing the impact damage of birds on flight safety to the minimum has always been the goal of continuous pursuit [1-3].

With the increase of bird populations and the number of aircraft flights over the world, the threat of bird strikes to the aviation industry, especially civil aviation, is increasingly prominent. Given the bird impact problem of aircraft, the airworthiness departments around the world have organized a lot of research work, developed a series of airworthiness standards, and increased the resistance of structural bird impact in the design and manufacturing process of aircraft.

In terms of the vigorous development of civil aircraft in recent years, higher requirements are put forward for airworthiness certification standards of transport aircraft. Civil aircraft design and manufacturing companies are required to not only strictly comply with airworthiness regulations but also have the ability to amend terms. However, due to the late start of the research on bird impact of civil aircraft, the establishment and revision of bird impact airworthiness regulations in China are formed following the corresponding airworthiness regulations of European and American countries, and there is no experience in the increase, decrease, and revision of bird impact clauses. The research and analysis of the European and American bird impact airworthiness clause and its revision background will have certain reference significance for the revision of the future bird impact airworthiness clause in China.

According to the relevant standards and specifications, this paper studies the contents of bird impact airworthiness clauses at home and abroad. It introduces the basis of making bird impact airworthiness clauses in detail, discusses adding empirical formulas to the understanding of bird impact airworthiness clauses to evaluate the resistance of bird impact, and adds airworthiness compliance verification for reference.

2. Airworthiness clause of bird strike at home and abroad

The airworthiness regulations of civil aircraft give the minimum safety standards of aircraft. There are two major civil aircraft airworthiness regulations in the world, namely, the Federal Aviation Regulations (FARS) of the Federal Aviation Administration (FAA) [4] and the certification specifications (CSS) of the European Aviation Safety Agency (EASA) [5].

For large transport aircraft, the airworthiness regulations of the United States, FAR25.571 damage tolerance, FAR25.631 bird strike damage, FAR25.775 windshield, and windows, put forward requirements for the aircraft's bird strike resistance. The requirements of CS25.571 damage tolerance, CS25.631 bird strike damage, CS25.775 windshield, and windows are made in CS-25 of EASA large aircraft certification code.

According to CCAR25 [6] of CAAC, it is the minimum standard. The list of applicable bird strike airworthiness terms is shown in Table 1. Different aircraft types may have different requirements, but the applicable terms include but are not limited to the contents listed in Table 1.

Table 1 Clauses involved in bird strike analysis and verification

Clause requirements	Title	Remarks
25. 571(e)(1)	Damage tolerance and fatigue assessment of structures	Discrete damage (bird strike)
25.631	Bird strike damage	For tailplane
25.775(b)(c)	windshield and windows	For windshield and supporting structures

Design requirements for which means of compliance are provided. This is that an aeroplane must be capable of continuing safe flight and landing after hitting a 1.8 kg bird withthe nose, wing, and other structures at the more critical of:

- Vc (cruise speed) at mean sea level or
- 85% of Vc at 8000-foot altitude.

Additionally, an aeroplane must be capable of continued safe flight and a subsequent normal landing after the empennage structure has been impacted by a 3.6 kg bird at cruise speed (Vc) at mean sea level.

In particular, it is pointed out that the assessment of damage tolerance (discrete source) should consider that the pilot can complete the flight safely after the impact caused by birds, and the assessment of damage tolerance only requires the assessment of residual strength, not the assessment of crack growth. Therefore, there are two main problems to be considered in the damage tolerance assessment. One is the determination of the damage location and scope. The other is the reasonable formulation of the residual strength load requirements of the structure. When the tail structure is impacted by a 3.6 kg (8 lb) bird, per articles 25.571 (E) and 25.631, the following two conditions shall be met after the leading edge of the tail is impacted by a bird:

a) Structural safety: if the front beam of the vertical tail is broken down, it shall be able to bear the static load reasonably expected in the safe return voyage (usually limited load);

b) System safety: key control system components must be placed in the protected area; protective devices (such as partitions or energy-absorbing materials) shall be used to ensure that the system components will not be damaged, or the key equipment shall not be arranged in the direct bird-strike area in the general layout.

The current standards for the design, manufacture, and certification of aircraft were formulated in the last century. Since the establishment of these standards, not only has the number of large birds in many parts of the world been increasing, but also the structural design of aircraft has been changing dramatically. However, when neither design nor manufacturing standards have changed, it makes it difficult to cope with new threats. The recent bird strike has resulted in thousands of serious aircraft injuries, which means there is a need to make changes to the bird-strike problem. Since 2003, Canada and the United States have revised their flight rules for bird strikes, such as banning high-speed flights below 10000 feet. However, compared with the modification of aircraft operation strategy, it is a faster, more efficient, and more economical solution to reduce or limit bird impact damage by adding empirical formulas to the rules and regulations and judging the crashworthiness of the structure.

3. Verification steps of bird impact airworthiness compliance

As a discrete source (for airframe structures) and a specific risk (for systems and equipment), bird strikes must be verified by aircraft type certification to ensure that the aircraft can continue to fly and land safely after the bird strike. Taking into account the requirements of domestic and foreign airworthiness authorities (FAA and EASA) for bird strike certification, the steps of strike impact compliance verification are summarized as follows:

3.1 Determination of bird hit parts

According to the statistics, bird strike mainly occurs in the nose (including windshield, radomes, pitot tubes, antenna, etc.), leading edges (such as slats), trailing edges (such as flaps), tail structure (horizontal stabilizer and elevators, vertical stabilizer and rudder), winglets, fuselage (including fairing, etc.), engine nacelle lip and landing gear in suspension and downstate, and landing gear doors.

3.2 Determination of flight status

Under the conditions of taxiing, takeoff, low-altitude flight, cruising, descent, approach, and landing, the bird strike has occurred at the flight altitude above or below 2500m.

3.3 Determination of bird strike penetration (or loss of parts)

In case of no structural penetration due to bird strike, the following situations shall be considered:

a. The influence of structural deformation caused by bird strike on internal structural components (such as dashboard, etc.);

b. The influence of structural deformation caused by bird strike on relevant equipment, systems or approved operation performance (the pilot's corrective action can be considered);

c. Influence of bird strike on systems and equipment;

d. Influence of bird strike on Head-up Display (HUD) installed in the cockpit, which will not hurt the pilot.

3.4 Specific risk analysis of bird strike

As a specific risk, the influence of bird strikes on the installation of key systems and equipment (such as control system components and electrical equipment) must be considered. If possible, these systems and equipment should not be installed directly behind the parts that may suffer bird impact to ensure that the aircraft's control system can still be steerable after bird impact, and the aircraft can continue to fly and land under control, although it may be necessary to adopt emergency procedures. This is usually accompanied by the increase of flight crew workload and the decrease of flight quality, but it does not require additional flight skills or physical strength of the flight crew.

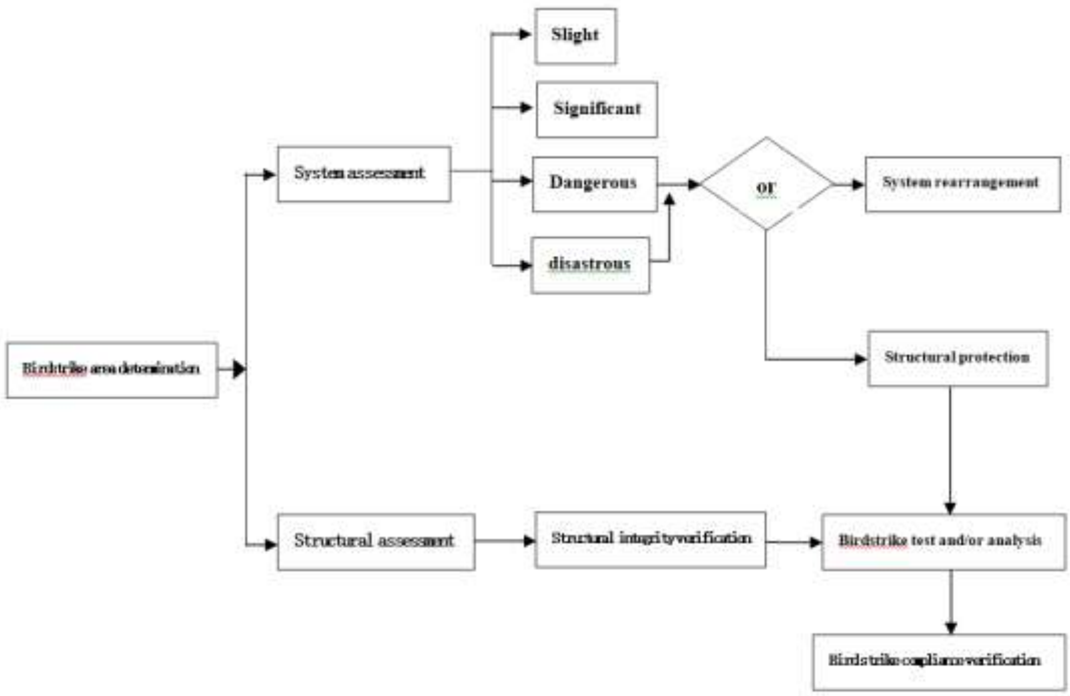

Figure 1 The steps of bird strike compliance verification

4. Bird strike airworthiness compliance verification method

The core goal of the airworthiness of the bird strike is to ensure the aircraft can return safely after bird strike, that is to say, the structural strength shall meet the requirements of residual strength, and the system safety analysis shall meet the specified requirements (initially determining that the impact level of system failure is not higher than class II). According to the typical engineering cases at home and abroad, bird-strike analysis and airworthiness verification usually adopt the method of combining numerical simulation analysis and bird-strike tests. In this paper, some effective and experimental empirical formulas are added into airworthiness certification to help the aircraft structure design judge whether the structure is penetrated or not and whether the structural strength requirements of bird strike are subjective to high load to further improve the aircraft structure bird strike airworthiness design, as well as supplementary support for bird-strike airworthiness verification.

4.1 Bird-strike structure penetration criteria

According to the long-term design and test results [7], the bird-strike penetration speed at the leading edge of the wing is calculated as follows:

$$V_p = f \cdot 56.7\delta M^{-1/3} sin^{-2/3}\theta exp\frac{850}{r^2+30r+1000} \quad (1)$$

In Eq. 1, V_p is the penetration speed, unit: m/s;

θis the incident angle, unit: ^{0};

φis the sweep angle of the leading edge, unit: ^{0}; $\theta = 90^0 - \varphi$;

r is the radius of the leading edge, unit: mm;

δ is the equivalent thickness of the leading edge skin, unit: mm;

M is the bird’s mass;

f is the correction factor. If the material of the structure is metal (e. g. Aluminiun), f=1.0.

Generally, the definition of this formula is concluded, based on the previous metal leading edge of a number of bird impact tests.If it is the composite leading edge, then it also needs a large number of tests to obtain the corresponding correction coefficient in Equation 1.

According to Eq. 1, in the early design without simulation and test data, the quantitative value of the design thickness of the structural skin can be preliminarily estimated as a reference.

According to the long-term design and test results, the bird-strike penetration speed for the windshield is calculated as follows:

$$V_p = \sqrt{K\delta^b/(\alpha sin\theta)} \quad (2)$$

In Eq. 2, V_p is the penetration speed, unit: m/s ;

θ is the incident angle, unit: ^{0} ;

δ is the equivalent thickness of the windshield, unit: mm ;

K, b and αare related to the properties of the material. For the glass material,

K=107~300, according to the quenching temperature, and b=1.5. αis taken from the test.

4.2 Ultimate load of a bird strike

With the difference of the flight height and speed, the relative speed of impact between the bird and aircraft is from about 70m /s to 450m/s. The impact process is very complex in milliseconds, and the aircraft structures have to bear a large impact load. Three empirical formulas are used here.

1) The first empirical formula [8] of the average impact force of the bird is given in Eq. 3.

$$F_{av} = \frac{11.625 m^{2/3} V^2 \sin\theta}{2 + ctg\theta}$$

(3)

Where F_{av} the average impact is force of the bird; m is the mass of the bird; V is the relative speed of the bird and the plane; θ is the angle between the velocity and the impact surface.

2) According to the research findings [9] and the selected shape parameters of the bird body, the parameters of the impact process are shown in Figure 2.

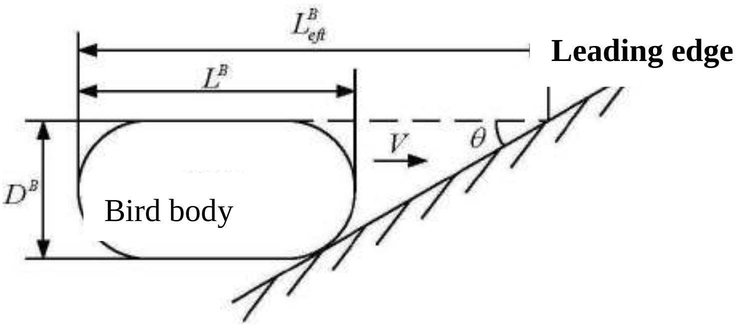

Fig. 2 The leading edge model of oblique impact

The load waveform of oblique impact increases gradually from zero to the peak and then decreases from the peak to zero. The rising time of the peak load is generally 0.2 times of the whole impact cycle. Therefore, the impact load on the rigid target is the triangular wave load (as shown in Fig. 3), and its load calculation formula is listed in Eq. 4. Equation 5 represents that the load changes with time. Equation 6 is involved in how to calculate the total impact time.

$$F_{\max} = 2M \cdot V \cdot \sin\theta / T \quad (4)$$

$$F(t) = \begin{cases} 5F_{\max} \cdot \dfrac{t}{T} & 0 \le t \le 0.2T \\ \dfrac{5}{4}F_{\max} \cdot (1 - \dfrac{t}{T}) & 0.2T < t < T \end{cases} \quad (5)$$

$$T = (L^B + D^B / tg\theta) / V \quad (6)$$

Where $F_{\max}$ is the peak load; M is the mass of the bird body; V is the velocity of the bird; L^B is the length of the bird; D^B is the diameter of the bird; θ is the impact Angle.

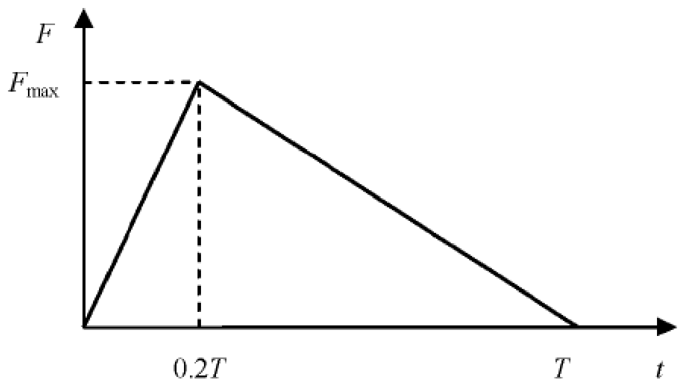

Fig. 3 The triangular wave load

According to the conservation of total impact energy, the formula for the peak impact load is obtained in Eq. 7.

$$F_{\max} = \frac{2M \cdot V^2 \cdot \sin\theta}{(12M / 5\pi\rho)^{1/3}(1.5 + \dfrac{1+\cos\theta}{2\sin\theta})} \quad (7)$$

3) If we suppose the impact collision is ideal rigid, the contact time (T) is defined as Eq. 8.

T=L/V （8）

The average load and the peak load are listed in Eqs. 9 and 10.

$F_{av} = M \cdot V / T$ (9)

$F_{max} = 2M \cdot V / T$ (10)

From the above formula, we can see that the last formula (Eq. 10) is the most conservative. The quantitative value of bird impact limit load in this section is used to check the static strength of the structure.

4.3 Numerical simulation analysis of bird strike

The numerical simulation of bird strike mainly includes modeling, determination of bird mass and bird impact velocity of each component, model verification, selection of impact point, dynamic response analysis, and selection of weak parts of bird impact.

4.4 Structural safety analysis

According to the response results of bird strike, the damage tolerance (discrete source) assessment method is adopted to conduct a structural safety analysis of the bird strike site, which must meet the requirements of the corresponding static strength loading conditions stipulated in 25.571 (e).

4.5 System security analysis

The system safety analysis focuses on the risk of flight control, hydraulic and power system damage caused by bird strike, or loss of aircraft control due to pilot injury. A dangerous situation in which the landing gear control system is damaged due to a bird strike is that the aircraft cannot land safely. A fire is induced by a fuel leak caused by a bird strike.

4.6 Test verification

The test verification includes the determination of the bird-strike test site, the criterion of the bird strike test qualification, and the preparation of the test assignment. Firstly, the selected bird-impact point should be the relatively dangerous part of the corresponding component and the part with the highest frequency in similar aircraft bird-strike accidents to verify the correctness of the analysis results of bird-strike responses. Second, according to the overall layout of the bird-strike site and the requirements of bird-impact airworthiness, combined with the safety analysis results of the aircraft structure and system, the test specification and test outline are provided with the test eligibility criteria (such as whether the structure is allowed to break down or the maximum allowable deformation of the structure, etc.). Finally, the program of bird-strike tests for each component is prepared, the verification of bird-strike tests is carried out, the test report is prepared, and the test results are comprehensively evaluated.

4.7 Comprehensive evaluation

According to the results of bird-strike response analysis, structural safety analysis, system safety analysis, and evaluation of the bird-strike test, the validation of bird strike airworthiness compliance is comprehensively evaluated, and the comprehensive evaluation conclusion is given. In case of a discrepancy between the theoretical analysis results and the experimental results, the experimental data shall prevail.

5. Summary

Bird strikes are inevitable. With the increase of the bird population and the development of the aviation industry, birds will pose a big threat to the aviation industry. Research on bird strike airworthiness documents is carried out in a comprehensive way to learn from the content of mature airworthiness provisions in foreign countries and understand the ideas and basis of their formulation. This paper studies and analyzes the contents, ideas, and basis of the mature airworthiness clauses in foreign countries, which lays a foundation for the formulation of the requirements of bird strike airworthiness under the operating environment of China.

To meet the requirements of bird-strike airworthiness regulations, this paper explains the design requirements of bird-strike damage, airworthiness design, and compliance verification of transport aircraft. In this paper, the empirical formulas of bird impact penetration and bird-strike limit load are added to airworthiness certification for preliminary evaluation of aircraft structure design and airworthiness compliance design, which can reduce the number of bird-strike simulation analysis and bird-strike tests, and provide the thickness of the leading-edge skin for the validation of airworthiness compliance of transport aircraft.

Conflict of Interest: The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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