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Development of parametric criteria for assessing aircraft damage in a collision with birds

U. V. Esipov, E. A. Bochkova, A. Yu. Medvedev

Don State Technical University (Rostov-on-Don, Russian Federation)

Introduction. Taking into account the relevance of aviation incidents that occur as a result of strikes (collisions) with birds entering the flight zone of an aircraft (AV) and a posteriori analysis of these events, the article considers and tests parametric models and criteria for the implementation of accidents.

Problem Statement. Based on the well-known fuzzy parametric model "load p – carrying capacity σ", the problem of finding a possible (fuzzy) measure of damage to the aircraft and (or) the pilot in a collision with birds with varying mass and speed of the bird, as well as the area and duration of contact on impact is posed. The results of its solution are aimed at justifying the ornithological safety of flights by developing proactive actions to scare away and avoid areas of bird congestion both during takeoff and landing, and on the route of the vessel.

Theoretical Part. To describe and evaluate the following events (outcomes): 1) damage; 2) destruction; 3) fall of the aircraft, the well-known mechanical criterion of exceeding the load over the load-bearing capacity was applied. At the same time, the parameters of the load p and the carrying capacity σ were described as fuzzy values, which allowed us to find the values of the probability measure (as a subjective probability) of the implementation of outcomes in conditions of even insufficient statistics. The load parameter is represented as amplitude pressure pulse during impact and the collision of birds with an aircraft as a function of calculating the variation of the mass of birds, speed of mutual rapprochement of the bird and the ship, the duration of the impact and the area of contact of the bird with the vessel: $p=mv/(\Delta t\cdot\zeta)$ (scientific results 1). Based on the data obtained on the values of cores and fuzzy intervals of load capacity, as well as data on the values of cores and fuzzy intervals of the pressure amplitude in the impact, a possible measure of each of the accident outcomes was calculated (scientific result 2).

Conclusion. When a bird strikes with a mass of at least 1 kg and at a mutual speed equal to or greater than 50 m/s, the destruction of the fuselage will occur with a probability measure of 1.0, and when the pilot is exposed to the fuselage fragments, it may hurt him and the ship may fall. With the help of the obtained scientific results, a unified and reliable insurance basis for the ornithological flight risk is achievable.

Keywords: demage, collision, accident, safety of flights, aircraft.

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Introduction. Taking into account the relevance and public response of aviation accidents [1, 2], which often occur as a result of strikes (collisions) with birds (bird strikes), in the aircraft operating zone [3], a posteriori analysis of these events [2, 4, 5], as well as taking into account the formation of research on ornithological safety [5, 6], the article considers and tests the criteria for the outcome of accidents based on the parametric model "load — weakening — load-bearing capacity" [7-9]. Most often, bird strikes occur at low altitudes during takeoff and landing in the daytime. In Russia alone, there are about 7,000 cases a year. The speed of flight of birds is quite high for having not enough time to react in time to an approaching airliner at low altitudes. It is known that the flight speed of quails reaches 40 km/h, gulls — 60 km/h, starlings — 80 km/h, crows — 90 km/h, ducks — 120 km/h, Golden eagles — 130 km/h, swifts — 160 km/h. The risk of a bird strike depending on the bird's altitude is [1]: if the altitude is up to 100 m — 45.8 %, up to 101-

400 m — 28 %, 401-1000 m — 12.7 %, 1001-2000 m — 7.5 %, 2001-5000 m — 5.2 %, over 5000 m — 0.8 %. According to Rostransnadzor statistics, until 2008, on average in Russia there were 1.2-1.5 bird strikes of aircraft with birds for every 100 thousand flight hours, and starting from 2018, this figure is already equal to 3 (for every 100 thousand flight hours). During 2008-2018, the following situation in the field of ornithological danger was observed [1]: 2008 — 93 bird strikes with an aircraft; 2009 — 85 bird strikes; 2010 — 54 bird strikes; 2011 — 43 bird strikes; 2012 — 32 bird strikes; 2013 — 43 bird strikes; 2014 — 69 bird strikes; 2015 — 53 bird strikes; 2016 — 72 bird strikes; 2017 — 45 bird strikes; 2018 — 55 bird strikes. Statistical analysis revealed 3 main types of bird strikes with parts of the aircraft: with the engine — 43 %, with the fuselage — 27 %, bents and deformation of the fuselage — 30 %.

Since 2001, the Russian Federation has developed deterministic models and programs for calculating [3-5] damage to the ship and its parts. However, well-known models for calculating the risk and probability of accidents do not allow explicitly taking into account such characteristics of the situation in the "bird — air environment — aircraft" system as: the mass and speed of the bird, the area and duration of contact during impact.

Problem Statement. Based on the well-known fuzzy parametric model "load p — load-bearing capacity σ" [7,9], the problem of finding a possible (fuzzy) measure of damage to the aircraft and (or) the pilot in a bird strike with varying mass and speed of the bird, as well as the area and duration of contact on impact is posed. The results of its solution are aimed at justifying the ornithological safety of flights by developing proactive actions to scare away and avoid areas of bird congestion both during takeoff and landing, and on the route of the aircraft.

Theoretical Part. The parametric model "impact (load) — shield attenuation — load-bearing capacity (susceptibility)" is used as the basis for quantitative assessment of the accident [7, 8]. Based on the analysis of accidents that occur when birds and aircraft collide, it is possible to identify the most likely events such as damage, destruction, or fall of an aircraft. To describe and evaluate these events, the well-known mechanical criterion for exceeding the load p over the load-bearing carrying capacity σ [9.10] is applied. Moreover, in the first approximation, the load and load-bearing capacity are considered as fuzzy values [8], which allows us to find the values of the probability measure (as a subjective probability) of the outcome in conditions of even insufficient statistics [7].

Using the condition that the force pulse of a frontal impact is equal to the instantaneous value of the amount of mutual movement in the system "a bird with mass m — an aircraft with speed v", the load parameter is represented as the amplitude of the pressure pulse when a bird strikes and collides with an aircraft [8]

$$p = F/\zeta = mv/(\Delta t \cdot \zeta), \quad (1)$$

where m — is the mass of the birds; v — closing speed of birds and aircraft; Δt — duration of impact; ζ — the area of contact of birds with the aircraft, F — force of the strike.

In fracture mechanics, the load-bearing capacity is most often assumed to be the stress corresponding to an irrevocable change in the shape of the structure, the beginning of flow or the formation of cracks [10]. In this work, the load-bearing capacity of the ship's fuselage was established as follows. According to the International Civil Aviation Organization, ornithological flight safety is based on the establishment of requirements for the load-bearing capacity of cockpit windows in the form of limit levels of the amount of movement on impact. In particular, the fuselage of an airplane or helicopter must withstand a bird strike of 0.9 kg at a speed of 50 m/s and 1.15 kg at a speed of 45 m/s [5, p.71], which is consistent with the expression (1) for the following values: $\Delta t = 0.01$ s and $\zeta = 10^{-1}$ m^2. This corresponds to the range of values of the mechanical stress of the beginning of destruction of the fuselage material 40-50 kPa.

Under the assumption of fuzzy parameters p and σ, a possible measure of the implementation of a parametric criterion describing damage is found from the expression [8]:

$$\pi_1 = Pos\,(p \geq \sigma_1),$$

where *Pos* (•) — *Possibility* operator[7, 9].

In the first approximation, assuming a linear approximation of the fuzzy parameters p and σ_1 (in the least informative variant of obtaining them), the following dependencies are used to calculate the probability measure [7, 9]:

$$\pi^L_i = 1 - \overline{zb}, \tag{2}$$

where $\overline{zb}$ — reduced parametric safety margin":

$$\overline{zb} = (\overline{\sigma} - \overline{p})/(\Delta_r+\Delta_s). \tag{3}$$

Here $\overline{\sigma}$ and $\overline{p}$ — are the "cores" of the fuzzy parameters of load-bearing capacity σ_1 and load p respectively; Δ_σ and Δ_p — are the "blurring intervals" of the fuzzy parameters of load-bearing capacity σ_1 and load p (рис. 1).

To generalize parametric modeling and quantify any event, a dimensionless representation of vertex outcomes is used based on a trapezoidal approximation of the load membership functions $\mu(s = p)$ and the load-bearing capacity $\mu(r = \sigma_1$ or $r = \sigma_2$ or $r = \sigma_3)$ (see Fig. 1) [9]. This means that the load-bearing capacity of the body, fuselage, and the aircraft itself is expressed as a"ruler" of the values of critical stresses σ_1, σ_2, σ_3 and their membership functions: $\mu(r = \sigma_1$ or $r = \sigma_2$ or $r = \sigma_3)$.

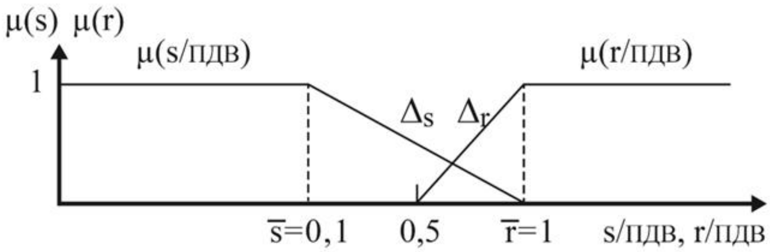

Fig. 1. Fuzzy dimensionless unified parametric model of vertex outcomes based on a trapezoidal approximation of the load membership functions $\mu(s = p)$ and the load-bearing capacity: $\mu(r = \sigma_1$ or $r = \sigma_2$ or $r = \sigma_3)$

We include the following in the vertex outcomes of the impact of birds on an aircraft:

1. VO1 — damage (deformation) of the body and (or) elements of the aircraft, parametric criterion:

$$p \geq \sigma_1,$$

where p is the area of possible change in the amplitude of the pressure pulse at impact, Pa; σ_1 is the minimum mechanical stress, Pa, or, in general, the area of change in the load-bearing capacity, which determines the damage (deformation) that affects the flight of the aircraft.

2. VO2 — destruction of the fuselage, leading to depressurization and (or) loss of the pilot's ability to continue flying, parametric criterion:

$$p \geq \sigma_2,$$

where σ_2 is the mechanical stress of the beginning of destruction of the fuselage material, which affects the pilot as a mechanical factor (formation of fragments of destruction and the impact of fragments on the pilot) and a chemical factor (depressurization).

3. VO3 — fall of the aircraft and (or) death of the pilot, parametric criterion:

$$p \geq \sigma_3,$$

where σ_3 — mechanical stress breakdown of the fuselage material, affecting the pilot, the aircraft's control system and leading to its fall.

For the assessment, we use a "three-level" representation of the membership functions in the form of an "assembly" of the aircraft's load-bearing capacity parameters, which describes the effect of increasing danger and the occurrence of vertex outcomes VO1, VO2 and VO3 with increasing loading, taking into account monotony. Based on the analysis of experimental and calculated data [1, 5, 8, 10], the following values of cores and blurring intervals of the load-bearing capacity parameters are obtained:

$$\sigma_1 = [1, 10] \text{ кПа}; \ \bar{\sigma}_1 = 10 \text{ кПа}; \ \Delta_{\sigma 1} = 5 \text{ кПа};$$
$$\sigma_2 = [40, 50] \text{ кПа}; \ \bar{\sigma}_2 = 50 \text{ кПа}; \ \Delta_{\sigma 2} = 10 \text{ кПа}; \quad (4)$$
$$\sigma_3 \geq 1000 \text{ кПа} \ \ \bar{\sigma}_3 = 1000 \text{ кПа}; \ \Delta_{\sigma 3} = 100 \text{ кПа}.$$

For these load-bearing capacity ranges, taking into account changes in the bird speed in the range of 40-60 m/s and the mass of 1-3 kg, as well as data on the duration and area of impact contact [2, 4, 5] in the ranges of 0.01–0.03 s and 0.05–0.1 m^{-2}, respectively, the following significant areas of change were selected and the amplitudes of the pressure pulse in the impact were calculated (Table 1).

Table 1

Calculated values of the amplitude of the pressure pulse of birds hitting the aircraft, $p = p(m, v, \Delta t, \zeta)$, kPa

Bird weight m, kg	Impact duration Δt, s		
	0.01	0.02	0.03
	Contact area $\zeta \cdot 10^{-1}$, m^2		
	0.5–1.0	0.7–1.0	0.8–1.0
	Velocity v, m/s		
	40	50	60
	$p = p(m, v, \Delta t, \zeta)$, kPa		
1.0	40–80	25–35.6	20–25
3.0	120–240	35.6–108	60–75

Based on the data on the values of cores and fuzzy load-bearing capacity intervals, as well as calculated data on the values of cores and fuzzy load intervals in the form of the pressure amplitude at the impact, the calculation of the possible measure of the outcomes VO1, VO2 and VO3 was performed using formulas (3) and (4) (Table 2).

Table 2

Source data on parametric models of vertex outcomes and calculated values of possible measures for their implementation

Vertex outcome	Possible measures	Calculated pressure impulse at impact, kPa $[\bar{p}_i, \ \bar{p}_i + \Delta_{\bar{p}i}]$	Lower limit of load-bearing capacity, kPa $[\bar{\sigma}_i - \Delta_i, \ \bar{\sigma}_i]$
VO 1	$\pi_1 = 0.5$	20–25	15–30
VO 2	$\pi_{21} = 0.297$	25–35.6	40–50
	$\pi_{22} = 1.0$	40–80	
VO3	$\pi_{31} = 0.051$	35.6–108	100–1500
	$\pi_{32} = 0{,}173$	120–240	

As follows from Table 2, the deformation of the body with the possibility measure $\pi_1 = 0.5$ will occur when it collides with a bird weighing 1 kg or more. When the area increases and the contact duration decreases when the aluminum wall is hit, there is no destruction in this range of speed and mass.

Here is an example of calculating the possibility measure for the outcome VO2, taking into account the data in Table. 2.

$\pi_{21} = 1 - (\bar{\sigma} - \bar{p})/(\Delta_r + \Delta_s) = 1 - (50 - 35{,}6) / (10 + 10{,}6) = 0{,}297$.

Taking into account the accepted boundary conditions, we find a possible measure:

π_{22} = 1 – (50 – 80) = 1,0.

Based on the data in Tables 1 and 2, the following conclusions can be drawn:

1. Destruction of the fuselage during the collision with a bird weighing equal to or more than 1 kg, at a speed equal to and more than 40 m/s, when the contact area is not more than 0.05 m^2 happens according to the possibility measure π_{21} = 0.3.

2. If the strike is stronger with the mass of birds over 1 kg and at a speed over 50 m/s the destruction of the fuselage happens according to the possibility measure π_{22} = 1.0. In addition, the effects of fuselage fragments at the pilot may cause air crash.

3. Fall of the aircraft and (or) death of the pilot will occur with the probability measure π31 = 0.051 when the body of the aircraft collides with a bird of mass equal to or more than 3 kg at a speed of 50 m/s and a contact area of 0.07 m^2 or less. When a bird strikes the body of the aircraft with a pressure pulse in the range of 120-240 kPa, the fall of the aircraft or the death of the pilot will occur with the probability measure π_{31} = 0.173.

Conclusion:

1. Based on the fuzzy parametric model "load p — load-bearing capacity σ", the problem of finding a possible (fuzzy) measure of damage to the aircraft is formulated and solved.

2. An analytical expression is proposed and tested of the load parameter in the form of the amplitude of the pressure impact on the ship as a function of the mass of birds, closing speed of the bird and the ship, as well as duration and contact area of the bird with the ship.

3. Taking into account the requirements of the International Civil Aviation Organization the load-bearing capacity of the cockpit windows was expressed as a fuzzy value of the mechanical stress of the beginning of the destruction of the material of the fuselage housing, the load-bearing capacity of the fuselage of the ship expressed as a range of values of critical stresses σ1, σ2, σ3 and their membership functions.

4. The authors have obtained possibility measures values as subjective probabilities for the lack of damage to the body, destruction of the fuselage and the aircraft falling in the range of 0. 051–1.0 in the collision with a bird weighing up to 3 kg and in the speed range of their closing speed up to 60 m/s.

5. When a bird strikes the body of an aluminum aircraft with a pressure pulse in the range of 120-240 kPa, the fall of the aircraft or the death of the pilot will occur with the probability measure of 0.173 and this approximately means the implementation of one of the five outcomes.

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Information about the authors:

Esipov, Yuriy V., Professor, Department of Life Safety and Environmental Protection, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344000, RF), Dr. Sci., Professor, ORCID: https://orcid.org/0000-0001-6018-5391, bulyur_rostov@mail.ru

Bochkova, Ekaterina A., Post-graduate student, Department of Life Safety and Environmental Protection, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344000, RF), ORCID:https://orcid.org/0000-0001-7989-2459, Bochkova.ekaterina2014@gmail.com

Medvedev, Aleksandr Yu., Master's degree student, Department of Life Safety and Environmental Protection, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344000, RF), ORCID: https://orcid.org/0000-0003-0758-9332, aleks.barsik@mail.ru

Contribution of the authors:

Yu. V. Esipov — scientific supervision, formulation of the research concept, obtaining and editing scientific results; E. A. Bochkova — literary analysis, preparation of scientific result 2, editing the text; A. Yu. Medvedev — collection and analysis of literary data, participation in the development of scientific results 1 and 2.