IMPACT SCENARIOS FOR COLLISIONS WITH UNMANNED AERIAL VEHICLES AND THEIR CONSEQUENCES TO ROTORCRAFT

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Abstract

This paper presents different impact scenarios for collisions between rotorcrafts and small unmanned aerial vehicles (sUAV) as well as the corresponding consequences. As the popularity and number of sUAV in the airspace increases continuously also increases the risk of a collision between unmanned and manned aircraft. Possible impact scenarios are defined within this paper based on bird strike data. Up to now, there are no relevant data for the collision with a sUAV. But sUAV are similar in size and mass to birds and due to this, bird strike data can be used to determine impact load cases and locations. EASA's suggestion of drone sizes will be adapted for the collision with rotorcrafts. Furthermore, the structure of a drone is described. A drone consists of at least four main parts, the battery, motors, structure and payload. Each of these components represents another threat and these are evaluated on the basis of their risk potential. The FAA penetration equation and further penetration equations are used to describe analytical the threat of a drone strike to a helicopter. The final analytic results are rated by engineering judgement due to uncertainties in the analytic approaches. Based on these results, a test- and simulation program is developed to fully characterize the threat of a drone strike to manned rotorcraft. The main results are that a drone strike poses a greater danger to rotorcraft than to commercial airliners. Impact tests need to be performed to fully characterize the threat and will be done in further research activities.

1. INTRODUCTION

The popularity and disposal of small unmanned aerial vehicles (sUAV) is increasing continuously. Therefore, a collision between such sUAV and manned aircrafts seems ever more likely.

There are legal requirements (allowable mass, prohibited flight zones, height restrictions) to hobby pilots, which should minimize the probability of an impact. However occurrences of the recent past show, that these limitations are not met on the one hand and are not sufficient on the other hand. A recent confirmed UAV mid-air collision happened above the beach in Staten Island, New York, on 21.9.2017. A small drone (DJI Phantom 4) crashed into the rotor system of a UH-60 Blackhawk army helicopter [1]. Analysing the threat and possible impact damage of a mid-air collision between a sUAV and a manned aircraft is very important. Current certification specifications (e.g. CS 25 & CS 29) are made for bird strikes. A complete different impact behaviour of aircraft structures is expected for drone strikes due to the different material density, stiffness and strength values of the UAV components. Within this paper, only mid-air collisions are in focus.

The FAA points out that there will be more large UAVs in the airspace than general aviation aircrafts by 2033. The threat of a mid–air collision ends not only in technical damage. The economic damage could be immense, too. In July 2017 the runway at Gatwick Airport London was closed due to the sighting of a drone. The repair costs of an aircraft after a collision are an additional point [2].

Due to the reason that helicopters and sUAV are sharing the same airspace, within this paper, different impact scenarios between those aircrafts are defined. For this purpose, the affected parts (windshield, canopy, main rotor and fenestron) of the rotorcraft are evaluated. Furthermore, the main components (battery, motors, structure and payload) of the drone are selected on basis of their risk potential. The corresponding consequences to the rotorcraft structure are determined by analytic approaches and engineering judgement. In order to fully characterize the threat of a drone strike to manned rotorcraft, a test- and simulation program is developed.

1.1. Literature Review

The "Alliance for System Safety of UAS through Research Excellence" (ASSURE) revealed in July 2017 a report about the severity of UAV collisions with manned airplanes. They investigated structures of business and commercial jets. Their results show that a collision with a 1.2 kg quadrocopter drone leads to a serve damage at the stabilizers. The damage of the wings is medium,

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while the windshield shows a low level of damage. The drone parts with the largest threat have high densities and stiffness values, e. g. motors and cameras [2–6]. They validated their simulations with tests on coupon level. The Civil Aviation Safety Agency (CASA) released a report about the potential damage of mid-air collisions between manned and unmanned aircrafts. The conclusion of their work is, that an UAV will be ingested into the engines. Collisions at velocities above 200 kts may result in penetration of the skin. They suggest experimental data determination to validate their calculated results [7]. They use the FAA penetration equation. La Cour-Harbo [8] determined with a probabilistic approach that the mass threshold for a human injury is 0.25 kg. Barber shows general relationships for impact forces and pressures on rigid and compliant targets for bird strikes [9]. These relationships are the basis for analytic approaches for drone strikes. Song and Schroeder investigated damage within advanced propulsion systems due to UAV ingestion by explicit numerical simulations [10]. They simulated a single impact case, where a 5.6 kg UAV is ingested into a high bypass engine. The conclusion is, that this collision is a significant threat to the whole airplane. Song and Schroeder extended their work in other papers. They compared a bird strike with drone strikes on composite engine fan blades [11]. Furthermore, they extended the results to more drone subclasses [12]. It can be said that the drones have a higher threat level than current CS (e.g. CS 25/CS 29) specify under their bird strike requirements. As the Civil Aviation Authority (CAA) points out, a large threat to manned aircraft are medium sized drone with a mass of 2 kg or less [13], due to unawareness of the operators. A study from UK identified that the tail rotor is very vulnerable. Even small drones could lead to a failure of the blades [14].

The threat of a mid-air collision between a drone and a helicopter and general aviation is generally higher than for commercial aircraft. There are two points, which lead to this assumption:

- Their operating areas involve lower – level flying which includes the typical flight level of drones
- Windscreens are not subjected to the same registration restrictions as commercial aircrafts

2. DRONE SIZES AND STATISTICS

2.1. Drone sizes

The European Aviation Safety Agency (EASA) splits up the category of drones into three subcategories: Open category, specific category and the certified category. The first one is also divided into four further levels and has a mass threshold of 25 kg. EASA estimates the threat from this category as a “low risk”. The specific category has a “medium risk” according to EASA and the last one has a “high risk” level. The sublevels of the open category are “Harmless”, “Small”, “Medium” and “Large”. EASA subdivided the open category by the threat of the drones to commercial airplanes [15]. The mass is the limiting factor. Drones of the harmless category have a maximum take-off weight (MTOW) of 0.25 kg; the MTOW of small drones is 0.5 kg, medium drones have a MTOW of 1.5 kg and drones of the large category have a MTOW of 3.5 kg. Only drones of the open category are investigated. The following Figure 1 illustrates the mass thresholds of the open category drone types. An example for each size can be seen.

Figure 1: Drone sizes and examples of EASA's "Open Category" and the breakdown into further subcategories

Drones of the open category are the largest threat to helicopters due to the unawareness of their pilots. In Germany, hobby pilots without a licence are allowed to fly drones with a MTOW up to 2.0 kg. This mass is larger than the mass of the largest bird of the bird strike regulations for commercial airplanes (1.81 kg). The maximum allowed flight altitude in Germany are 100 m above ground with a maximum speed of 20 m/s. Due to this facts, drones are a significant threat to helicopters.

2.2. Statistical Evaluation

Figure 2 shows the estimated number of drones in German airspace. It can be seen that the number of drones, which are used in commercial areas, is almost constant from 2017 to 2020. In 2017 four times more drones were sold than in 2016. In contrast to this is the usage of drones within the hobby area. The number of drones for hobby usage will be doubled from 2016 to 2020. All in one there will be about 1,13 Million drones within the German airspace by 2020 [16]. The study from the German Air Traffic Control (DFS) does not look at what types of drones are sold.

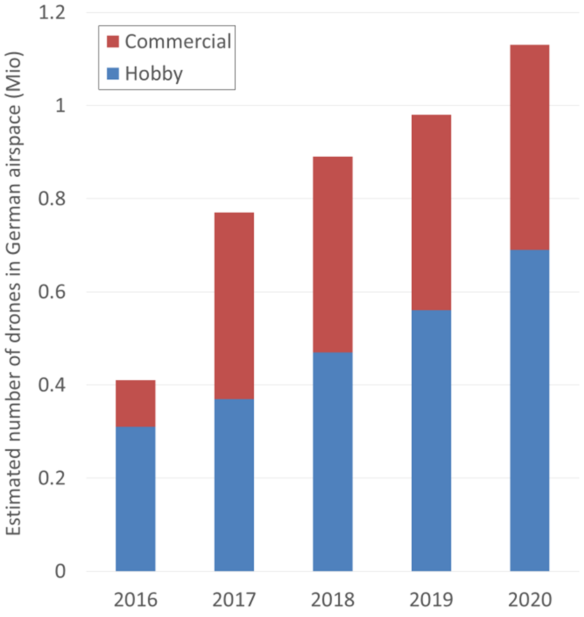


Figure 2: Estimated number of drones in German airspace, DFS (2017) quotes after [17].

The number of incidents between drones and aircrafts has been rising since 2015. 14 incidents happened 2015, 64 in 2016. In 2017, there were 89 incidents with civil drones in Germany. It can be said that the threat rises continuously. [16]. Figure 3 illustrates the rise of incidents.

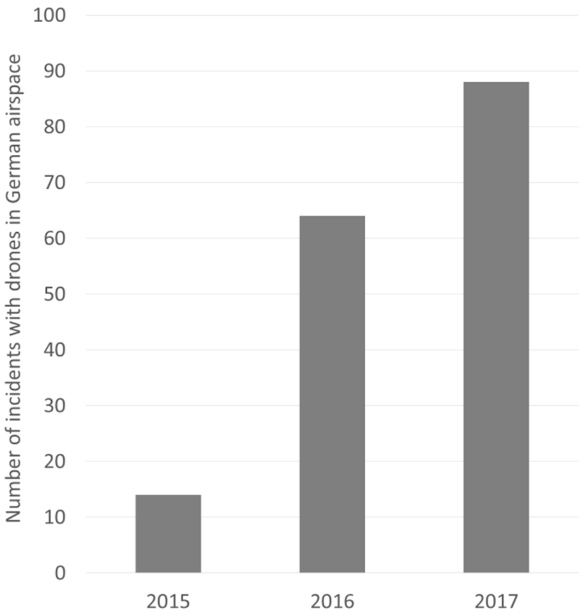


Figure 3: Number of incidents with drones in German airspace [16]

3. DAMAGE POTENTIAL

3.1. Estimated damage potential based on bird strike data

The Aviation Safety Network Database (ASN) provides data from 17 descriptions of confirmed and suspected drone strikes with aircrafts [18]. 10 drone strikes are confirmed, 7 are suspected. Up to now, there have been no fatalities due to drone strike. The CAA estimates that there are two near encounters each million flights. The real collision threat would be less than this value [13].

Due to the small number of confirmed drone strikes, a statistical evaluation can not be performed. Bird strike data have been collected for more than 100 years. Due to the similar size and mass of birds in comparison with drones, bird strike data can be used as a basis for determining endangered structures.

Atkins and the UK Foord & Environment Research Agency performed a study about the current aircraft certification requirements in relation to bird strike risks. They investigated bird strikes in the US, Canada and UK from 1990 to 2007. Table 1 shows the outcome of the study for the number of bird strikes on helicopters. The helicopter types are divided according to their certification specification in small (CS 27) and large (CS 29) rotorcrafts [19]. It can be seen that the highest number of strikes for small helicopters occurs on the windshield. For large helicopters, most bird strikes occur on the rotor system. Nevertheless, bird strikes on windshields lead to more damage than on rotors, according to the study. These data are used as a basis for possible damage locations due to drone strike. It has to be said that there are uncertainties because a drone will not show the same behavior like a bird when it comes to a mid – air collision. The behavior of birds during an impact is assumed to be like a flowing fluid. In contrast, the behavior of a drone during impact will be completely different due to the materials.

Table 1: Nunber of bird strikes and percentage of damage on H/C dependend on size and component [19]

	CS-27	% Damage	CS-29	% Damage
Radome	0	-	1	0.00
Windshield	38	68.4	29	24.10
Nose	7	57.1	11	27.30
Rotor	26	11.5	90	7.80
Fuselage	8	12.5	18	16.70
Landing Gear	1	0	4	0.00
Lights	0	-	1	0.00
Tail	4	25	6	0.00

Derived from the results of Table 1 it is assumed that the most affected parts for mid – air collisions with drones will be the windshields as well as the rotor system.

The threat of a collision with a windshield part is, that there could be penetration, which can be seen in Figure 4.

Figure 4: Penetration of windshield [20]

The penetration of the windshield could lead to injuries of the pilot or occupants. Damages on the rotor system, flight control system and anti torque system could lead to a possible loss of control. The real threat depends on the drone size, parts, speeds and impact location. Figure 5 shows an overview about possible events after a proximity between a drone and a rotorcraft. The figure is taken and adapted from [13].

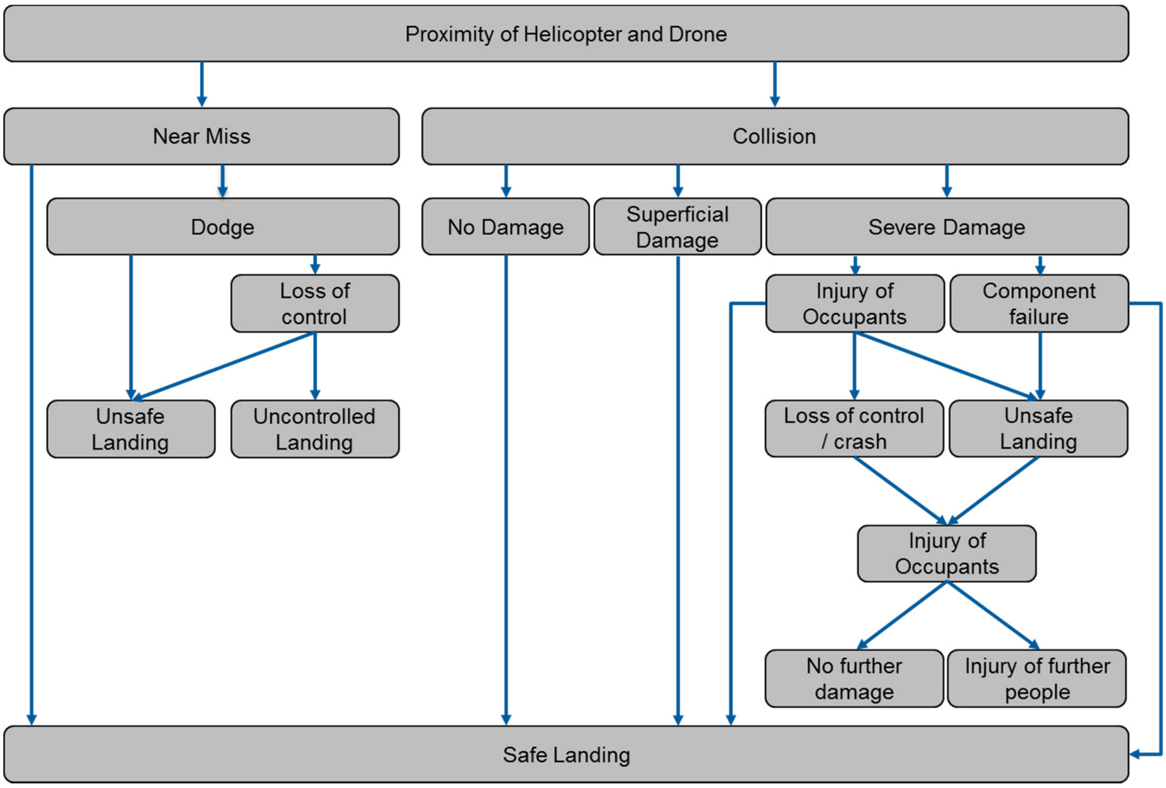


Figure 5: Possible events after a proximity between drone and helicopter - taken and adapted from [13]

3.2. Drone structural components

A DJI Phantom 2 is dissembled into its parts. Each component is weighed. The five heaviest components are listed in the following Table 2. The results are rounded to whole numbers.

The whole DJI Phantom 2 weighs 983 g without camera system and gimbal. The lithium polymer battery is the heaviest component with 368 g. Both sides of the casing consists of plastic materials. The top side weighs 76 g, the opposite casing weighs 97 g. The motherboard is a circuit board within the drone and weighs 67 g. One of the four motors weighs 50 g. A motor consists of aluminum, copper and steel. Nevertheless the motors pose a greater threat during a collision than the casing and the motherboard. The motors of the drone are exposed and outside the structure while the motherboard is inside the drone structure. Based on the material they are made of, it is assumed that the motors behave like ballistic projectiles. It can be said by engineering judgement, that the battery and the motors pose the largest threat to manned aircraft within a mid-air collision, due to their weight and location. Figure 7 and Figure 6 show the battery and the motor.

Table 2: DJI Phantom 2 component weights

Component	Weight [g]
DJI P2 (without camera)	983
Battery	368
Casing Down	97
Casing Top	76
Motherboard	67
Motor	50

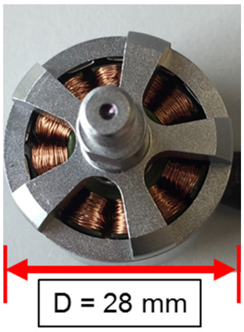


Figure 6: DJI Phantom 2 motor

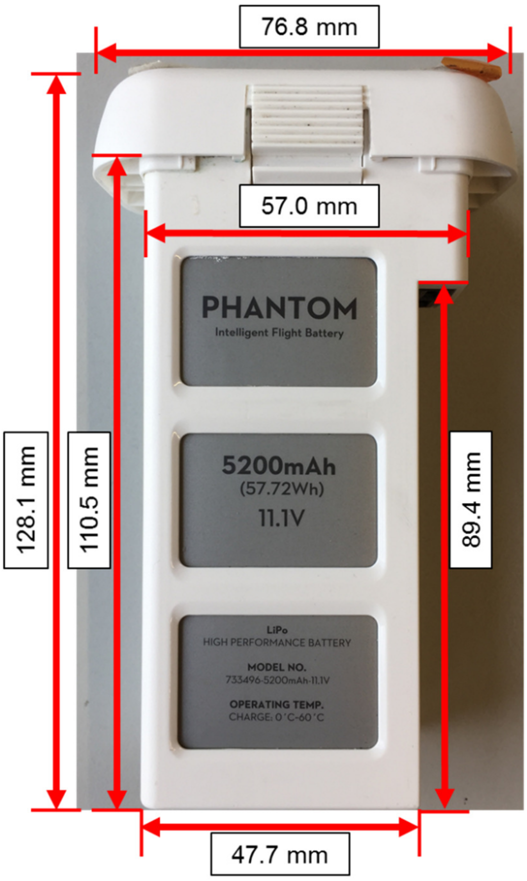


Figure 7: DJI Phantom 2 battery

4. DRONE STRIKE ANALYTICAL APPROACHES

Additional important, next to simulations and experiments, are analytic approaches to model a drone strike. The main problem is, that the determination of the ballistic limit of an aircraft structure is only possible by performing extensive tests. With an analytic approach it would be possible to design the structure to withstand a drone strike. Within this chapter, analytic approaches for determination of ballistic limit speeds resp. critical energies are introduced.

While birds can be assumed as flowing fluids, this assumption is not valid for sUAV due to their components and materials. The main difference is the mass and density of the drone parts. This leads to different results for bird- and drone strike analysis.

It is possible to determine the ballistic limit speed v_{50} with the FAA penetration equation (1). This equation is valid for isotropic materials. This equation leads to conservative and accurate results in turbine fragment tests [21]. The penetration equation is based on the energy, which is needed to punch a hole in a sheet of metal [7].

(1) $$v_{50} = \sqrt{\frac{2LC_S t^2}{m\cos^2\theta}}$$

L is the perimeter of the projectile, C_s is an empirically determined shear constant resp. strength, t is the target thickness, m is the projectile mass and θ is the angle between projectile velocity vector and the plane of the target. Only perpendicular impacts are investigated, which leads to $\cos\theta = 1$. Equation (1) has two shortcomings. The first one is the empirical determination of the parameter C_S. The other one is the determination of the perimeter L.

CASA's study [7] is taken and expanded with further analytic formulations from ballistic impact engineering. Corbett et al [22] reviewed different analytic approaches to determine the critical energy which is needed to penetrate a plate or shell. It is assumed that the critical ballistic limit speed v_{50} is reached if the kinetic energy E_{kin} equals the critical energy E_c.

(2) $$E_{kin} = E_c \rightarrow v_{50} = \sqrt{\frac{2E_c}{m}}$$

The different formulas, based on Taylor's (3) [23] and Bethe's (4) approach are very similar. They only vary in one factor.

(3) $$v_{50} = \sqrt{\frac{2.66\pi r_p^2 t\sigma_y}{m}}$$

(4) $$v_{50} = \sqrt{\frac{4\pi r_p^2 t\sigma_y}{m}}$$

Taylor defined the work for unsymmetric deformation in [23]. With (2) the critical velocity can be calculated by formula (5):

(5) $$v_{50} = \sqrt{\frac{\pi r_p^2 t\sigma_y}{m}}$$

r_p is the projectile radius, σ_y is the dynamic yield strength. Woodward [24] developed the Thompson model for unsymmetric failure (6):

(6) $$v_{50} = \sqrt{\frac{2}{m}\left(\pi r_p^2 t(\frac{1}{2}\sigma_y + A\rho\left(\frac{v_0 r_p}{L_o}\right)^2\right)}$$

The constant $A = 1$ for conical projectiles and $A = 1.86$ for ogival projectiles. ρ is the target density and L_0 is the projectile length, v_0 is the initial projectile velocity.

For a first analysis it is assumed that $C_S = \sigma_y$. The ultimate shear strengths are taken from CASA [7]. Aluminium has a shear strength of $C_s = 276\,MPa$ and polycarbonate (lexan) of $C_S = 68\,MPa$. The following values in Table 3 are taken from CASA. They are expanded with projectile parameters (motor and battery) from a DJI Phantom 2 Quadcopter.

Table 3: UAV dimensions from [7] including DJI P2 component values

	Item	Geometry	Dimensions [mm]	Weight [g]
Quadcopter Small	Motor A	Cylinder	D = 45; L = 12	67
	Battery A	Block	25 x 50 x 65	160
	Camera A	Block	42 x 60 x 30	190
Quadcopter Big	Motor B	Cylinder	D = 47; L = 33	154
	Battery B	Block	45 x 45 x 138	583
	Camera B	Block	148 x 110 x 74	820
Single Engine	Motor C	Cylinder	D = 118; L = 120	2730
DJI Phantom2	Motor DJI	Cylinder	D = 28; L = 25	50
	Battery DJI	Block	77 x 44 x 128	368

Figure 8 and Figure 9 show calculation results for all presented formulations for the penetration speed of aluminium samples. The blue bar is the typical final approach speed of a commercial airliner with $85\,m/s$. The green bar is a typical highest cruise speed of a helicopter assumed as $75\,m/s$. The initial projectile velocity is assumed to be $80\,m/s$. The density of aluminium is $2.7\,g/cm^3$.

The density of polycarbonate (lexan) is $1.2\ g/cm^3$. The dots are calculated values for the specific formulas. If the value is below the bar, it is likely that the impactor will penetrate the sample. If the value is above the bars, the penetration of the material is unlikely. It can be seen that the different formulas lead to various results. While the FAA penetration equation leads to conservative results, the calculation with formula (4) predicts no penetration for both aluminium samples by the highest helicopter cruise speed.

CASA calculates the damage threat for polycarbonate plates with various thicknesses with the FAA penetration equation, too. In Figure 10 and Figure 11 the calculation results for all formulas are shown for polycarbonate. It can be seen that the thick polycarbonate plate is likely to penetrate if Motor C or Battery B hits the structure. Another result is, that equation (1) is not the most conservative approach for thick structures, due to the quadratic influence of the target thickness in the FAA equation.

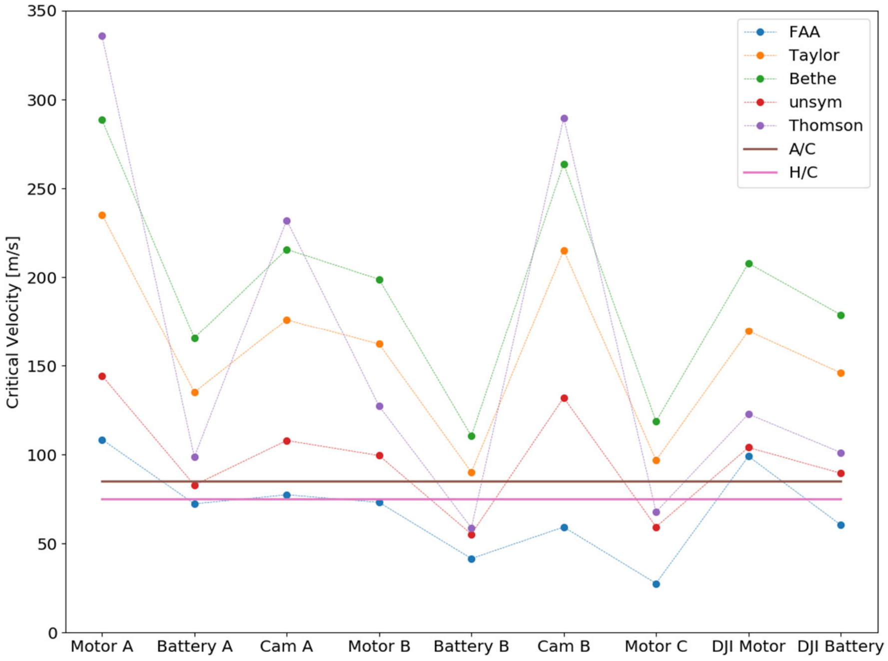


Figure 8: Analytic calculation of the critical velocity of aluminium with t = 3.175 mm

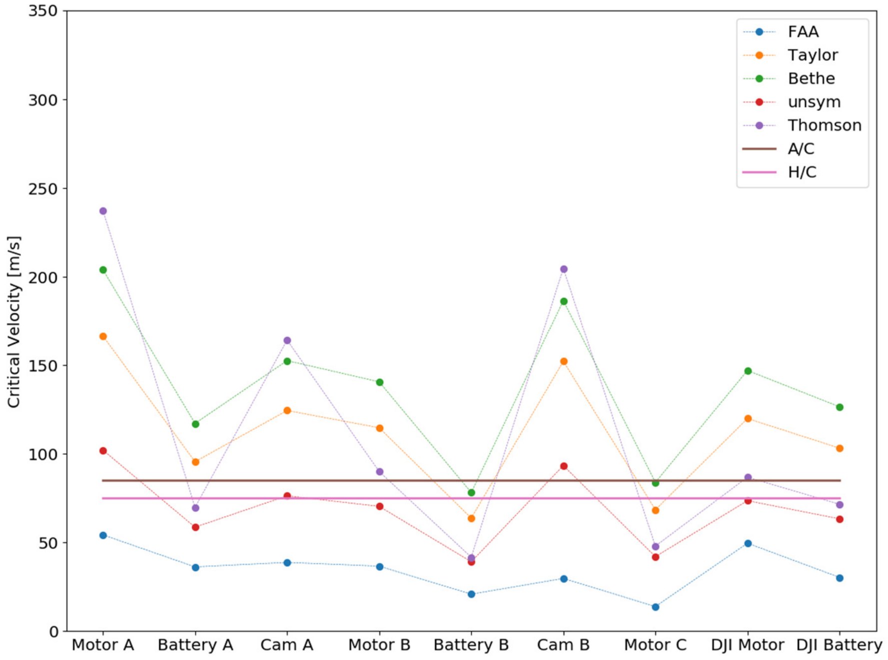


Figure 9: Analytic calculation of the critical velocity of aluminium with t = 1.5875 mm

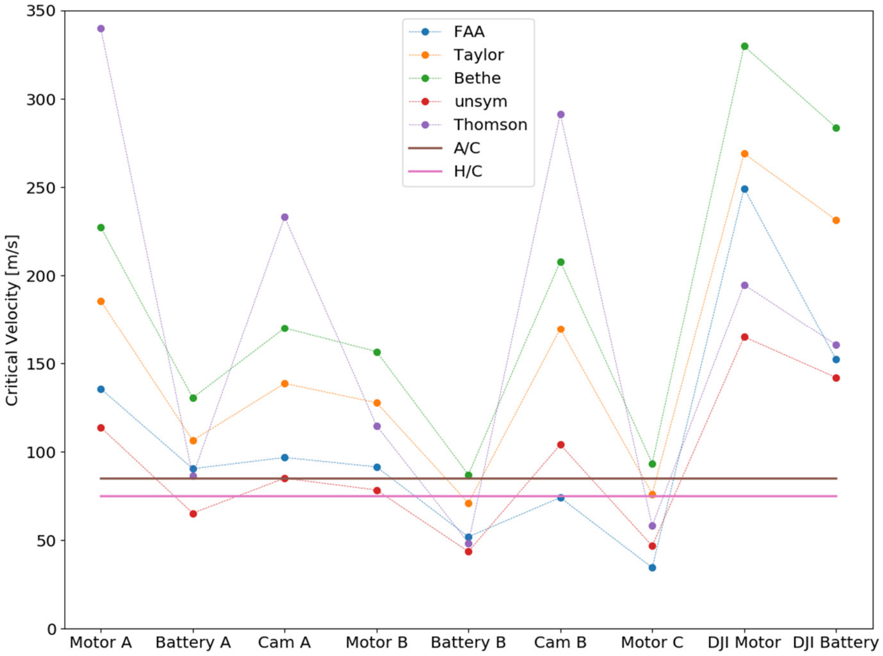


Figure 10: Analytic calculation of the critical velocity of polycarbonate samples with t = 8.00 mm

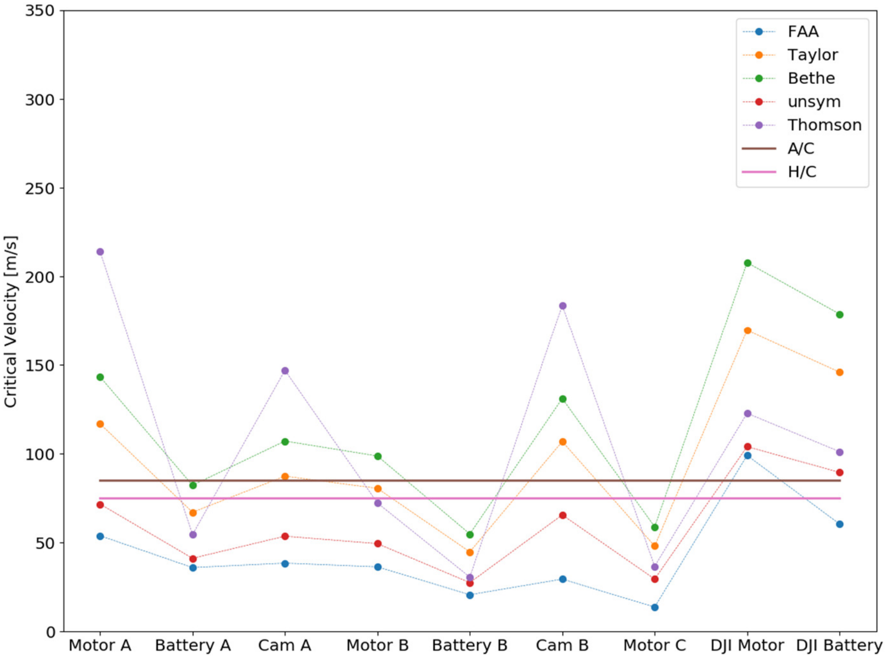


Figure 11: Analytic calculation of the critical velocity of polycarbonte samples with t = 3.175 mm

Is the thick polycarbonate plate left out, components of a DJI Phantom 2 are likely to penetrate the different structures. The current EASA drone class of a DJI Phantom 2, specified by its threat to commercial airliners, is “medium”. This category seems to underestimate the threat for aircrafts. The criteria in the certification specification CS 29.631 for large rotorcraft is, that there is no penetration of the windshield and that a continued safe flight and landing is possible after a 1 kg bird hits the aircraft. As the calculations results show in Figure 11, the polycarbonate could be penetrated by drone components of medium size. The mass of the UAV components is less than 1 kg. Polycarbonate is a possible material for H/C windshields. Due to this fact, the threat should be classified as “large” for rotorcrafts colliding with drone of a MTOW = 1 kg or higher. The threat for fixed wing aircrafts should be investigated, too. The harmless and small categories are not adjusted. Drones with a MTOW between 500 g and 1000 g could be classified as a “medium” threat. Table 4 shows the suggested drone classes and their specifications in respect to their threat to rotorcrafts.

Table 4: Suggestion fo generic drone threat specifications for rotorcrafts

Drone Class Threat	Component	Weight [g]
Harmless	Drone	250
	Battery	65
	Motor	7.5
Small	Drone	500
	Battery	130
	Motor	15
Medium	Drone	1000
	Battery	296
	Motor	36
Large	Drone	over 1000

The results show a strong variance depending on the calculation approach. The calculation results need to be validated by experimental data.

It has to be pointed out that this suggestion is based on first analytic calculations and engineering judgement. No impact penetration tests are performed to verify the results. The following chapter will present a suggestion for possible test campaign to verify the real drone threat.

5. DRONE STRIKE EXPERIMENTAL APPROACHES

The determination of the threats of drones shows an importance of performing impact tests. The following chapter presents a possible test campaign for performing impact tests to analyze the real threat of drone strikes.

5.1. Extended Building Block Approach

The approach chosen follows the classic building block approach widely used in aeronautics. Testing efforts are accompanied with Finite Element Analysis (FEA) during the complete process. Therefore the term extended building block approach gives a better description of the planned work. This extended building block approach can be seen in Figure 12.

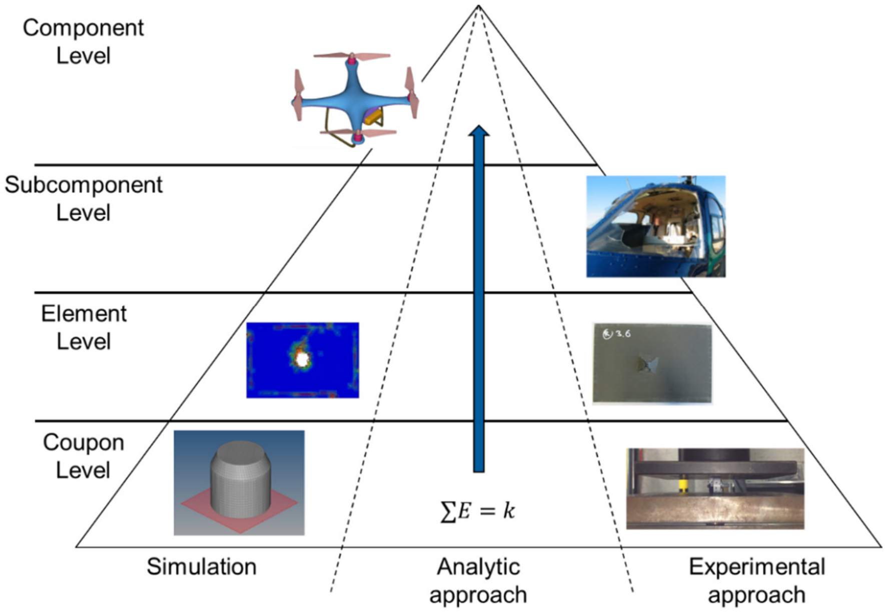


Figure 12: Extended building block approach

Each test level is also used as kind of screening effort with the possibility for adjustments for higher test levels.

Based on disassembly of widely used drones the most threating drone components for impact scenarios are defined. Motor and battery package are considered as potentially most harmful components. The shown and preplanned test matrix relies at first instance on these components not excluding additional parts for final test setup if applicable.

5.1.1 Coupon Level

At coupon level different kind of tests are foreseen. To derive basic data and impression of the behavior of drone components quasi-static testing in standard hydraulic test rigs will be performed. This is used as input for the FEA analysis, too. These parts of coupon level tests are regarded as level 1 – test campaign.

First high speed impact testing of drone components on a rigid target plate are regarded as level 2 – testing campaign. A gas gun testing device with specific measurement equipment like light barriers, load cells and laser sensors will be used for these tests. High speed camera footage and force-time-curves of the impact events are primary output of this experimental work. Impact velocities are under discussion.

5.1.2 Element Level

Level 3 – testing efforts are considered already as element test level. These include the impactors identified during pre-tested levels. The setup will be extended for impact tests of deformable rectangular target samples. They represent structural items most likely threatened by a drone impact event. Velocities are according to the ones used for level 2 – testing to achieve straight results. Testing devices and setup will be the same as for level 2 testing. Post-impact investigation will give first impressions of possible kinds and size of damage.

5.1.3 Subcomponent Level

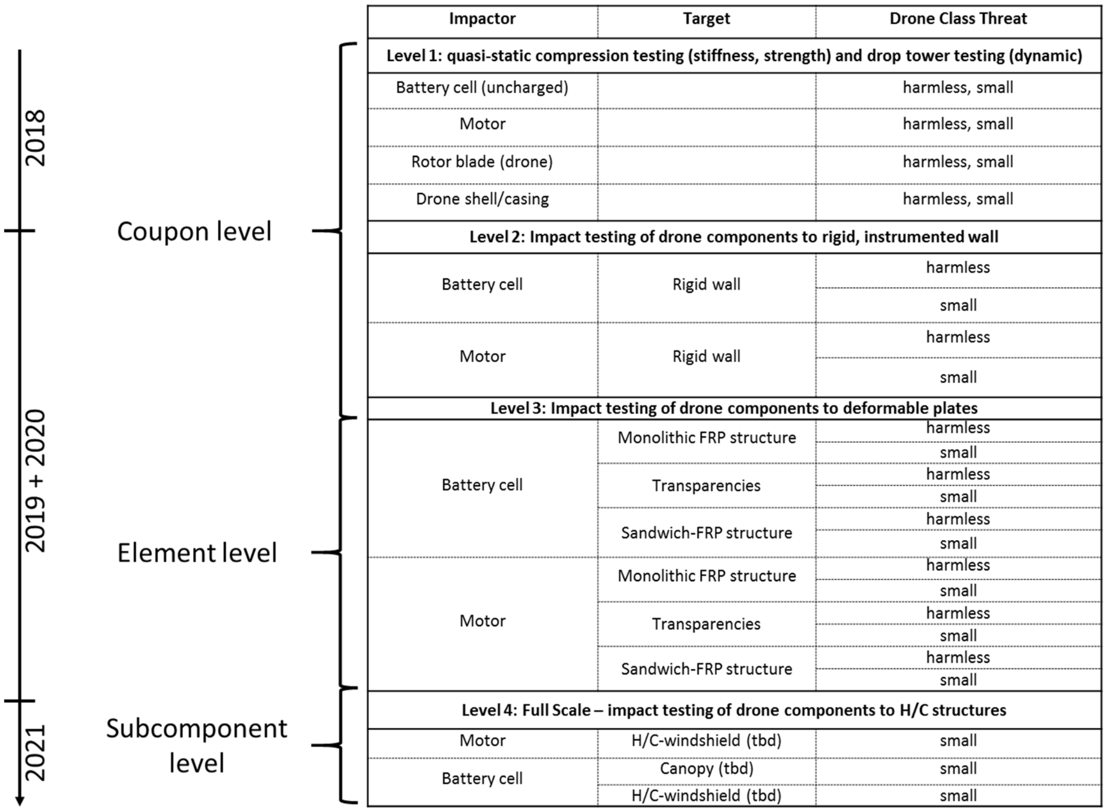
Subcomponent level testing according to the extended building block approach will be considered as level 4 - testing. These will include impact testing with a gas gun device of drone components to full scale helicopter (H/C) structural parts. Detailed definition of test articles and setup have to be defined. Measurement setup will provide high speed camera videos and force-time-curves. Post impact investigation will show the occurring damage of drone impact events.

5.1.4 Component Level

On component (full size drone) or H/C-level no testing campaign is intended to be carried out. These investigations will be only performed FEA based and validated in the test series of lower levels.

5.2. Test Matrix Summary

Fehler! Verweisquelle konnte nicht gefunden werden. shows a summary of planned testing campaign over all levels together with envisaged timeline of the project.



Impactor	Target	Drone Class Threat
Level 1: quasi-static compression testing (stiffness, strength) and drop tower testing (dynamic)		
Battery cell (uncharged)		harmless, small
Motor		harmless, small
Rotor blade (drone)		harmless, small
Drone shell/casing		harmless, small
Level 2: Impact testing of drone components to rigid, instrumented wall		
Battery cell	Rigid wall	harmless
		small
Motor	Rigid wall	harmless
		small
Level 3: Impact testing of drone components to deformable plates		
Battery cell	Monolithic FRP structure	harmless
		small
	Transparencies	harmless
		small
	Sandwich-FRP structure	harmless
		small
Motor	Monolithic FRP structure	harmless
		small
	Transparencies	harmless
		small
	Sandwich-FRP structure	harmless
		small
Level 4: Full Scale – impact testing of drone components to H/C structures		
Motor	H/C-windshield (tbd)	small
Battery cell	Canopy (tbd)	small
	H/C-windshield (tbd)	small

Figure 13: Test matrix proposal with timeline

6. CONCLUSION AND OUTLOOK

In conclusion it can be said that drones pose a greater threat to rotorcraft than to commercial airliners due to their field of application. Calculation results show that even small drone parts could penetrate aircraft materials. The number of drones as well as the number of incidents is continuously increasing. There are not enough drone strike data hence bird strike data is used to determine affected helicopter structural parts. Birds and drones are comparable in size and weight. The impact behaviour will vary because a bird consists 90% out of water. The highest number of strikes can be assumed for rotors and windshields. The heaviest component of a drone is the battery. Due to the exposed location and its materials, the drone motor is another specific component with a large threat to rotorcraft. Different approaches for determining the ballistic limit speed are taken from ballistic impact engineering algorithms and compared with the FAA penetration equation. The penetration equation leads to conservative results. It predicts penetration for all calculated examples dependent on projectile size and mass. The component location is not considered. The calculation results show a strong variance depending on the analytic approach. The results have to be validated by tests to determine a suitable penetration equation. EASA's suggestion for drone classes within the open category (up to 25 kg), specified by their threat to commercial airliners, seems not valid for rotorcrafts. CS 29.631 defines that a continued safe flight and landing must be possible after a 1 kg bird strikes the rotorcraft. Based on this specification and the calculation results it is proposed that the threat from every drone for a rotorcraft with a MTOW above 1 kg is categorized as "Large". In addition a test matrix is presented for validation of the analytic results with test data. In the end, based on the results of the presented test campaign and analysis it may proposed that for drone strike requirements, a similar approach could be used as is currently proposed in AC 29-2C, Change 4, AC 29.631 for birds and is revised and extended towards drone strike events.

Further research is needed, especially in the area in performing real tests. Furthermore, the analytic methods should be adjusted to calculate and estimate the loads during a drone strike event.

Acknowledgements

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Copyright Statement

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