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EVALUATION AND QUANTIFICATION OF THE POTENTIAL CONSEQUENCES OF BIRD STRIKES IN URBAN AIR MOBILITY

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Abstract

The development of air taxis, driven by advances in electric propulsion, promises new opportunities for Urban Air Mobility. As the aviation industry directs increasingly more attention towards the development of such vehicles, however, new operational challenges and safety concerns are emerging. A major bottleneck for the aviation authorities will be the integration of Urban Air Mobility vehicles into the existing airspace. A successful integration is challenging and needs to consider several aspects. One of these is the hazard of bird strikes. While bird strike poses a risk to any type of aircraft, the risk is expected to be higher in the case of urban air vehicles due to several reasons. Flying at lower altitudes, future air taxis will be more likely to collide with birds. In addition, air taxis are expected to be smaller and have lower certification requirements than conventional aircraft, and will hence be more vulnerable to damaging collisions. In this paper, a detailed impact force analysis is conducted to evaluate and quantify the consequences of collisions between air taxis and birds in terms of impact force, and additionally a Graphical User Interface is developed to visualize the results. By considering both bird-related and aircraft-related parameters in the analysis, a comprehensive evaluation is obtained that provides improved insight into the bird strike problem in the context of Urban Air Mobility. Results are evaluated in the context of bird strike requirements for Vertical Take Off and Landing vehicle proposed by EASA. The conducted analysis implies that the current specifications could be further strengthened by considering additional factors such as bird speed, aircraft material density, angle of impact and depth of penetration.

Keywords: air taxi, collision, bird strike, certification requirements, impact force, Urban Air Mobility.

Nomenclature

$\Delta E_{kinetic}$	Kinetic energy transfer
$\rho_{aircraft}$	Density of the aircraft
ρ_{bird}	Density of the bird
$\rho_{material}$	Density of the impacted material
$\rho_{projectile}$	Density of the projectile
θ	Angle of impact
A	Surface area
d	Depth of penetration
$d_{cylinder}$	Depth of penetration of cylindrical bird
$d_{ellipsoid}$	Depth of penetration of ellipsoidal bird
l	Length of the bird
m	Mass of the bird
r	Radius of the bird
V	Volume of the bird
$v_{aircraft}$	Speed of the aircraft
v_{bird}	Speed of the bird
$V_{material}$	Volume of impacted material
$V_{projectile}$	Volume of the projectile

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1. Introduction

Driven by advances in electric propulsion as well as the increasing urgency of addressing environmental issues, new types of aircraft and new forms of mobility are emerging [16]. Particularly Urban Air Mobility (UAM) is becoming an increasingly concrete prospect [19]. While private drones are expected to be allowed to operate at up to 2,500 ft (762 m) [7], UAM vehicle [2] operations are intended to take place between 1,000 and 4,000 ft [6]. According to the Federal Aviation Administration (FAA) Wildlife Hazard Management Manual, 92 % of birds fly below an altitude of 2,500 ft (762 m) [5]. While 88 % of reported strikes occurred below this altitude, and an additional 6 % between 2,500 ft and 4,500 ft [9]. Consequently, drones and air taxis will predominantly operate in the altitude range most exposed to bird strike. This suggests a significantly increased probability of collisions between these future airspace users and birds, representing a safety hazard to both aircraft and birds.

Hence, it is important to evaluate the consequences of potential collisions between birds and air taxis which would eventually contribute to safe integration of UAM traffic in the existing urban airspace. This paper aims to quantify the consequences of collisions between UAM vehicles and birds, and to formulate potential counteracting measures to attenuate damaging collisions. The effects of collisions are characterised in terms of kinetic energy and penetration depth, and the influence of various aircraft-related and bird-related parameters on collision severity is evaluated. Additionally, a Graphical User Interface (GUI) is developed to visualize the results. Based on the obtained results, recommendations are formulated to reduce the impact of collisions. Moreover, current certification requirements are considered and suggestions are made for potential adjustments to these requirements for the UAM case.

This paper is structured as follows. Section 2.describes the methodology proposed to assess the effect of collisions between birds and air taxis. Section 3.explains the key results obtained by implementing the developed methodology. A critical discussion of these results and their implications is provided in Section 4.Section 5summarises the main conclusions obtained and provides recommendations for future research.

2. Methodology

The first step of this study is to evaluate and quantify the consequences of collisions between birds and air taxis. Following this, a GUI is developed for visualisation and analysis of the results.

2.1 Consequences of damaging collisions on air taxis

In order to obtain a Permit to Fly (PTF), air taxis will have to demonstrate their airworthiness. For an aircraft to be airworthy, it has to comply with certain specifications formulated by the aviation authorities. In Europe, European Union Aviation Safety Agency (EASA) has published a proposal for ‘Means of Compliance with Special Condition VTOL’ [1]. These certification specifications contain requirements regarding strikes with individual as well as multiple birds. In order to be proportionate to the nature and risk of the particular activity to be conducted by a Vertical Take Off and Landing (VTOL) aircraft, two certification categories are introduced in this special condition, namely ‘Basic’ and ‘Enhanced’, linked to the intended type of operations [1]. VTOL aircraft of the category ’Basic’ have to meet requirements regarding controlled emergency landing [1]. VTOL aircraft certified in the category ‘Enhanced’ have to meet requirements for continued safe flight and landing, and be able to continue to the original intended destination or a suitable alternate vertiport after a failure. The critical mass of a single bird to withstand at an operating altitude up to 8,000 ft (2,438 m) is 2.2 lbs (1 kg) for both categories [1]. Moreover, the windshield directly in front of occupants and the supporting structures for these panels should be capable of withstanding a bird impact without penetration for maximum speeds above 50 kts (25 m/s). In a multiple bird strike scenario, an evaluation should be performed up to the maximum speed in level flight with maximum continuous power up to 4,000 ft (1,219 m) Above Mean sea level (AMSL). The critical mass per individual of flocking birds amounts to 1 lbs (0.45 kg).

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[2] In the rest of this paper the term air taxi will be used.

A key factor in determining the effect of a collision is the amount of kinetic energy absorbed by the airframe or the engines upon impact,

$$\Delta E_{kinetic} = \frac{1}{2} \cdot m \cdot (v_{aircraft} + v_{bird})^2 \tag{1}$$

where, $\Delta E_{kinetic}$ is kinetic energy transfer, m is bird mass, $v_{aircraft}$ is aircraft speed and v_{bird} is bird speed. Hence, the impact speed and the mass of the bird involved play an important role in determining the damaging potential of a collision [13]. The cruising speed of air taxis is expected to be between 150 and 200 kts (77.1 m/s - 102.88 m/s) [10] as compared to conventional aircraft which cruise at 450 - 500 kts (231 m/s - 257.2 m/s) [18]. The cruise speeds of many birds range between 10 and 58 kts (5 - 30 m/s), see Table 2. Due to the lower speed of air taxis in comparison to conventional aircraft, the bird velocity will have a stronger influence on the impact resulting from a collision.

Risk is defined as the product of the likelihood of an event and its expected outcome [8]. In the context of bird strikes, several parameters influence the outcome and likelihood of a collision and these can have multiple concurring effects. While the probability of collision reduces as an aircraft climbs to a higher altitude [9, 14], the impact of collision, or the kinetic energy transfer, increases at higher altitude. The reason for this is the increased speed of the aircraft during cruise and the fact that larger and faster birds fly at higher altitudes [13].

Equation 1 is a general kinetic energy equation which can be used to quantify the damage caused by a bird strike. For a more in-depth analysis, however, a number of underlying bird-related and aircraft-related factors should be considered as well. Therefore, this research develops a step-wise model to evaluate the contributions of these factors. The considered factors are shown in Table 1. The Table also clarifies how different parameters are correlated, whether or not they are a function of other variables, and, where relevant, what literature sources values for the parameters were based on.

Variable	Symbol	Correlation	Nature	Values taken from
Mass of the bird	m	$m = \rho \cdot V$	Independent	[12]
Density of the bird	ρ_{bird}	$\rho_{bird} = \frac{m}{V}$	Independent	[12]
Radius of the bird	r	$r = \sqrt{\frac{m}{\rho_{bird} \cdot \pi \cdot l}}$	Dependent	Equation 5
Speed of the bird	v_{bird}	-	Independent	[12]
Length of the bird	l	-	Independent	Modelled here [12]
Density of the aircraft	$\rho_{aircraft}$	-	Independent	Constant
Speed of the aircraft	$v_{aircraft}$	-	Independent	[13]
Angle of Impact	θ	-	Independent	Constant
Depth of Penetration	d	$l \cdot \frac{\rho_{bird}}{\rho_{aircraft}} \cdot \frac{v_{bird} \cdot sin\theta + v_{aircraft}}{v_{aircraft}}$	Dependent	Modelled as a function

Table 1 – List of variables influencing the impact force [13]

The specific steps to obtain these variables are explained in the next Sections. In order to quantify the consequences of collisions, impact forces were calculated for collisions between air taxis and a sample set of 11 bird species. The obtained results will be used to draw general conclusions. The bird species and their key characteristics relevant for this study are summarised in Table 2. Sample birds were chosen to cover a wide range of sizes and masses, allowing for general conclusions to be drawn.

Species	Mass (kg)	Density (kg/m^3)	Length (m)	Wing span (m)	Speed (m/s)
Common Grackle	0.096	809	0.31	0.40	13.411
Starling	0.071	776	0.22	0.38	22.352
House Sparrow	0.023	751	0.16	0.24	12.777
Mallard	1.328	739	0.57	0.90	29.057
Turkey Vulture	1.8	700	0.72	1.8	26.822
Laughing Gull	0.321	700	0.43	1	6.705
Bald Eagle	6.3	693	0.90	2.3	20.116
Canada Goose	3.976	669	0.92	1.5	17.881
Rock Dove	0.323	648	0.33	0.70	36.111
Ring-billed Gull	0.425	644	0.48	1.1	17.881
Herring Gull	1.044	602	0.66	1.5	17.881

Table 2 – Characteristic properties of different birds [4, 12]

2.2 Calculation of force of impact

Impact force is the force applied over a period of time when two or more bodies collide [3], and can be used to assess whether the impact resistance of a material is sufficient to bear expected collision forces. The impact resistance of a material is defined as its ability to withstand a particular impact force without any plastic deformation [3]. In this paper, impact force analysis is performed to evaluate the effect of collisions between air taxis and birds. The obtained results are then used to formulate safety requirements for air taxis. In the following Section, impact force will be calculated by considering the general equation of kinetic energy, equation 3. In subsequent steps, additional factors from Table 1 are included into the analysis.

Impact force F is generally defined as

$$F = \frac{E_{kinekic}}{d} \tag{2}$$

where *d* is penetration depth.

Calculation of kinetic energy transfer is thus a prerequisite step for impact force analysis in all three following modelling cases considered, however each case considers different parameters and makes different assumptions in calculating impact force.

Case 1 only considers bird mass and aircraft speed when calculating kinetic energy. Case 2 additionally considers bird speed, bird geometry, bird density (i.e. length and “radius”), aircraft material density and penetration depth. Case 3 additionally considers impact angle. The modelling undertaken in each of the three cases is described in the next Sections. The results obtained for each of these three cases are then compared to determine the influence of different factors on the consequences of collisions.

2.2.1 *Case 1 - Quantification of kinetic energy transfer*

This is the simplest, baseline case considered. Bird speed is considered negligible and head-on impact is assumed. The bird is considered a point mass, the aircraft a rigid body. Aircraft speed is set equal to cruise speed.

This results in the following basic kinetic energy equation.

$$\Delta E_{kinetic} = \frac{1}{2} \cdot m \cdot v_{aircraft}^2 \tag{3}$$

The case was tested at aircraft speeds of 150 kts (77.166 m/s) and 200 kts (102.88 m/s), based on the expected cruising speed of air taxis [18].

2.2.2 *Case 2 - Quantification of impact force considering bird shape and penetration depth*

Compared to case 1, case 2 additionally considers bird shape and penetration depth. This requires approximate modelling of the shape of the bird. Bird geometry was modelled in a simplified way by using elementary geometric shapes. Based on a preliminary analysis, it was found that approximating birds as cylinders provides sufficient insight for initial studies. A more realistic representation of birds as ellipsoids increases complexity but was found not to increase the accuracy of results significantly. Therefore, birds are assumed to be cylindrical throughout this study.

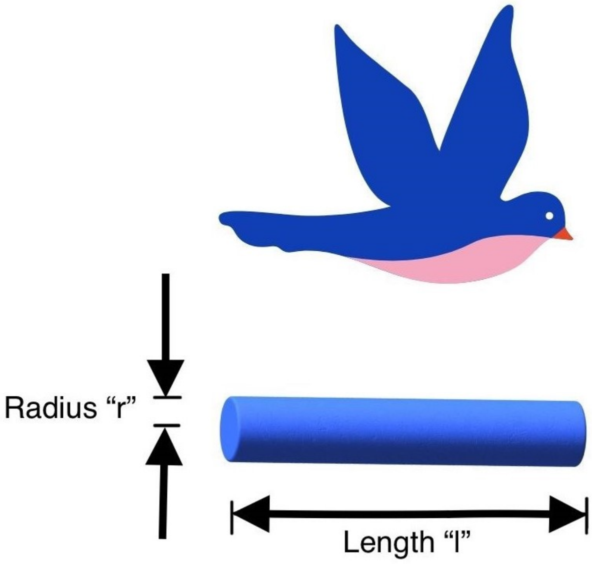


Figure 1 – Approximation of bird geometry as a cylinder.

As shown in Figure 1, the bird is modelled as a right circular cylinder. The height of the cylinder is assumed to be equal to the length of each bird, while the radius is calculated for each bird based on its volume, which in turn is obtained from its known density and mass.

$$V = \pi r^2 l = \frac{m}{\rho_{bird}} \tag{4}$$

$$\boxed{r = \sqrt{\frac{m}{\rho_{bird} \cdot \pi \cdot l}}} \tag{5}$$

where V is the volume of the bird, r is the radius of the bird, l is the length of the bird, ρ_{bird} is the density of the bird and m is the mass of the bird.
The resulting radii for each bird species, based on the assumed cylindrical geometry approximation, are given in Table 3.

Species	Radius r (metres)
Common Grackle	0.0110
Starling	0.0115
House Sparrow	0.0078
Mallard	0.0316
Turkey Vulture	0.0337
Laughing Gull	0.0184
Bald Eagle	0.0567
Canada Goose	0.0453
Rock Dove	0.0219
Ring-billed Gull	0.0209
Herring Gull	0.0289

Table 3 – Resulting radius of the cylindrical bird

Penetration depth was modelled as a function of bird length l, bird density ρ_{bird}, aircraft density $\rho_{aircraft}$, bird speed v_{bird} and aircraft speed $v_{aircraft}$.

Calculations were adapted from Newton's approximation for impacting projectiles at supersonic speeds [15], accounting for the lower speeds considered in the current study. Based on conservation of linear momentum, penetration depth for impacting birds was thus modelled as follows.

$$m \cdot v = \text{const.} \tag{6}$$

$$m_{bird} \cdot (v_{bird} + v_{aircraft}) = m_{aircraft} \cdot v_{aircraft} \tag{7}$$

$$l \cdot A \cdot \rho_{bird} \cdot (v_{bird} + v_{aircraft}) = d_{cylinder} \cdot A \cdot \rho_{aircraft} \cdot v_{aircraft} \tag{8}$$

$$\boxed{d_{cylinder} = l \cdot \frac{\rho_{bird}}{\rho_{aircraft}} \cdot \frac{v_{bird} + v_{aircraft}}{v_{aircraft}}} \tag{9}$$

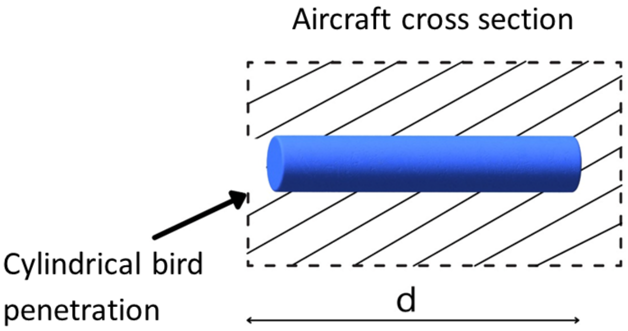


Figure 2 – Schematic clarifying cylindrical bird penetration following collision.

Note that if the speed of the aircraft is very high as compared to the speed of the bird, then the term $(\frac{v_{bird}+v_{aircraft}}{v_{aircraft}})$ is approximately equal to 1 and Newton's original approximation is obtained again.
For all calculations, it is assumed that the structure of air taxis is made out of Carbon Fibres Reinforced Plastic (CFRP), which has a density of **1,750** kg/m^3 [2].

2.2.3 Case 3 - Quantification of impact force considering angle of impact

In case 3, in addition to bird shape and density, the angle of impact of the collision is taken into account for calculating the impact force.

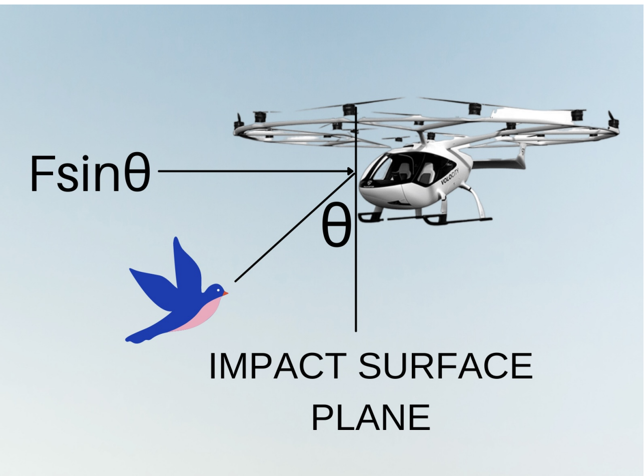


Figure 3 – Bird Impacting an eVTOL UAM aircraft at an angle θ [11]

Depth of penetration needs to be separately calculated for each bird as it is dependent on the angle of impact.

$$\boxed{d = l \cdot \frac{\rho_{bird}}{\rho_{aircraft}} \cdot \frac{v_{bird} \cdot \sin\theta + v_{aircraft}}{v_{aircraft}}} \tag{10}$$

2.3 Impact force analysis considering all variables

Lastly, all previously mentioned influencing factors were included in a single impact force model, which was used to compute the final results. Based on the definition of impact force as ratio of kinetic energy transfer to penetration depth, the following more comprehensive formulation was obtained by substituting the respective values from equations 1 to 10

$$F = \frac{\Delta E_{kinetic}}{d} \cdot sin\theta \tag{11}$$

$$F = \frac{\frac{1}{2} \cdot m \cdot (v_{bird} \cdot sin\theta + v_{aircraft})^2}{d} \cdot sin\theta \tag{12}$$

$$\boxed{F = \frac{\frac{1}{2} \cdot m \cdot (v_{bird} \cdot sin\theta + v_{aircraft})^2}{(l \cdot \frac{\rho_{bird}}{\rho_{aircraft}} \cdot \frac{v_{bird} \cdot sin\theta + v_{aircraft}}{v_{aircraft}})} \cdot sin\theta} \tag{13}$$

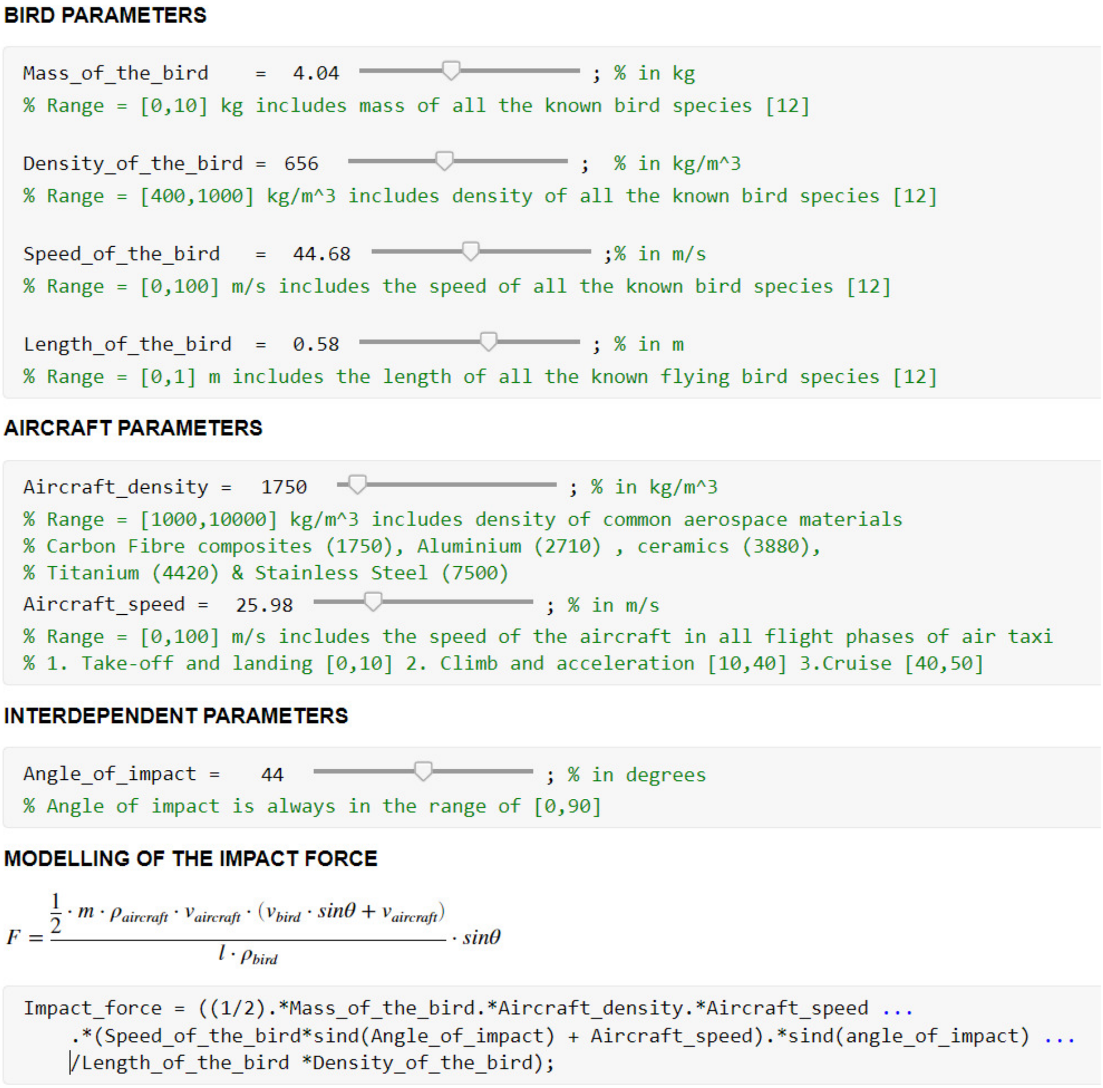
$$\tag{14}$$

Simplifying the above equation yields:

$$\boxed{F = \frac{\frac{1}{2} \cdot m \cdot \rho_{aircraft} \cdot v_{aircraft} \cdot (v_{bird} \cdot sin\theta + v_{aircraft})}{l \cdot \rho_{bird}} \cdot sin\theta} \tag{15}$$

2.4 Impact Force Visualisation GUI

To visualize the obtained results, a GUI including all dependent and independent variables was developed in MATLAB. Variables are grouped into *bird parameters, aircraft parameters and independent parameters*. Within the GUI, all parameters can be easily varied using sliders. This allows the user to analyse and visualize data depending on different sets of input parameters particular to the desired use-case. The interactive part of the GUI, where the user can define their desired input parameters can be seen in Figure 4. The output plots of the GUI can be observed in Figures 5 - 7.



BIRD PARAMETERS

```
Mass_of_the_bird    =  4.04                    ; % in kg
% Range = [0,10] kg includes mass of all the known bird species [12]

Density_of_the_bird =  656                    ;  % in kg/m^3
% Range = [400,1000] kg/m^3 includes density of all the known bird species [12]

Speed_of_the_bird   =  44.68                   ;% in m/s
% Range = [0,100] m/s includes the speed of all the known bird species [12]

Length_of_the_bird  =  0.58                    ; % in m
% Range = [0,1] m includes the length of all the known flying bird species [12]
```

AIRCRAFT PARAMETERS

```
Aircraft_density =   1750                    ; % in kg/m^3
% Range = [1000,10000] kg/m^3 includes density of common aerospace materials
% Carbon Fibre composites (1750), Aluminium (2710) , ceramics (3880),
% Titanium (4420) & Stainless Steel (7500)
Aircraft_speed =   25.98                    ; % in m/s
% Range = [0,100] m/s includes the speed of the aircraft in all flight phases of air taxi
% 1. Take-off and landing [0,10] 2. Climb and acceleration [10,40] 3.Cruise [40,50]
```

INTERDEPENDENT PARAMETERS

```
Angle_of_impact =   44                    ; % in degrees
% Angle of impact is always in the range of [0,90]
```

MODELLING OF THE IMPACT FORCE

$$F = \frac{\frac{1}{2}\cdot m\cdot \rho_{aircraft}\cdot v_{aircraft}\cdot (v_{bird}\cdot sin\theta + v_{aircraft})}{l\cdot \rho_{bird}}\cdot sin\theta$$

```
Impact_force = ((1/2).*Mass_of_the_bird.*Aircraft_density.*Aircraft_speed ...
    .*(Speed_of_the_bird*sind(Angle_of_impact) + Aircraft_speed).*sind(angle_of_impact) ...
    /Length_of_the_bird *Density_of_the_bird);
```

Figure 4 – Impact force visualisation GUI

The developed GUI can be downloaded as a MATLAB Live script and Python Jupyter script by clicking on the respective hyperlinks. The next Section presents the key results obtained based on the presented impact force analysis.

3. Results

For each bird species considered, penetration depth was computed based on the developed models. Results were obtained for different scenarios, covering variations in all the considered parameters, i.e. impact angle, bird speed, aircraft speed, bird mass and aircraft material.

3.1 Impact force analysis

In this section, the resulting penetration depth, kinetic energy transfer and impact force for all the cases are demonstrated. The penetration depths for each considered bird are given in Table 4, both in metres and as multiples of the respective bird body length *l*.

Species	$d_{cylinder}$ (metres)	$d_{cylinder}$ (*l)
Common Grackle	0.1682	0.5426 l
Starling	0.1258	0.5718 l
House Sparrow	0.0800	0.5000 l
Mallard	0.3313	0.5812 l
Turkey Vulture	0.3881	0.5390 l
Laughing Gull	0.1869	0.4346 l
Bald Eagle	0.4493	0.4992 l
Canada Goose	0.4331	0.4707 l
Rock Dove	0.1793	0.5433 l
Ring-billed Gull	0.2157	0.4494 l
Herring Gull	0.2796	0.4236 l

Table 4 – Depth of penetration of the bird sample data

Species	$\Delta E_{kinetic}$ (J) at 150 kts - Case 1	$\Delta E_{kinetic}$ (J) at 200 kts - Case 1	$\Delta E_{kinetic}$ (J) at 150 kts - Case 2 and Case 3	Impact force (N) - Case 2	Impact force at $\theta = 60^\circ$ (N) - Case 3
Common Grackle	286	508	394	2,323.83	2054.01
Starling	211	376	352	2,790.63	2,492.03
House Sparrow	68	122	93	1,160.62	1,024.34
Mallard	3954	7028	7,492	22,491	20,222.45
Turkey Vulture	5,359	9,526	9,732	25,038.75	22,465.66
Laughing Gull	956	1,699	1,129	6,021.65	5,271.31
Bald Eagle	18,757	33,341	29,811	66,308.63	59,068.30
Canada Goose	11,838	21,042	17,959	41,300.82	36,745.08
Rock Dove	962	1,709	2,072	11,523.38	10,421.26
Ring-billed Gull	1,265	2,249	1,920	8,878.63	7,823.31
Herring Gull	3,108	5,525	471	16,833.53	14,952.62

Table 5 – Absorbed kinetic energy for the different bird species

A key observation of the analysis is that without considering the angle of impact and surface curvature, the impact force is highest (Case 2). If angle of impact is taken into account, impact forces reduce.

Moreover, if two birds with the same body densities are compared (e.g. Laughing Gull and Turkey Vulture, $\rho = 700 kg/m^3$, cf. Table 2), it can be seen that their impact forces differ. In the given example, the impact force for the Turkey Vulture is higher in each of the cases analysed (cf. Table 5). This is due to the higher mass of the Turkey Vulture compared to the Laughing Gull, and implies that mass is the dominant factor influencing impact force, as compared to density. Furthermore, it can be noted that the Bald Eagle as the heaviest bird has the highest impact force in all three cases.

Comparing the impact forces of the Rock Dove and Ring-billed Gull, it can be observed that despite the Ring-billed Gull having a greater mass (cf. Table 2), its impact force is smaller, as seen in Table 5. The reason is that the speed of the Ring-billed Gull is significantly smaller than that of the Rock Dove. Therefore, it can be concluded that if two birds with almost identical masses are compared, then the speed of the bird is crucial for evaluating the impact force.

Comparing the impact force results from case 1, which is the baseline case with no additional factors, and case 2, which considers bird speed, bird shape, aircraft density and penetration depth, shows that bird speed has a significant impact on air taxi - bird strikes. The reason is that the average cruising speed of air taxis is expected to be in the range of 150-200 kts (77 - 103 m/s) [18] and the average bird speed according to Table 2 is 39.1 kts (20.1 m/s). Therefore, the speed of the air taxi is not many times the speed of the bird. As a result, the speed of the bird has a significant effect on

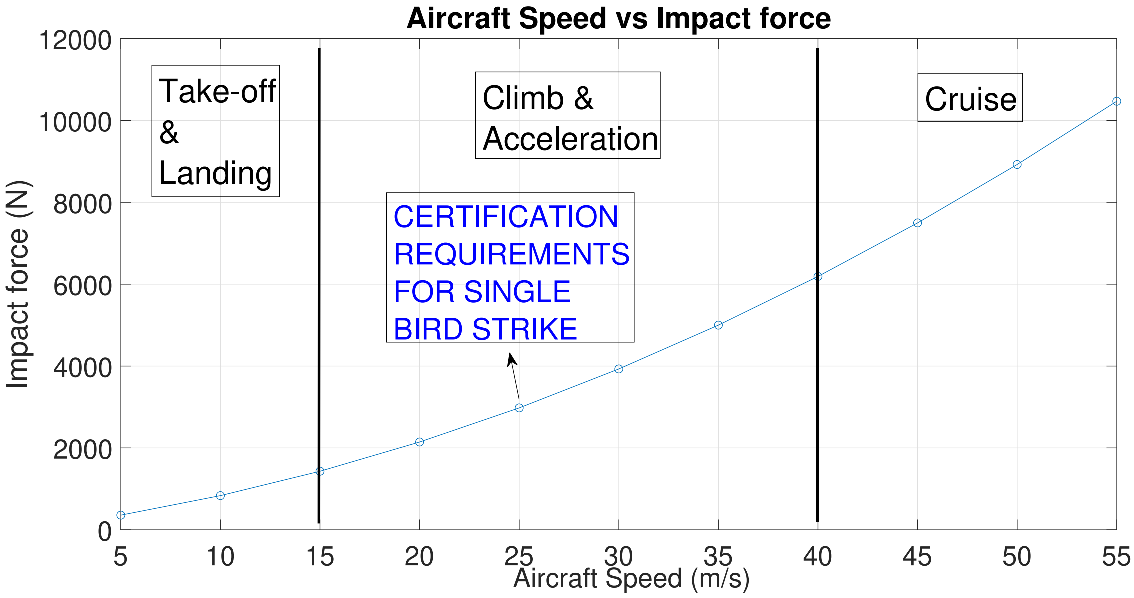


Figure 5 – Aircraft speed versus impact force for bird mass equal to 1.328 kg, bird speed equal to 25.98 m/s, aircraft density equal to 1750 kg/m^3, angle of impact equal to 60° and bird length equal to 0.16 m.

the impact force calculations. As seen in Table 5, for instance, despite its lower mass, the rock dove has a larger associated impact force than the heavier ring-billed gull, due to its higher flight speed. If the speed of the bird is neglected, as done in Case 1, the absorbed kinetic energy is significantly underestimated.

Comparing the results for cases 2 and 3, it can be observed that impact force is directly proportional to $\sin\theta$. Hence, for impact angles below 90° (no head-on collision or orthogonal impact), the impact force is reduced for the same bird density and radius. Hence, in cases where all collision avoidance systems fail, a key priority for an air taxi would be to try and reduce the angle of impact.

Figures 5 - 7 show the results obtained for one specific bird, the Mallard, assumed to have the properties given in Table 2. This allows for the impact of parameters unrelated to the bird to be evaluated more closely. Note that these results can be plotted for any other bird species with the help of the developed GUI.

Figure 5 plots the impact force against the aircraft speed, for a fixed aircraft density of 1,750 kg/m^3 and a fixed angle of impact of 60°. The plot is divided into three Sections, representing the three main flight phases of air taxis, i.e. take-off & landing, climb & acceleration, and cruise. It can be seen that an air taxi is subjected to maximum impact force during cruise. Hence, the severity of potential collisions is higher during this flight phase.

Figure 6 shows the relation between angle of impact and impact force. Aircraft density is assumed to be 1,750 kg/m^3 and aircraft speed 7.16 m/s. These results again show that impact force reduces at a low angle of impact, suggesting that head-on collisions should be avoided to decrease the impact force on the air taxi.

Figure 7 plots penetration depth against impact force. Aircraft density is fixed at 1,750 kg/m^3, aircraft speed at 77.16 m/s and angle of impact at 60°. It can be observed that the obtained curve is hyperbolic, indicating an inverse relationship between penetration depth and impact force. For low penetration depths, impact force thus increases.

Figure 8 illustrates the relationship of impact force and bird mass for all bird species considered. For this calculation, a constant bird speed of 25.98 m/s was assumed, i.e. the average speed across all considered bird species. Aircraft speed was set to 77.16 m/s, i.e. the proposed cruising speed of air taxis [18], aircraft density was assumed to be 1,750 kg/m^3, the density of carbon fibres, angle of impact was assumed to be 60° and bird length was set equal to 0.16 m, the average length across all considered bird species. Moreover, current certification requirements specified by EASA [1] are also included in the plot to provide a comparative perspective. It can be observed that current certification

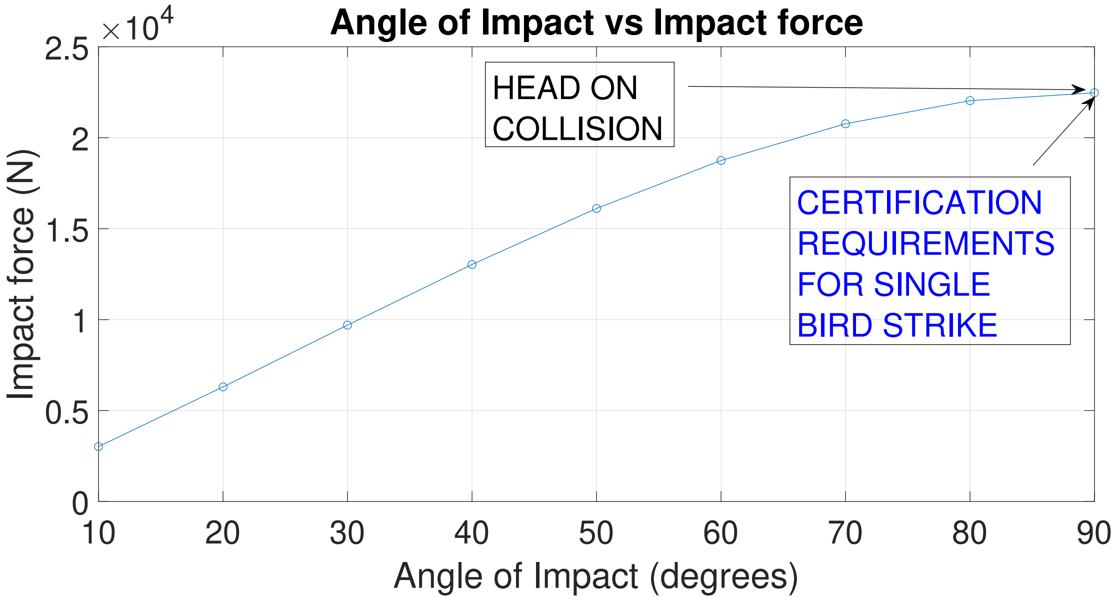


Figure 6 – Angle of impact vs impact force for bird mass equal to 1.328 kg, bird speed equal to 25.98 m/s, aircraft speed equal to 77.16 m/s, aircraft density equal to 1750 kg/m^3, angle of impact equal to 60° and bird length equal to 0.16 m.

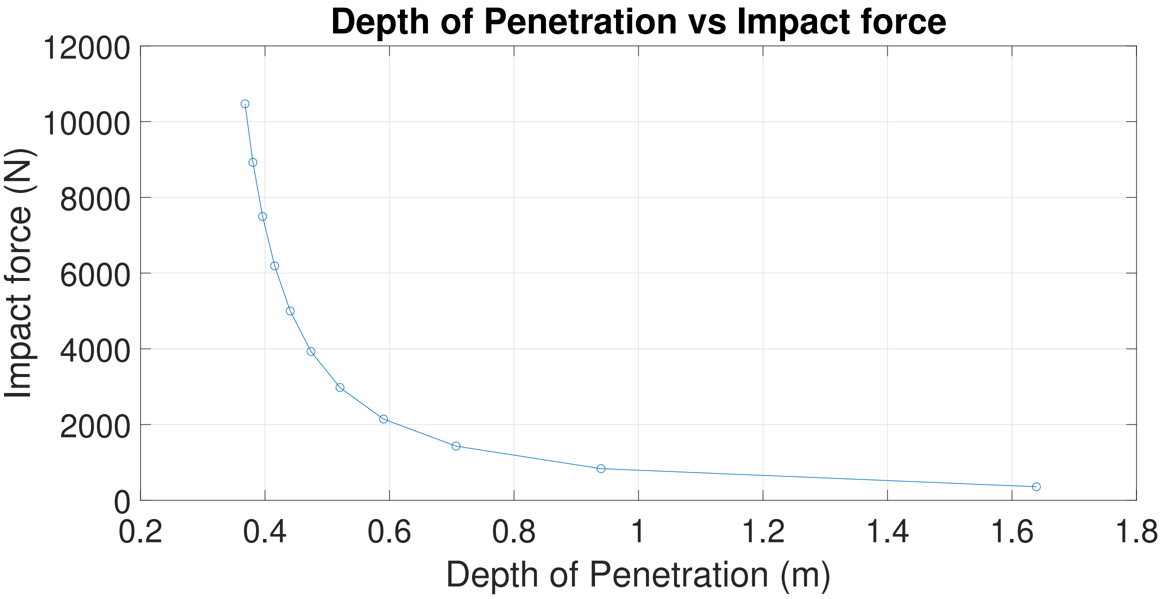


Figure 7 – Depth of penetration versus impact force for bird mass equal to 1.328 kg, bird speed equal to 25.98 m/s, aircraft speed equal to 77.16 m/s, aircraft density equal to 1750 kg/m^3, angle of impact equal to 60° and bird length equal to 0.16 m.

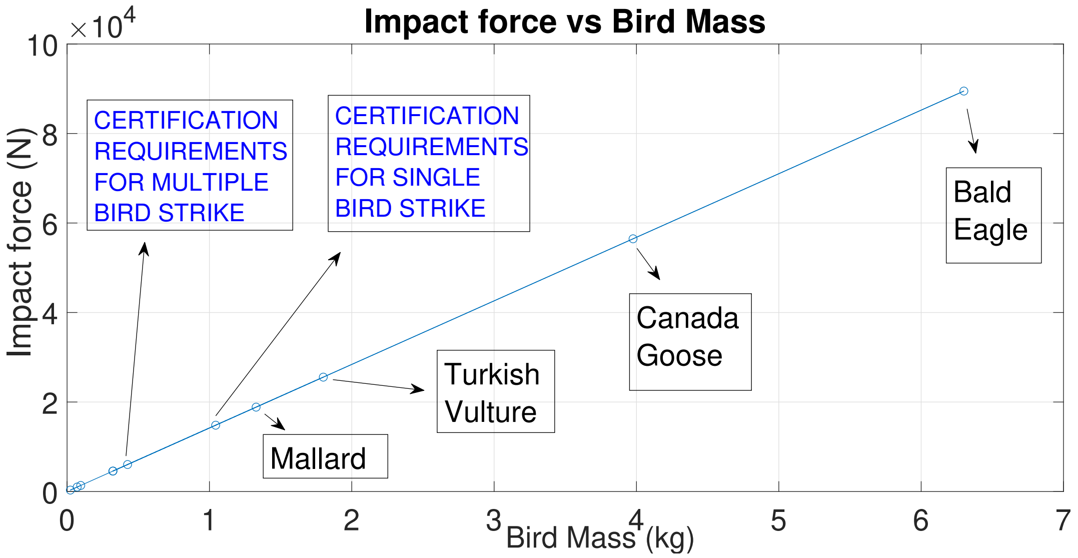


Figure 8 – Bird mass versus impact force for bird speed equal to 25.98 m/s, aircraft speed equal to 77.16 m/s, aircraft density equal to 1750 kg/m^3, angle of impact equal to 60° and bird length equal to 0.16 m.

requirements do not account for the case of birds such as turkey vultures or bald eagles, which have a higher mass and lead to a greater impact force.

Figure 9 plots impact force against bird speed for all the bird species considered. For this calculation, aircraft speed is assumed to be 77.16 m/s, aircraft density 1,750 kg/m^3, angle of impact 60° and bird length 0.16 m. As expected, faster birds have a higher impact force than slower ones.

Figure 10 shows the relationship between different aerospace materials and the impact force for a Mallard with the properties given in Table 2. Here, aircraft speed is equal to 77.16 m/s and angle of impact is assumed to be 60°. The most common material for air taxi manufacturing will likely be CFRP, which has the lowest impact force among the materials considered.

Figure 11 shows a 3D surface plot relating impact force, aircraft speed and bird mass, for a constant bird speed of 29.05 m/s, aircraft density of 1,750 kg/m^3 and angle of impact of 60°. Impact force is calculated for combinations of aircraft speed and bird mass, covering the entire range considered for each parameter. Additionally, as per the 'Means of Compliance with Special Condition VTOL' published by EASA [1], the current certification requirements relevant for future air taxis are included in the plot for comparison. According to the certification requirements, an air taxi should withstand a maximum impact force of 2255.37 N for a single bird strike. However, according to the impact force analysis considering common bird species and expected average air taxi cruise speed (see Figure 11), air taxis may have to withstand higher impact forces than those specified by current certification requirements, especially for bird flocks.

Following the evaluation of the effect of individual parameters, the next Section discusses potential measures to either prevent collisions between air taxis and birds, or mitigate the consequences of these.

4. Discussion

Ranked from most to least influential, the main bird-related parameters influencing impact force are bird mass, bird speed and bird length. In addition, aircraft-related parameters such as aircraft speed and aircraft material density substantially influence the impact force. Lastly, the collision impact angle affects the impact force as well. Among all the parameters considered, aircraft speed, bird speed and bird mass have the greatest influence on the impact force. Following the evaluation of the results in the previous Section, this Section discusses the main implications of the findings, particularly in the context of existing certification requirements.

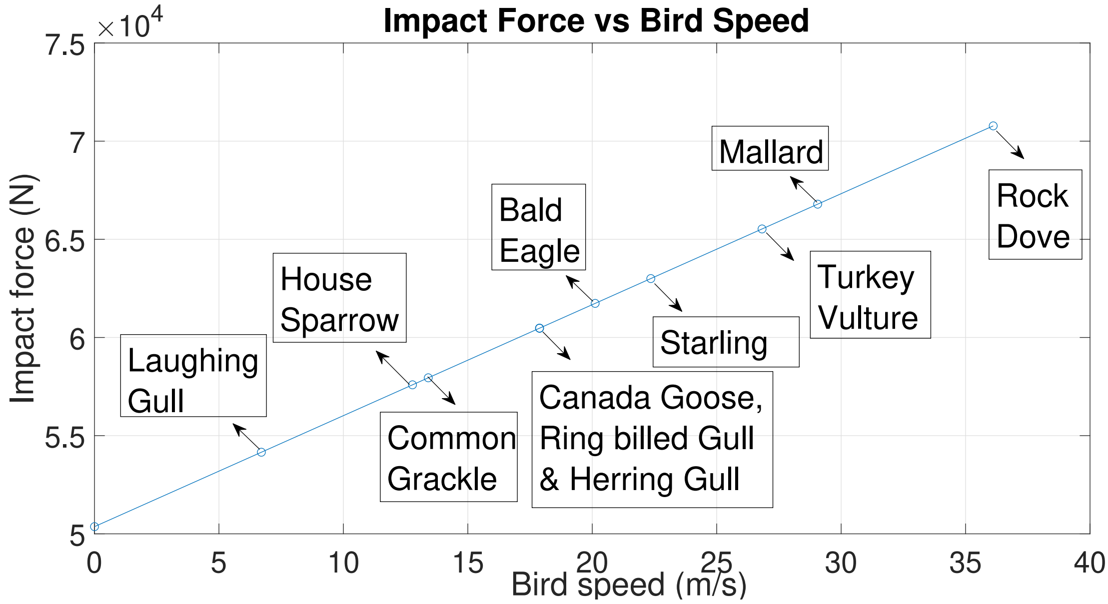


Figure 9 – Bird speed versus impact force for bird mass equal to 1.328 kg, aircraft speed equal to 77.16 m/s, aircraft density equal to 1750 kg/m^3, angle of impact equal to 60° and bird length equal to 0.16 m.

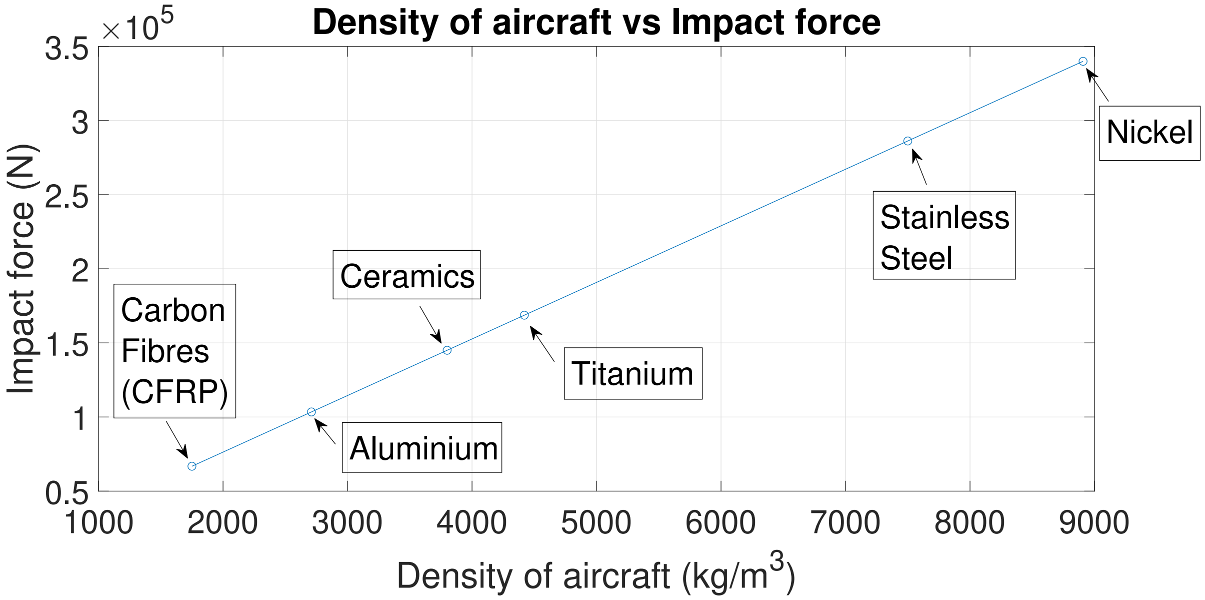


Figure 10 – Aircraft density with common aerospace materials versus impact force for bird mass equal to 1.328 kg, bird speed equal to 25.98 m/s, aircraft speed equal to 77.16 m/s, angle of impact equal to 60° and bird length equal to 0.16 m.

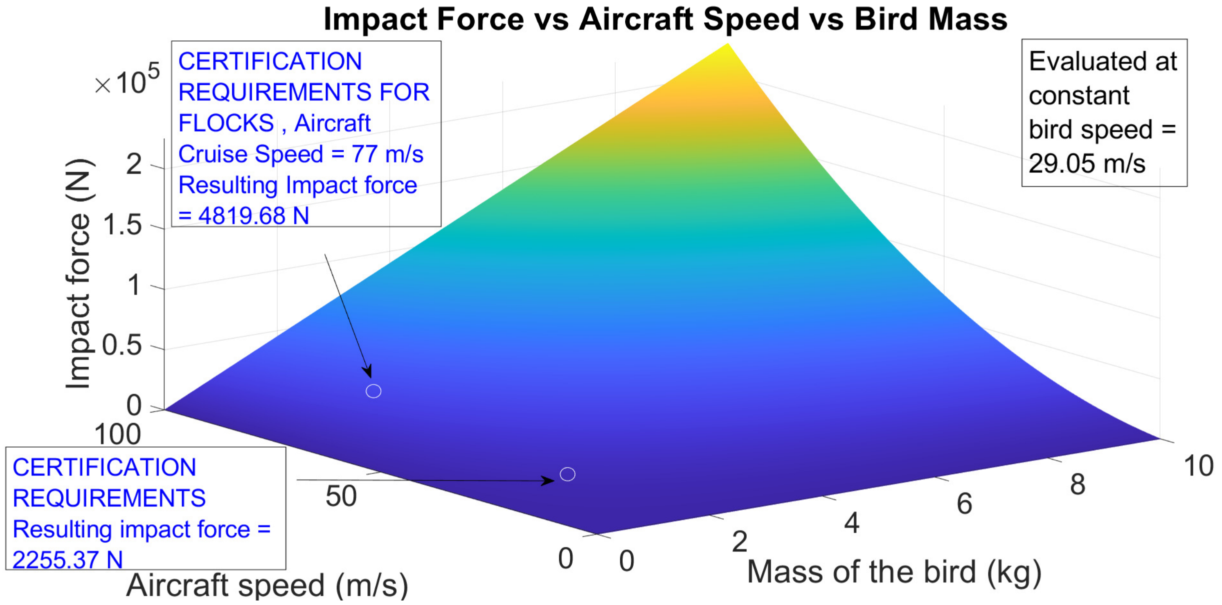


Figure 11 – Surface plot of impact force versus aircraft speed versus bird mass for bird speed equal to 25.98 m/s, aircraft density equal to 1750 kg/m^3, angle of impact equal to 60° and bird length equal to 0.16 m.

4.1 Comparison of different impact force models

Comparing equation 15 with the simple impact force equation 2, it can be observed that in the latter bird parameters such as bird speed and bird density, aircraft parameters such as aircraft density, and independent parameters such as angle of impact are not considered. According to case 2.2.2, if the speed of the bird is not negligible as compared to aircraft speed, the impact force can be highly underestimated with equation 3. Moreover, as aircraft density is not considered, no relationship can be derived between aircraft material and impact force. It is observed in equation 15 that with increase in density of the aircraft material, the impact force increases. Also, the angle of impact plays a key role in determining the impact force as according to equation 15, impact force reduces at low angle of impact. Considering that air taxis might have a more flexible flight profile compared to fixed-wing aircraft, there should be requirements for a fast change of flight path angle. These conclusions cannot be studied and analysed from equation 2. Therefore, for more realistic and precise impact force analysis, consideration of all the dependent variables is necessary.

4.2 Current certification requirements and recommendations based on presented analysis

The current certification requirement for single bird strike as proposed by EASA is to withstand collision with a 1 kg bird at critical cruise speed. For bird flocks, the requirement is to sustain a 0.45 kg bird strike at critical cruise speed.

4.2.1 Single Bird strike evaluation

This research has analysed different factors influencing air taxi collisions with birds, and their respective contributions. Based on the obtained results and analysis, the following conclusions can be drawn.

Influencing factor : Bird Mass

Bird mass is crucial in evaluating the resulting impact force. From Figure 8, Figure 11 and Table 2, it can be seen that there are number of bird species with masses higher than the certification limit, e.g. the Mallard is already above the limit. Considering the increased exposure of VTOL aircraft to birds as well as the increase of critical bird species in Europe [17], an increase of the critical mass in the certification specifications would be strongly beneficial.

Influencing factor : Aircraft Speed
In Figure 5, it can be observed that impact force is substantial (in the range of 1,000 - 3,000 N) at speeds above 50 kts (25 m/s). Therefore, collisions with relatively heavy birds such as the Turkey Vulture, Canada Goose or Bald Eagle become critical. As a result, an increase in threshold speed above the currently specified 50 kts (25 m/s) should be considered. Moreover, windshield impact resistance is currently certified in terms of aircraft speed. However, it is observed in this paper that along with aircraft speed, bird speed and bird mass also play an influential role. Hence, it may be more effective to certify the windshield impact resistance in terms of kinetic energy instead of aircraft speed or to add a buffer in terms of higher certification aircraft speeds to account for the contribution of bird speed.
Additionally, this paper has also identified some additional parameters which are not included in the current certification specifications but appear to have a significant role. These factors are discussed next.

Influencing Factor : Bird Speed
As identified in Section 4.1of this analysis, bird speed plays an important role in causing damage, particularly for air taxis as their maximum cruising speed is low (200 kts or 102 m/s) as compared to that of conventional aircraft. Hence, along with maximum cruise speed, it is recommended to evaluate the maximum bird speed of critical species at the operational cruise altitude of the VTOL and to add it as a safety buffer to the certification velocity.

Influencing Factor : Depth of Penetration
Depth of penetration plays a key role in impact analysis. Figure 7 shows that at low penetration depths, impact force is considerably higher. Therefore, along with maximum aircraft velocity, the use of penetration depth as a certification parameter for aircraft to show means of compliance is recommended. Since the calculations performed within this work are based on several assumptions and penetration depth is challenging to estimate theoretically, practical tests are recommended to calculate more realistic values and validate the current results.

Influencing factor : Angle of Impact
Observing Figure 6, it can be deduced that impact force increases at higher angles of impact. In the certification requirements, angle of impact is not included and the worst case of head-on collision is assumed which corresponds to an orthogonal impact. Given that impact forces decrease at lower impact angles, the use of curved structures could be considered in air taxis as a way of reducing the effective angle of impact. For an in-depth analysis of the effect of increasing curvature, however, further empirical research is recommended.

Influencing factor : Aircraft Material Density
Figure 10 shows that impact force increases for higher material densities. Air taxis are proposed to be made of mostly CFRP and aluminium, which have lower material densities and relatively high impact resistances compared to other aerospace materials such as ceramics, titanium, stainless steel and nickel. Moreover, as CFRP and aluminium are lighter than other aerospace materials, they are the most suitable construction materials for air taxis. In spite of this, as impact force is influenced by material density, it is proposed to include the material of construction of the aircraft in certification requirements as different materials are subjected to varying impact forces.

4.2.2 Multiple bird strike evaluation

Flocks have a higher kinetic energy and therefore constitute a greater hazard. Unlike an individual bird, a flock will lead to near-concurrent impacts at several locations on the airframe. Therefore, given the reduced critical mass of 1 lbs (0.45 kg), already relatively light birds such as Mallards may prove hazardous. For this reason, emphasis should also be placed on developing adequate multiple bird strike' criteria. Considering the existing mass criterion for flocks, shown in Figures 8 and 11, as well as the current results obtained, it is recommended to define higher values in the requirements.

5. Conclusion and Future Scope of Work

In this paper, impact force analysis was performed to evaluate and quantify the consequences of collision between air taxis and birds. Impact force analysis was carried out considering several influencing factors such as bird speed, aircraft speed, bird length, impact angle, aircraft material density and penetration depth. A final impact force relation was developed that considers all of these factors. To visualize the results, an impact force GUI was developed which enables the user to change the values of all variables according to the use case. The variables which have the most influence on the magnitude of the impact force are aircraft speed, bird speed and bird mass, in the given order. Results were also compared to the current certification requirements for impact resistance of VTOL aircraft as published by EASA. Based on the obtained results, suggestions for complementing current bird strike requirements for UAM were formulated. By including bird speed and aircraft material density, impact force can be estimated more precisely, which may allow for the definition of more accurate specifications. Results also suggest that a smaller impact angle can significantly reduce impact force, hence using more curved structures on the fuselage may be beneficial plus having additional assistant systems to enable short-term changes of the impact angle.

Future work will include modelling the birds with more accurate and realistic shapes. This may allow for a more precise estimation of impact depth. Additionally, experimental testing using scaled physical models will allow for the current model to be validated and potentially enhanced.

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7. Copyright Statement

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