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Analysing bird strikes in fast-time

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Abstract. To better understand bird strike occurrences as well as the effect of operational risk-reducing measures, a fast-time simulation environment was developed. It allows the simultaneous simulation of bird movement and air traffic. Furthermore, collisions as well as near misses between birds and aircraft are recorded. The design was validated with Monte- Carlo simulations involving bird movement from all seasons as well as different air traffic flight plans. It was demonstrated that approximately three times as many bird strikes take place during the simulation compared to the number of collisions reported for the reference airport. Contributing factors to this overestimate are missing bird behaviour in the simulation and limited bird strike reporting at the reference airport. Seasonal correspondence and reproducibility of the results were confirmed. To evaluate the simulation's ability of estimating potential damage, the almost 8000 simulated strikes were classified within the aviation authorities' certification requirements regarding impact-resistance. Therefore, the kinetic energy of the recorded collisions and the certification requirements were calculated. The analysis revealed that 3.2% of all bird strikes caused damage in the simulation. In comparison, US bird strike statistics showed 0.6% damage over a 26-year period. The analysis of the simulation outcome revealed that the share of damaging strikes is strongly increased by the strikes caused by flocks. By enhancing the model with flock compositions from the US or a comparison to European strike reporting data, more accurate results are expected.

1.0 Introduction

At and around airports, surveillance technology to track bird movement is increasingly available. To date, the information generated is mainly used by the local wildlife control units to locate hotspots of bird activity (McKee et al. 2016). With those data, patterns of bird movement trends can be analysed and the effect of novel measures to reduce the risk of bird strikes can be evaluated. This work presents a fast-time simulation environment to visualize bird movement data and to simulate it alongside air traffic movement. The tool also counts collisions as well as near misses between birds and aircraft. The goal of this tool is to enable a better understanding of bird strike risk and the potential for aircraft damage. Furthermore, it can be used to analyse the effect of risk-reducing measures at and around airports. This paper starts by providing a brief overview of the simulator design and a description of how model output was verified. The focus of the paper is to evaluate the simulation design's potential to estimate damage caused by bird strikes. For this purpose, the kinetic energy of every collision between birds and aircraft within the simulation was compared to the certification requirements defined by the European and US aviation authorities. The results were compared to multi-year reports of the US Federal Aviation Authority (FAA).

2.0 Methods

2.1 Simulation Environment

To provide a simulation environment for the visualization and analysis of bird strike risk as well as the evaluation of the efficacy of novel risk-reducing measures, the BlueSky Open Air Traffic Simulator developed by Delft University of Technology served as the base. The simulator can be downloaded from https://github.com/TUDelft-CNS-ATM/bluesky (Hoekstra 2019). Based on open data and the open-source programming language python, this simulator enables the real- and fast-time simulation of air traffic flows (Hoekstra and Ellerbroek 2016). For the underlying aircraft performance, the user can choose between a model based on open data and Eurocontrol's Base of Aircraft Data (BADA) Version 3 (Eurocontrol 2014, Metz et al 2016, Sun 2019]. The resulting design allows the analysis of Air Traffic Management (ATM) concepts. The simulator is organized in individual modules. To represent bird movements and record the interaction between birds and aircraft, specialized modules were developed and connected to the simulator. The adapted simulation environment is available from (Metz 2018).

2.1.1 Bird Movement

For this project, we developed modules to represent bird movement and to detect collisions between birds and aircraft. Models were verified with Monte Carlo Simulations (Metz et al. 2017, Metz t al. 2018). Time-stamped bird positions were used to simulate bird movement. The bird's trajectory between known positions is interpolated linearly by the simulation. The bird is removed from the simulation after its last known position. The input data require information about bird size and, in case of flocks, the number of birds represented by the track. The accepted size categories are small, medium and large. These categories are based on the definitions within the aviation authorities' engine certification requirements (FAA 2011). No bird behaviour or reactions to aircraft are included. Hence, an overestimate in recorded bird strikes is expected.

2.1.2 Collision Detection

To identify collisions between birds and aircraft, protected zones around every bird and every aircraft are defined as visualized in Figure 1. If any protected zones overlap, it is considered to be a bird strike and the respective bird is removed from the simulation. To enable a more in-depth analysis, the characteristics of the birds and aircraft involved in each strike are recorded. Bird strikes are relatively rare events. Therefore, to enhance the sample size for analysis, near misses were introduced as an additional risk measure. A near miss is counted every time the distance between the centre of protected zones of a bird and an aircraft is less than 50 m.

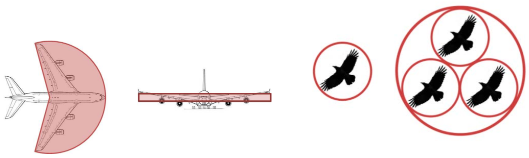

Figure 1: Protected Zones of Aircraft and Birds (from Metz et al. 2017)

2.1.3 Simulation Design

This simulator design was tested for the extended airport environment of Eindhoven airport in the Netherlands. For this airport, bird movement data from avian as well as weather radar was obtained. To consider the influence of the season on the bird strike risk, simulations were performed for 1 day per month within 1 year. Along with bird movement, three air traffic intensities were simulated. In the high scenario, 954 flights took place per day; 501 in the medium scenario and 305 in the low scenario. In all scenarios, one runway was in operation. In every scenario, 100 Monte Carlo simulation runs were performed. The input parameters regarding bird movements were randomized as described in Metz et al. (2018). In total, 3,600 scenarios resulted. The recorded bird strikes were compared to reports collected over 10 years at Eindhoven airport and analysed regarding their numerical and seasonal distribution. For this study, the kinetic energy of every strike was used to calculate the potential of damage as described in the subsequent section.

2.2 Damage Identification

To evaluate the potential for bird-strike related damage within simulations, kinetic energy was defined as the determining criterion. Kinetic energy is defined as

$$E_{kin} = \frac{1}{2} \cdot m \cdot v^2 \qquad (1)$$

where E_{kin} refers to kinetic energy in Joules, m to mass in kilograms (kg) and v to velocity in meters per second ($m\ s^{-1}$).
To calculate the impact of a bird strike on an aircraft, the bird's mass as well as the total

Table 1: Certification categories valid in Europe and the US relevant for this study (CS: Certification Specification; CFR: Code of Federal Regulations)

Europe - EASA	**US - FAA**
CS-23 Normal aeroplanes Aeroplanes with a passenger-seating configuration of 19 or less and a maximum certified take-off mass of 19,000 lbs (8,618 kg) or less (European Aviation Safety Agency 2010)	*14 CFR Part 23 Normal category airplanes* Airplanes with a passenger-seating configuration of 19 or less and a maximum certificated take-off mass of 19,000 lbs or less (Federal Aviation Administration 2016)
CS-25 Large aeroplanes Turbine-powered aeroplanes of more than 12,500 lbs (5,700 kg) maximum certified take-off mass, excluding commuter airplanes which are covered by the category *normal aeroplanes* (European Aviation Safety Agency 2010)	*14 CFR Part 25 Transport category aircraft* Multi-engine airplanes with more than 19 seats or a maximum take-off mass greater than 19,000 lbs (Federal Aviation Administration 2019).

velocity of bird and aircraft are relevant. For simplicity, only the predominating aircraft velocity was used to calculate the kinetic energy at the time of impact.

2.2.1 Damage Threshold

Certification Criteria To evaluate whether simulated bird strikes are damaging, their kinetic impact was compared to the European and US aviation authorities' certification requirements for aircraft. Depending on the aircraft size, different certification requirements are in place. In the context of commercial aviation, which is the focus of this study, the categories *normal* (European Aviation Safety Agency (EASA))/*normal category airplanes* (Federal Aviation Administration (FAA)) and *Large Aeroplanes* (EASA)/*transport category aircraft* (FAA) are relevant. The definitions, which are basically similar between agencies, are provided in Table 1. Within the simulations, only aircraft of the category *normal aeroplanes*/*normal category airplanes* were represented (European Aviation Safety Agency 2017, Federal Aviation Administration 2016) The requirements concerning the impact resistance of airframes from bird strikes are similar in European and US regulations. They cover the following aspects.

1. Windshield: The windshield must withstand the impact of a 4 lb (1.8 kg) bird (e.g. a Great Black-backed Gull) at cruise speed without penetration.
2. Structure: The aircraft must be able to successfully complete the flight after an impact with a 4 lb (1.8 kg) bird. The reference velocity for this test case amounts to cruise speed at sea level or 0.85 x cruise speed at an altitude of 8,000 ft (2,438 m), whichever is more critical.
3. Empennage (Federal Aviation Regulations (FAR) only): The aircraft must be able to successfully complete the flight after an impact with an 8 lb (3.6 kg) bird (such as a Greylag Goose) at cruise speed.
4. Pitot tubes: To prevent damage to all pitot tubes in case of a bird strike, sufficient separation is required.

Engine ingestion tests must be passed to demonstrate impact resistance. No hazardous engine effect may occur during testing. According to European Aviation Safety Agency (2010), hazardous engine effects include

i. non-containment of high-energy debris,
ii. concentration of toxic products in the engine bleed air for the cabin sufficient to incapacitate crew or passengers,
iii. significant thrust in the opposite direction to that commanded by the pilot,
iv. uncontrolled fire,
v. failure of the engine mount system leading to inadvertent engine separation,
vi. release of the propeller by the engine, if applicable,
vii. complete inability to shut down the engine.

Depending on the engine's diameter and the size of bird tested, different thrust settings have to be applied. EASA requires tests involving single and flocking large birds. The FAA adds tests regarding small and medium single and flocking birds (European Aviation Safety Agency 2010, Federal Aviation Administration 2011).

For this study, the criteria regarding windshield, structure and engines were analysed. Because the empennage section is excluded from the protected zone in the simulation (Figure 1), the corresponding criterion was not applicable. The criterion considering the pitot tubes was also not considered because it is not related to impact resistance. The references for

Table 2: Kinetic energy criteria (sources: European Aviation Safety Agency 2019, Federal Aviation Administration 1964)

Component	Kinetic Energy Criterion
Windshield	$E_{kin} = \frac{1}{2} * 4\ lb * \left(v_{reference}\right)^2$
Structure	$E_{kin} = \frac{1}{2} * 4\ lb * \left(0.85 * v_{reference_{8000ft}}\right)^2$ $E_{kin} = \frac{1}{2} * 4\ lb * \left(v_{reference_{sealevel}}\right)^2$
Engine	$E = \frac{1}{2} * m_{bird} * \ (200\ kts\ )^2$

Table 3: Bird mass categories and average mass per category used for this study (sources: Australian Transport Safety Bureau 2019, Federal Aviation Administration 2011])

Size Category	Mass Range (lbs)	Mass Selected for Simulations (lbs)	Example Bird
Small	< 0.19	0.095	Common Woodpigeon
Medium	0.19 - 2.54	1.365	Rook
Large	> 2.54 - 8.05	2.4	Mallard
Very Large (ATSB only)	> 8.05	5.295	Grey Heron

kinetic energy are visualized in Table 2. Because this study only considers bird strikes up to 3000 ft AGL, the structure criterion including $v_{reference_{sealevel}}$ was selected. Consequently, the criteria for windshield and structure are identical.

Bird masses within the criteria for windshield and structure resistance are fixed. In the engine criterion, the bird mass to be included depends on the specific test conditions: size and individual or flocking birds and the surface area of the engine inlet throat. For this study, the highest and thus most critical bird mass of 6 lb (2.7 kg) was selected. The test conditions for the impact resistance of structure and windshield include aircraft reference velocities. These were obtained by aircraft type from the BADA 3 data base.

Simulated Data To determine the kinetic energy of strikes in the simulation, the following input parameters were included. Birds of the mass categories as defined by the FAA (Federal Aviation Administration 2011) were assigned to the average mass of that category. To determine a mass for the category large, the additional category very large as defined by the Australian Transport Safety Bureau (ATSB), was used as upper limit (Australian Transport Safety Bureau

2019). Table 3 provides documentation of the respective categories. The simulated aircraft represents turbofan aircraft of the wake categories medium, heavy and super as defined by International Civil Aviation Organization (ICAO) (ICAO 2017). The study analysed damage caused by strikes with all categories of birds represented in the simulation. The damage resulting from collisions with individual birds and flocks of birds were evaluated individually.

Table 4: Damaging bird strikes in the US between 1990 and 2016 (n = 141,538; Dolbeer et al. 2016)

Component	Hits (%)	Damaged per Category (%)	Damaged in Relation to all Strikes of all Categories (%)
structure	40.6	10.8	3.9
windshield	16.6	4.3	0.7
engines	12.4	25.8	3.2
other components	30.4	11.0	3.5
sum	100.0	-	11.3

Data To validate the study outcomes, the calculated damage rates were compared to bird strike reports gathered over 26 years in the USA (Dolbeer et al. 2016). Only bird strike records in which the damage was described as substantial or destroyed, which are expected to exceed the certification requirements, were included. The damage categories “none”, “minor”, “uncertain” and “unknown” were excluded. To evaluate the effect on the aircraft's structure, reports containing information about strikes on the nose, the wings and the fuselage were included. Table 4 shows the proportion of bird strikes experienced and those that caused damage for the relevant component types. The proportions, when excluding the remaining components, are defined in Table 5. Only 2.1% of all bird strikes were reported to have caused serious damage or led to destruction of an aircraft. Therefore, the proportion of serious damaging strikes considered in the model is considered to be 2.1% of all damaging strikes (i.e., far right column of Table 5).

3.0 Results

The Monte Carlo simulations revealed that according to the simulation, approximately three times more strikes occur than are reported for the reference airport. Bird movement information was extracted from reports from Eindhoven airport collected during a 10-year period. Movement patterns varied seasonally. An in-depth description of the results can be found in (Metz et al. 2017).

3.1 Simulated Damage

To analyse the potential impact of simulated bird strikes, their kinetic impact was compared to the certification requirements of the aviation authorities. Strikes exceeding the requirements were defined as damaging. There were 7879 reported strikes. The rate of damaging strikes was calculated for flocking birds, individual birds and all birds. Of all strikes, 15% involved flocks of birds. These caused 93.5% of all damaging strikes..

Table 5: Share of damaging strikes for the aircraft components considered in this study (from Dolbeer et al. 2016).

Component	Percentage damaged in relation to all damaging strikes of all categories	Percentage of damaging strikes in the categories substantial and destroyed	Percentage damaged in relation to all strikes of all categories when only considering substantial and destroyed
structure	35.2		0.75
windshield	6.4	2.1	0.1
engines	28.5		0.6

Table 6: Percentage of damaging strikes when considering all birds, flocks of birds and individual birds as well as the reference

	Damaging strikes all birds (%)	Damaging strikes flocks (%)	Damaging strikes individual birds (%)	Damaging strikes reference (%)
structure	2.8	18.1	0.1	0.75
windshield	2.8	18.1	0.1	0.1
engines	4.4	26.1	0.6	0.6

Table 7: Share of damaging strikes when considering all birds, flocks of birds and individual birds as well as the reference

Bird Group	Damaging strikes simulation (%)	Damaging strikes reference (%)
all birds	3.2	
individual birds	0.3	0.6
flocks	20.0	

Of the 65% of strikes where individual birds were concerned, they caused 6.5% of all damages. Table 6 summarizes the share of damaging strikes per component struck and damage category. The total damage rate results from standardizing the proportion of damaging strikes for each component category with the number of total occurrences (Table 7). Figure 2 presents the distribution of kinetic energy in relation to the certification criteria for structure, windshield and engines as well as bird groups

4.0 Discussion and Conclusions

With input data representing bird movement from avian and weather radar and different air traffic intensities, the simulation model overestimates the risk of bird strikes by a

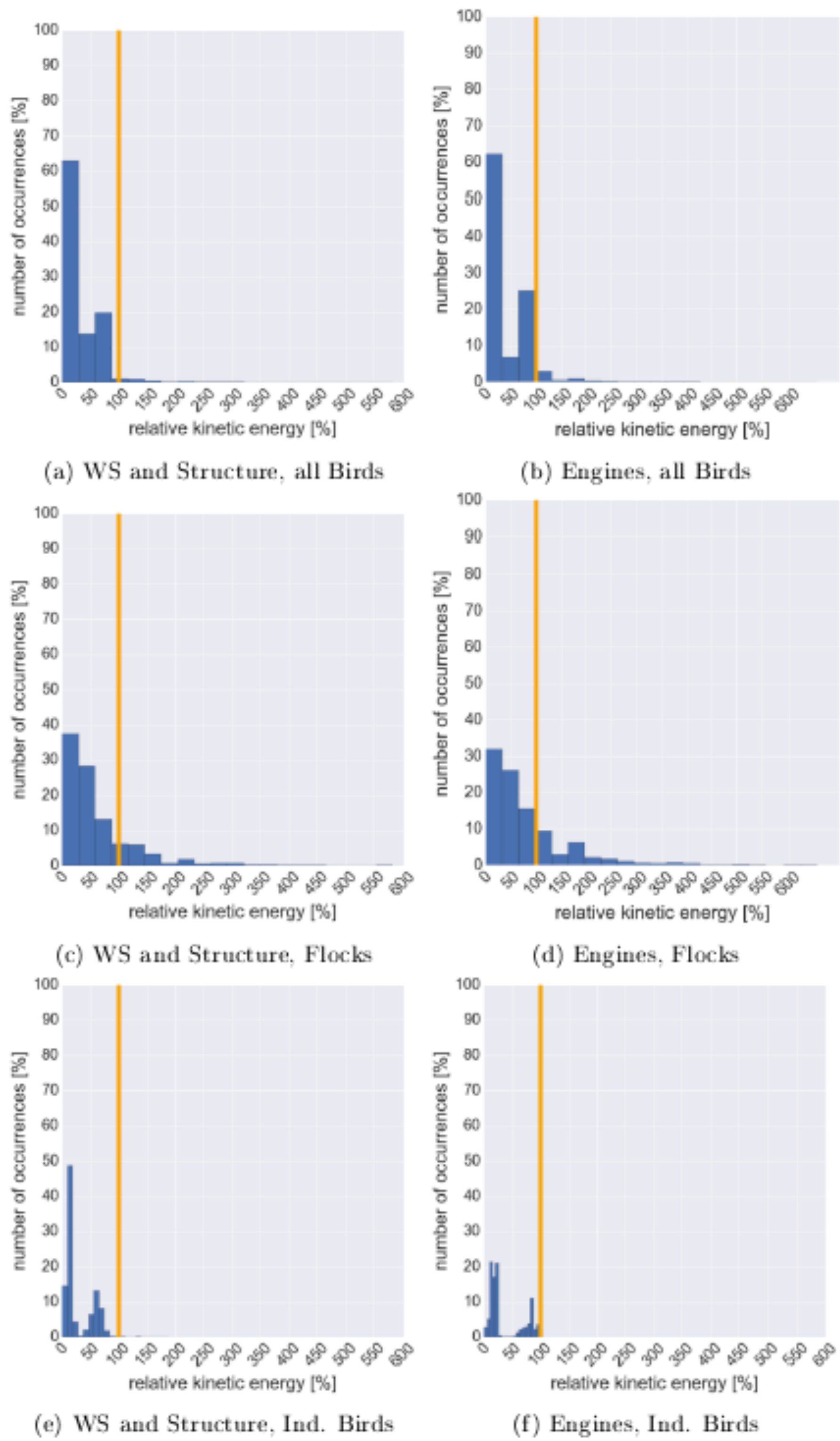

Figure 2. Distribution of kinetic energy for all birds, flocks and individual birds for the categories windshields (WS) and structure as well as engines (the orange bar represents the kinetic energy of the certification requirements).

factor of three when compared to observations from the reference airport. An overestimate was expected because no response of birds to aircraft was included in the simulation. The high seasonal correspondence between simulated and real data indicates the validity of the assumptions underlying the simulation. An in-depth discussion of the general simulation findings is provided in (Metz et al. 2017, Metz et al. 2018). This paper focused on the damage caused by simulated strikes. For this purpose, the kinetic energy at the time of the impact was calculated for all simulated strikes. This was compared to the kinetic energy aircraft have to withstand to comply with the certification criteria of the aviation authorities. The analysis was performed on the impact resistance of structure, windshields and engines. It was found that the damage rate is higher for engines than for structure and windshields. This is due to the different certification requirements of the components. Even though the applied bird mass is higher in the engine criterion (see Table 5), the reference velocities in the other criteria exceed the 200 kts applied to the engine criterion. Hence, the kinetic energy at which a damage results is higher for windshields and structure resulting in a lower number of occurrences.

Two certification requirements with different reference velocities are presented for aircraft structure (see Table 2). The aircraft has to be able to withstand the impact of the lower velocity. In the simulations performed, the criterion for aircraft structure referring to the reference speed at sea level was used to determine when damage occurred. Consequently, the results for structure and windshield are identical. The damage rates calculated in this study are higher than those reported to the FAA. Damage is strongly influenced by the biomass involved in the bird strike. Within the simulation, 15% strikes involving flocks of birds caused 93.5% of all damaging strikes. Hence, the overall damage rate of 3.2 % is strongly influenced by strikes caused by flocks of birds. With the exception of the reference value for engine damage, all references lie between the values for individual birds and all birds. This indicates an overestimate of the damaging strikes caused by collisions with flocks of birds created by a strong shift in kinetic energy experienced by the individual components as can be seen in Figures 2c and 2d. One reason might be that the flock model underlying the simulation environment originates from European data, while the reference values are obtained from the USA. For further validation, either data to generate a flock model for birds flying in the USA or comprehensive bird strike data from Europe in general and the Netherlands in particular would be required. Another contributing factor could be from the definition of protected zones (Figure 1). In the model, birds in flock fly in dense formation. The mass of all birds in the flock is used to calculate the kinetic energy of the impact. However, in reality, flocks fly in varying formations. In most strikes, not all birds are hit and not all of them strike the aircraft at the same location. Furthermore, due to the curved shapes of the aircraft's front surfaces, the impact force is reduced where glancing blows are experienced. As well, the calculations for the kinetic energy of simulated strikes do not include the relative velocity of the bird towards the aircraft's flight path. It is expected that due to the much greater aircraft speed, the influence of the bird velocity is relatively small. Hence, only a small improvement of the model is expected when including relative bird velocity. The simulation environment presented in this paper provides an opportunity to model the risk of bird strikes and to perform an initial estimate regarding the potential for damage. Simulated results deviate from reference values. However, due to the high number of occurrences both in the reference data and in this study, the offset should be relatively constant. By calibrating the model accordingly, the simulator output can be used for initial damage calculations. Further enhancements of the model could be achieved by refining the calculation of kinetic energy for flocks of birds. In addition, a validation with European bird strike reports would be beneficial.

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