INTERNATIONAL JOURNAL OF AUTOMOTIVE SCIENCE AND TECHNOLOGY

2023, VOL. VOL. 7, NO: 2, 95-103 www.ijastech.org e-ISSN: 2587-0963

Experimental and Numerical Approach on Bird Strike: A Review

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Abstract

Bird strikes are one of the biggest threats to flight safety in aviation. Bird strikes occur in every 2000 flights. In addition, factors such as the increase in the number of flights in the globalizing world and the migration status of birds play a role in the increase of these cases. 90% of foreign body damage in aviation is caused by bird strikes. In 15% of bird strikes, the aircraft is seriously damaged. In the event of a bird strike, the most critical parts of the aircraft are the nose, windshield, engine, inlet, wing front edges. Bird strikes usually occur during the landing and take-off moments of the aircraft. Aircraft components must have a certain durability to minimize damage for flight safety. Criteria for critical parts are set in aviation regulations. To meet these criteria, aircraft components must successfully complete bird strike certification tests prior to flight. Due to the cost of physical tests, analyzes based on numerical simulations are carried out in parallel with certification tests. The purpose of this analysis is to predict the damage to the aircraft by the verified bird model, to make changes to the aircraft component design and material when necessary, and to reduce the cost. Bird model is considered as hydrodynamic with length-to-diameter ratio of 2. According to the studies in the literature, the modeled bird weight varies between 1kg and 4kg depending on the bird species. Bird model density is determined as 940kg/m3 - 960kg/m3 according to bird species. The error rate of the results obtained from the techniques used in determining the bird strike impact modeling methodology varies between 2% and 4%. In this review, the theoretical background of the bird strike problem, finite element analysis (model bird materials, bird modeling methods, bird geometry) and tests in the relevant literature will be discussed.

Keywords: Bird Strikes, Aircraft, Fight safety, Crash

Research Article
https://doi.org/10.30939/ijastech..1293572

Received 06.05.2023
Revised 29.05.2023
Accepted 31.05.2023

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1. Introduction

The term bird strike, in its most general definition, is a crash between birds and aircraft, particularly conventional take-off and landing (CTOL) aircraft [1]. The term is also used for birds crashing into power lines, wind turbines, automobiles, and other means of transportation. Although bird strike is only one of many known causes of aviation accidents, it is among the most dangerous accidents in terms of flight safety [2]. About 90% of various foreign body damage (FOD) to aircraft structures is caused by bird strikes [3]. Another reason why bird strike accidents come to the fore is the frequent occurrence of these accidents. Khan et al. stated that according to records, a bird strike occurs approximately every 2,000 flights [4].

These accidents, defined as bird strikes in aviation, started with the invention of motorized aircraft. The first recorded bird strike occurred in 1905 while Orville Wright was flying over a cornfield in Ohio [5]. Documents containing statistical data on human, product and monetary losses caused by bird strikes in military and commercial aviation are published every year. Based on the statistical data in the literature, we can deduce that bird strikes have increased year by year. This situation can be explained by the increase in the number of flights with globalization, the spread of bird populations around the world and the migration status of birds [6]. In the United States, for example, 11,666 bird strike cases were recorded by the Federal Aviation Administration (FAA) in 2020. This number increased by 33 percent in one year and 15,556 bird strike cases were recorded in 2021. According to the document published in 2022, it was stated that the annual cost of bird strikes to the US civil aviation industry in 2021 was 139,469 hours of aircraft downtime and approximately $328 million in financial losses. This cost is estimated to exceed $1 billion annually worldwide. These financial losses include damage, repair, and operational losses of decommissioned aircraft [6]. A typical case of bird strike is shown in Figure 1.

Fig 1 Typical bird-strike event scenario

Aircraft carries the risk of encountering birds while cruising, taking off or landing [7]. While 95% of bird collisions in and around airports occur at the level of 1065 meters, 74% of these collisions occur at the level of 150 meters. Taking these data into consideration it can be stated that precautions for minimizing the risk of bird strikes should start directly from the airport and its surroundings. Within this context, the necessity of establishing an airport-specific wildlife management plan emerges [8].

Bird strike damage depends on the weight and density of bird, the area where bird strikes to the aircraft component, and structural features of that area. A bird weighing 1.8 kg can create an impact of about 17 tons when it crashes into an aircraft with a speed at 460 km/h, and about 45 tons when it crashes into an aircraft with a speed of at 740 km/h [8-9]. The force of hitting the aircraft varies depending on the speed and weight of the impacting object and the direction of the collision. The impact energy is related to the square of the difference between the bird speed and the aircraft speed. For this reason, bird and aircraft speeds are important in terms of damage. However, high-speed collisions cause significant property damage as well as fatal accidents. Therefore, certain parts critical to flight safety, such as the engines, wing leading edges, and cockpit area, must continue to function to ensure a safe flight after one or more bird strikes. According to the FAA, the rate of material damage to aircraft components from bird strikes is only 15%. [10].

The damage rates to the components of the aircraft as a result of bird strikes are shown in Figure 2.

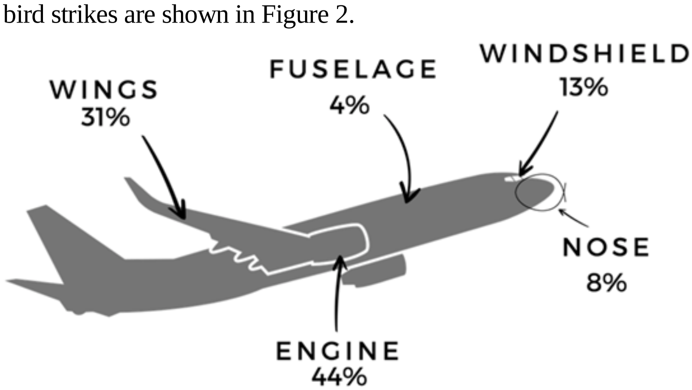

Fig. 1 Aircraft components subject to bird strike

Upon understanding that the bird strike problem has such great importance in aviation, various inspection organizations such as the American Federal Aviation Administration (FAA), the European Aviation Safety Agency (EASA), and the International Civil Aviation Organization (ICAO) took steps to inspect companies producing for the aviation industry with standards and regulations. In addition, these control mechanisms check the approval of products by completing the necessary tests before they are put into use [11].

In the past, when computer simulation capabilities were not as advanced as they are today, the only option was to create and test a bird-safe design of aircraft components, then redesign and retest it [12]. The unnecessary cost of full-scale testing and the need for retesting in cases such as design changes have led to the use of computer aided analysis studies. With advanced computer and software technologies, complex and higher-order nonlinear problems can be modeled. With the help of numerical design and analysis, it is aimed to simulate the collision event that occurs in a very short time and to design the components that may be exposed to bird strikes in accordance with this situation, thus reducing the test costs. Today, it is increasingly possible to replace certification tests of aircraft structures with verified simulations of bird strikes. These developments contribute to companies both in terms of cost and time. However, bird model validation is still an issue due to differences between analytical solutions and experimental data [13].

This review article aims to present the computational procedures and different bird model setups used in bird strikes through a literature review. First, some information will be shared about the hydrodynamic foundations for numerical bird modeling, the representative bird materials used, and the experimental data already obtained for bird model validations. Then, different numerical methods developed for bird modeling and the numerical differences between them will be presented. Bird strikes are characterized by high-intensity and short-term loading. Materials are subject to non-elastic strains and large deformations due to high strain rates. The elastic-plastic behavior observed in the product material allows us to interpret the interaction between the bird and the target. In finite element software, various approaches have been used to construct the bird model in case of impact. These are referred to as Lagrange, ALE, and SPH approaches. The article will highlight the advantages, disadvantages, and reasons for applying these methods. Additional topics such as appropriate projectile geometry, material selection, and the contact algorithm between the projectile and structure will also be covered.

2. Theoretical Background

The bird strike case can be evaluated as a hydrodynamic collision based on studies in the literature. The moment of collision takes place in the order of microseconds. Considering the structural features of the projectile during impact, the collision can be evaluated in four main stages: elastic, plastic, hydrodynamic and sonic [14].

In elastic collisions, the material strength is higher than the internal stresses occurring in the impacting element, and the structure of the material can withstand the stresses in such collisions. In the category where the plastic collision occurred, internal stresses increased with the increasing collision speed. The strength of the material is now close to the fluid-like phase and can withstand internal stresses of material. With the increase in the collision speed, the hydrodynamic collision phase starts and the internal stresses in this phase exceed the residual material strength, causing the material to behave like a fluid. At this collision speed, the material strength does not determine the collision response, but rather the material density. In high-velocity shooting tests, it can be observed that real birds exhibit flow behavior as if they were in fluid-like form. In this phase, the bird is considered a "soft body" at the respective speeds as the stresses occurring in the bird are much higher than its own strength. Towards the end of the collision, as the collision speed increases, the forces that can hold the material together become very high and the object now shows fragmentation behavior [12].

At the moment of the impact, four main phases which are shown in Figure 3 appear on the object: (a) initial shock at contact, (b) impact shock decay, (c) steady flow and (d) pressure decay [14-15].

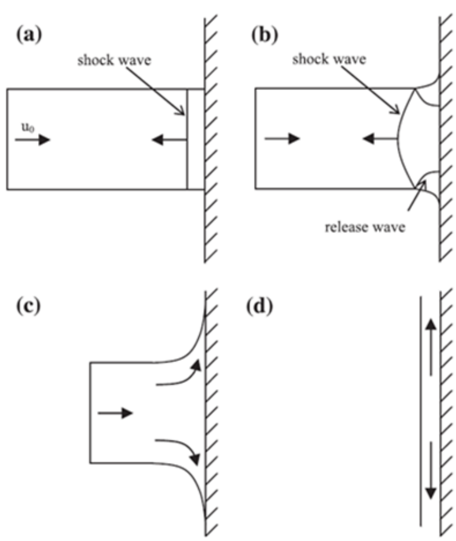

Fig. 2 Schematic of shock and release wave diagram in soft body impactor

The moment of impact, the load exhibits a behavior of spreading over a wide area. A shock wave is formed inside the object parallel to the crash surface and propagates along the object. While a shock wave is formed due to high pressure on one side of the object, the presence of a free zone on the other side causes the surface of the object to be exposed to pressure and the object to begin to spread from this side. With the formation of this propagation wave, the pressure value tends to decrease significantly. After the pressure value reaches its maximum level within microseconds before the propagating wave, it goes into the phase of decreasing towards smooth flow behavior with this propagating wave. The peak at which the pressure reaches its maximum value is called the Hugoniot pressure [16]. The pressure curve is shown in Figure 4.

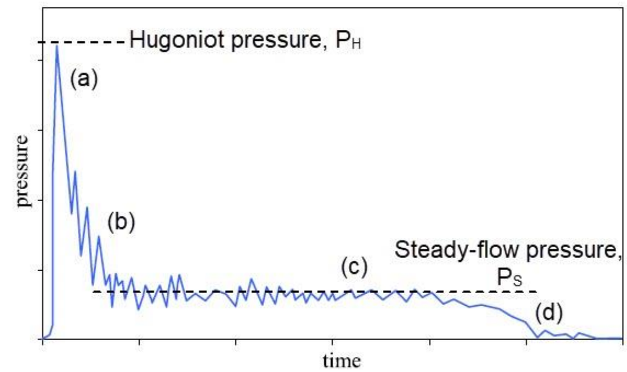

Fig. 3 Typical pressure curve for normal soft body impact on a rigid flat plate

Due to the response of the material strength to the shock wave and propagation wave, the pressure value fluctuates until it reaches smooth flow conditions. A continuous pressure drop is observed after smooth flow is achieved. Then the pressure value reaches zero. In this phase, the bird shows the flow behavior on its rigid plate.

The value of Hugoniot pressure P_H given by Eq. (1), varies according to the shock wave velocity v_s, the initial velocity v_0, and the density of the material that has passed into the fluid-like phase ρ_0 [17-19].

$$P_H = \rho_0 u_0 u_s \tag{1}$$

The steady-flow pressure P_s given by Eq. (2), can be determined using Bernoulli relationship. P_s is related to the density of the fluid-like material ρ_0 and the initial velocity v_0.

$$P_s = \frac{1}{2} \rho_0 u_0^2 \tag{2}$$

The total duration of the impact t_D given by Eq. (3) is related to the length of the impacted object L and the initial velocity u_0.

$$t_D = \frac{L}{u_0} \tag{3}$$

3. Substitute Bird Material and Geometry

A part produced in the aviation industry must meet the specified certification process criteria in bird strike tests. For bird strike certification tests, the birds that will crash into aircraft components must be real birds. Conversely, the substitution bird is more suitable for experimental studies and non-certification testing. Since the materials are not homogeneous in each bird, different impact loads may occur. When designing the bird model, it should be taken into account that fluid densities may differ between bird species [20]. Bird strike data from real bird tests should also be available from an artificial bird model. In addition, the use of real birds in the tests caused hygiene problems, which led to the search for ways to use artificial birds in the preliminary certification processes [21].

For accurate data flow in bird strike certification tests, numerical modeling of bird geometry must be accurate. In this modeling process, the bird's material and geometry is selected. Although the artificial bird and the real bird do not have to have exactly the same characteristics, they must have the same pressure load at the time of impact. The modeled bird should be designed for this aim [22].

The artificial bird used in experiments and numerical analysis have a geometry that represents a simplified bird body, such as a cylinder, hemispherical cylinder, ellipsoid, or spherical [23]. The bird models are shown in Figure 5. Stoll and Brockman stated that the most accurate and common technique used in bird modeling is the hemispherical cylinder model [24]. Many studies in literature have referenced the hemispherical cylinder model in bird modelling [25-27]. Kalam et al. analyzed their impact on the plate using four different bird models with an arc weight of 1.82 kg and a diameter-to-length ratio of 0.5. In this study, theoretical and analysis results were evaluated. More similarity was observed between the theoretical and the analysis results of the hemispherical cylinder model [28]. Hedayati and Rad numerically investigated the effect of a bird against a rigid flat plate [27]. First, they collected data from a hemispherical cylinder striking a rigid flat plate. Then, a numerical bird model was obtained using the data image created by scanning a real bird. The effect of voids in the bird's body are modeled using air-filled numerical bird model elements. According to the results obtained, it was seen that the maximum pressure reached by the non-porous bird model was lower than the porous model. Modeling the cavities with air-filled numerical bird model elements affected the results more accurately. This theory can be explained as the bird model porosity effect. Considering the experimental results, the porosity ratio of the bird model has a significant role in the bird strike event. The substitute bird material that researchers use in their experimental studies usually contains 90% water and 10% air [29-32]. Results from previous studies show that a bird model with only 10% porosity significantly overestimates Hugoniot pressures when compared to experimental results from a real bird. In Hedayati studies, the Hugoniot pressure of the 10% porous gelatin bird model has been shown to decrease by 50% compared to the Hugoniot pressure of the non-porous gelatin bird model [30]. According to Nizampatnam's studies, the porosity of the bird gel material needs to be increased in order to get a more realistic approximation of the Hugoniot pressures results observed in test data. According to the study, the relationship between the effect of impact loads and the porosity of the bird material was investigated and it was stated that the porosity of the bird gel material should be between 30% and 40%. Since gelatin material is a soft material with a specific gravity of water, it behaves similarly to bird stress, pressure distribution and disintegration upon impact. Therefore, gelatin material is commonly used in bird strike tests [12]. The volumetric strength values and impact loads of the gelatin material are computed from the equations of state [33].

4. Bird Model Validation

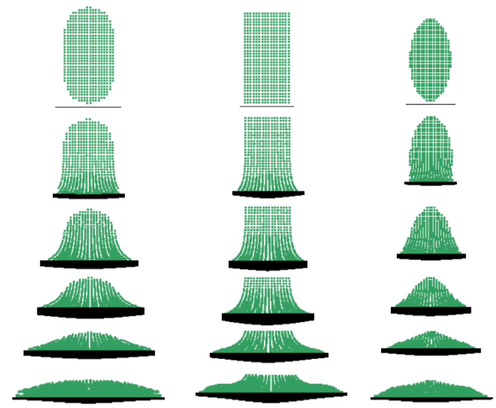

Fig. 4 Various geometries for the SPH bird model

Bird model verification is mandatory in order to perform numerical simulations of bird strikes on aircraft components. Experimental data are needed to validate the bird model. Accordingly, Lavoie investigated the bird strike problem with experimental test setup and simulation tools to validate the existing numerical model data [13][34]. In Wilbeck's experimental results, the pressure values caused by the bird striking a rigid flat plate were compared with a numerical method and the bird model was validated. A cannon is used to strike the projectile at the rigid plate. The cannon is connected to a high compressed pressure air reservoir. This compressed air can launch the projectile several hundred meters in milliseconds. [18][20].

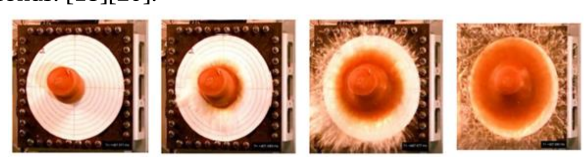

Fig. 5 Deformation of the projectile striking the rigid plate

Test facilities can observe different phases of the collision moment by using high-speed video cameras to examine changes in the target part over time [35]. Pressure and stress distribution on the part can be observed thanks to the pressure and strain gauges mounted on the target part. Tested products are measured and evaluated to determine their compliance with certification [36].

Bird model validation studies were limited in literature. For this reason, the authors referred to the study of Barber and Wilbeck in most of their publications on bird validation studies [37]. As part of these studies, Barber and Wilbeck mounted surface pressure transducers on a rigid flat plate and performed bird strike tests. They also observed how the weight and velocity differences of the bird models affected the pressure-time graphs. However, the pressure sensors used in the study were not suitable for transient impact loads and accordingly, a noise occurred in pressure-time data [18][38-39]. The distance between the cannon and the rigid plate has not been determined. In addition, there is no information about whether the geometry of the bird model preserves its geometric structure at the time of the crash. As a result, the collected data can inform about the behavior of projectile during bird strike. However, the data cannot be used as a reference for accurate results [18][40]. In later studies, it was observed that there was a similarity between the test data and the analysis results. [41-46].

5. Finite Element Modeling of Bird Strike

In experimental tests, geometric shapes representing the bird are used. The bird element modeled for finite element analysis should also have the same shape as the bird geometry used in the experimental tests. There are many studies investigating the effect of bird model geometry. Some geometric shapes used in bird model geometry have been accepted in the literature. These shapes are cylinder, the hemispherical end cylinder, ellipsoid and sphere. The effect of four projectile shapes on shock and steady flow pressure was investigated [12]. According to the results, numerical analysis data closest to the experimental data were obtained using hemispherical end cylinder geometry [47]. In Lavoie et al. study, a compressed air gun threw a 1 kg bird onto a rigid flat plate with 0.305×0.305 m2 area and 0.0127 m thick, and the bird came out of the barrel at a speed of 100 m/s. The speed of the thrown bird while contacting the rigid flat plate was read as 95 m/s. Thus, in the numerical study, the speed of the bird model was accepted as 95 m/s mass 1 kg and density 950 kg/m^3. The diameter of the hemispherical bird model is 93 mm and the model length is 2 times the diameter [34]. In these studies, similarity was observed between the experimental and numerical data.

Bird strikes occur when the speed of aircraft is high. From an analytical point of view, we define a bird crashing an airplane as a soft surface crashing a large, hard, strong surface. Soft-surfaced objects are easily deformed and tend to flow over the target they collide with. Therefore, the bird behaves like a fluid [48-49]. It has been observed that the artificial bird material data modeled by the finite element method is very similar to the experimental data. Since the deformation in the bird structure is excessively large, difficulties are encountered in finite element analysis solutions due to large mesh distortion. In the numerical analysis approach, there are ways to overcome this problem with both mesh-based and mesh-independent solution techniques. The most commonly used methods are Lagrange Method (LM), Euler Method (EM), Arbitrary Langrange-Euler Method (ALE) and Smoothed Particle Hydrodynamics Method (SPH) [13][34][50] which are shown in Figure 7.

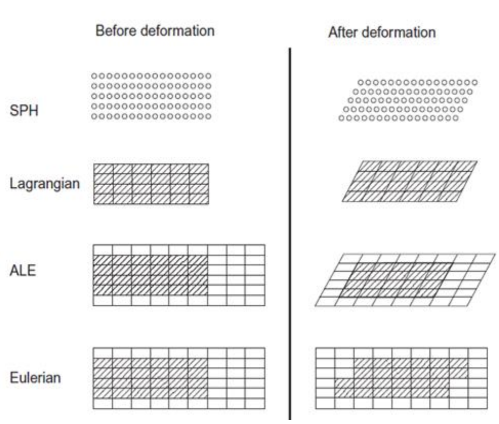

Fig. 7 Undeformed and deformed elements in different methods

The Lagrange method is mostly used in the analysis of solid objects. Each node corresponds to the material point that determines the position of the material during simulation. Therefore, mesh nodes move with the material. The Lagrange method approach is shown in Figure 8. Niering used the Lagrange method in the analysis of bird strikes on the engine fan blades and stated that the method did not meet the appropriate results [51]. Airoldi and Cacchione stated that the collision analysis data of the bird geometry modeled by the Lagrange solution method are similar with experimental data [47]. In some studies in the literature, researchers used the Lagrange solution method as a primary approach while creating bird model [20][52-54].

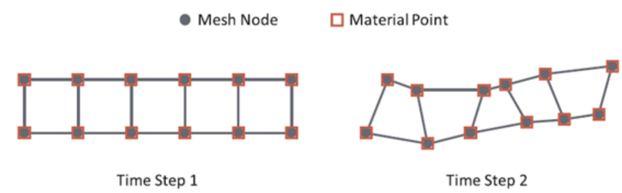

Fig. 8 Lagrangian elements description

The Euler method is mostly used in the analysis of fluid bodies. In the Euler method, mesh nodes are fixed in space, and the material points can travel in this mesh. The Euler method approach is shown in Figure 9. The Euler method yields good results in large-scale deformation problems, since the numerical mesh includes both the regions where the material is present and where it will be located in the future with the effect of motion. However, since the bird strike problem involves solid-fluid interaction, the Euler method alone cannot give the desired results [55]. In some studies in the literature, researchers used the Eulerian method as a standard approach while creating the bird model [56-57].

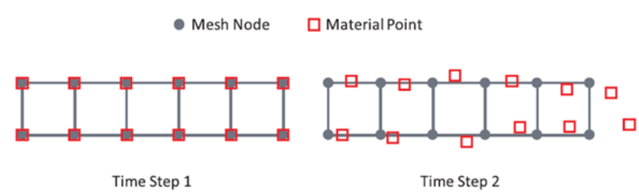

Fig. 9 Eulerian elements description

The ALE method is a combination of Lagrange and Euler approaches. In the ALE solution technique, the discretized reference volume can move or contract/expand to follow boundary movements. The position of the bird material is determined by comparing its position relative to the Euler mesh node [55]. The ALE method approach is shown in Figure 10. Some study in literature, researchers used the ALE method as a standard approach while creating the bird model [58-59].

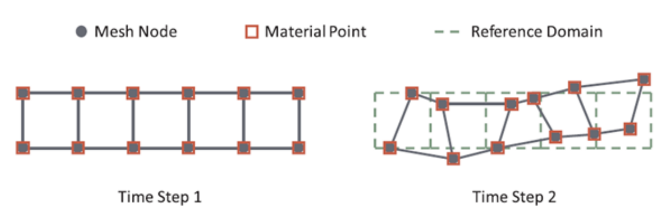

Fig. 7 Arbitrary Lagrangian Eulerian (ALE) elements description

The SPH method is a non-mesh Lagrangian technique. It is possible for a fluid material to be represented by several discrete particles interacting with each other. Each SPH element has a mass obtained by dividing the total density by the number of particles. The SPH element represents the hydrodynamic and thermodynamic properties of the fluid structure at its location [60]. In the definition of the SPH methodology, neighbor search procedure has great importance. This procedure evaluates how the two particles will interact with each other. The effect of the particle covered by the procedure is created within a sphere of radius $2h$, where h is the interpolation length. The interpolation length of each particle changes over time. As the particles are separated from each other, the interpolation length increases and as they get closer to each other, the interpolation length decreases at the same rate. A sufficient number of particles must be near the central particle to validate the approach of continuous environment variables [61-62]. The particle relationship is shown in Figure 11.

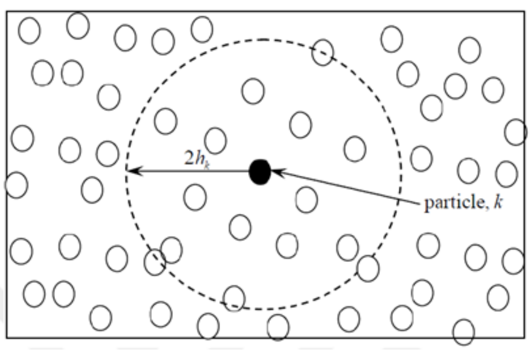

Fig. 8 SPH k-particle neighborhood

In particular, the large number of deformations that occur during the collision of the bird model prepared with the mesh-independent solution technique is best represented, and the closest results to the real conditions are approached. Unlike classical finite elements, the particle structure is used in the SPH method, not the mesh elements. The disadvantage of the SPH method is that the interparticle bond is calculated multiple times. In this method, the fluid is expressed as independent interacting particles. SPH particles have their own mass, velocity, and material strength. A particle interacts with particles neighboring it at a certain distance. In this method, the time step of the particles is very low and is constant throughout the fluid deformation [30]. The researchers tried to compare the numerical analysis they obtained using the SPH method with the data in the literature. As a result of this comparison, it was stated that appropriate data were obtained with the SPH method [63-69].

The contact algorithm is the definition of the relationship between the designed bird model and the target structure. This algorithm simulates the fluid-structure interaction at the time of contact. It also simulates the bird model deformations at impact and the movement of bird model elements/nodes over the target surface. The algorithm has been created based on the technique that preserves the energy at the time of collision [70].

6. Conclusions

Aircraft structures are faced with various problems and 90 % of all incidences are caused by foreign object damage such as bird strike.

Bird strikes are of great importance in the aviation industry as they seriously threaten flight safety. Improvements are still being made to understand the bird strike phenomena, identify its effects, and improve flight safety. A pioneering experimental study was performed by Wilbeck and Barber to observe and evaluate the pressure loads and flow behavior of a soft object striking a flat target. Based on the research study, new products or new processes were developed and optimized to better understand the behavior at the time of crash.

The bird strike event is a highly complex equation between the bird and the structure that takes place over a period of a few milliseconds. Since this interaction has a remarkably high energy, large deformations are observed in both the projectile and the target structure. Among other bird models, hemispherical bird geometry gives the most realistic results. When defining the equation of state, it should be taken into account that the bird shows fluid-like behavior when it crashes the target structure at high speed. Although different modeling techniques such as Lagrange, Euler, ALE, and SPH can be used in bird strike analysis, the SPH method gives the most realistic results, as stated in many studies. SPH method is used to simulate the flow behavior of the bird striking the target structure with hydrodynamic equations. Although the SPH technique is not used as a standard modeling technique in bird strike studies, it has been observed to be more compatible with experimental data than other approaches in the literature. However, companies still must perform physical tests in the certification processes of aircraft structures. The development of the SPH approach or the identification of a well-defined method in the bird strike scenario may result in the replacement of experimental testing by simulation techniques in certification processes.

The accuracy of bird verification tests is determined by launching artificial bird material at the target multiple times at different speeds [71-80].

Bird models give the most realistic results when the bird geometry has an aspect ratio of 2. It has been observed that this ratio gives the closest result in almost all reference studies.

In the studies in the literature, the use of 10% porous gelatin bird models gives successful results for the validation of real bird data.

Bird weights used in validation tests or simulations are usually between 1kg and 4kg. Bird model density is determined according to the bird species and has a value between 940kg/m3 - 960kg/m3. The velocities of the artificial birds used in the tests and the bird models used in the simulations have a large velocity range from 75 m/s to 250 m/s. In the literature, the solution of bird strike problems has been investigated by using different software such as LS-DYNA, PAM-CRASH, ABAQUS, DYTRAN, and RADIOSS. Some studies and study methods in the literature are listed in Table 1. These studies indicate the year of article and compare the software used by the authors, bird modelling, bird features and crash affected plate or aircraft components.

Table 1. Bird strike simulation papers and modeling data in technical literature.

Paper	Year	Software				Bird Modelling			Bird								Load Case			
											Geometry									
		LS-DYNA	PAM-CRASH	ABAQUS	DYTRAN	Lagrange	Eulerian/ALE	SPH	Mass	Velocity m/s	cylinderical	hemispherical	elliptical	spherical	Dimensions [mm x mm]	Density [kg/m3]	Plate	Leading edge	Fan blade	Windshield
[79]	2020	x	x					x	3.6 kg	120-210		x			106 x 212	950	x			
[78]	2022	x						x	1.8-3.6 kg	115-289		x			114 x 228	923-942		x		
[76]	2023			x		x			80-160 g	124-224	x				18 x 36	950	x			
[75]	2021			x			x		1.8 kg	95-100		x			114 x 228	950				x
[74]	2020	x						x	550 g	200	x				80 x 108	936		x		
[71]	2014		x					x	1.8 kg	70-170		x			75 x 98	940	x			
[61]	2013	x						x	1.8 kg	155	x				212 x 106	950	x			x
[72]	2017			x				x	300-400 g	108-139	x	x			114 x 228	960-1040	x			
[56]	2007			x		x	x		32 g	100-200		x			30 x 50	940	x			x
[53]	2004	x				x			10-116 g	77-242				x	50 x 50	950			x	

Acknowledgement

Authors present their appreciation to TÜRK HAVACILIK VE UZAY SANAYİİ A.Ş. for data providing and enabling the preparation of this study.

Conflict of Interest Statement

We hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. We also declare that, as required by these rules and conduct, We have fully cited and referenced all material and results that are not original to this work.

CRediT Author Statement

Murat Altin: Conceptualization, Supervision
Erkan Boyaci: Conceptualization, Investigation, Writing – review & editing

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