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Collision Severity Evaluation of Generalized Unmanned Aerial Vehicles (UAVs) Impacting on Aircraft Engines

Sivakumar Anush Kumar, Mohd Hasrizam Che Man, Hu Liu, Kin Huat Low*

Abstract — This paper is devoted to investigating the collision severity of generalized UAVs impacting aircraft engines. The peak impact force and fracture of the CFM56 engine blades were evaluated using FEM and Explicit Dynamics simulations on ABAQUS. In this study, Multiple Linear Regression (MLR) analysis was performed to obtain appropriate dimensions for the modelling of quadcopter UAVs. Maximum Take-off Mass (MTOM) values of 0.5kg, 1kg, 2kg were assigned based on dimensional analyses from 39 commercial UAVs. For the simulation, parametric variations in MTOM, aircraft speed of UAV, and rotational speed of engine fan blades were adopted. Results indicated that contact forces to the blades due to collision were more severe with UAV MTOM of 1 kg and above. This was prominent in the most severe case, with the UAV camera having a head-on collision with a fan blade. However, it was notable that simulations were case-dependent as the UAV trajectory and point of collision varies for each scenario. Further studies are required to consider the influence of various UAV trajectories and component level sizing on the engine collision severity.

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have garnered high popularity due to their extensive range of applications. Furthermore, UAV technology is also being vastly utilized in airports for inspection of maintenance procedures and monitoring of luggage and cargo. By 2025, the UAV market size is forecasted to expand to USD 42.8 billion from USD 22.5 billion in 2020 [1]. Consequently, the soaring growth of the UAV market has likely contributed to a rise in airborne conflicts such as mid-air collisions between UAVs and aircraft.

In contrast, bird strike collisions can aid in determining the likelihood of an aircraft structure is impacted. Amongst the 30 fatal bird-strike accidents that occurred since 1960, 23 were due to one or more engines being struck [2]. Hence, the risk of hazardous consequences is more significant when birds are ingested into engines as it is likely to result in partial or total loss of thrust [3]. Subsequently, collisions between aircraft and UAVs are more severe than with birds due to the highly dense material composition and increased impact airspeed of UAVs [4]. This highlights the need to

study the collision severity of UAVs and aircraft, particularly collisions leading to engine ingestions.

The aim of this study was to investigate the collision severity of generalized quadcopter UAVs impacting an aircraft engine using Finite-Element Analysis (FEA) simulation on ABAQUS. To model the generalized UAV, dimensional analyses were performed on UAVs to identify appropriate dimensions. Simulations were centered on collisions between quadcopter UAVs and aircraft leading to engine ingestions. Currently, there is little standardization and no conclusive research as to which UAV model to adopt for simulation studies. As such, UAV modelled with generalized dimensions and primitive shapes were adopted to represent most UAVs in the commercial market.

Insights from this study would aid aviation authorities to establish hazard severity thresholds to minimize the likelihood of a collision. This study would further facilitate the development of new safety regulations for UAV manufacturers and operators.

II. LITERATURE REVIEW

The literature review will be divided into two areas: collision severity studies and authoritative research on UAV collisions.

A. Collision Severity Studies

CASA, in collaboration with Monash University, performed a damage assessment for a potential mid-air collision with a small UAV [4]. The study assumed that the high-density components of an UAV such as the motors, battery pack and camera pose the greatest penetration threat. Results from the study concluded that a collision between UAV and commercial aircraft is highly likely to result in engine ingestion. However, it is important to note that the study concluded that its results should be regarded as rough estimates as actual UAV components were not used.

FAA, in conjunction with the Alliance for System Safety of UAS through Research Excellence (ASSURE), studied and evaluated the collision severity of UAVs with aircraft jet engines [5, 6]. Simulations were modelled with non-linearity and explicit time integration. The Johnson-Cook constitutive model was selected for the UAV main frame as it best captures the elastic and plastic characteristics, strain-rate, and temperature variations of the material. Results from the study showed that the damage classification on the engine is highest during the take-off

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scenario, in which the rotational speed of the fan reaches its maximum.

Vignjevic et al. performed parametric studies on bird strikes to aircraft blades using the Smoothed Particle Hydrodynamics (SPH) model of the bird [7]. Results from the study indicated a peak impact force of 170 kN for the hemispheroidal model.

B. Authoritative Research on UAV Collisions

The European Aviation Safety Agency (EASA) 'Drone Collision' Task Force was assembled to assess the risk of collision between drones and aircraft [8]. The research focused on drones widely available in the market and classified them according to the 'Open Category' which was recommended by EASA. The drones were categorized to limit the assessment, as well as better represent the bulk of UAVs available in the market. The four classifications of drones in the 'Open Category' are indicated in TABLE 1. Results from the study highlight that an aircraft colliding with a 'Large' drone shows the highest risk of penetration and damage as the kinetic energy at 250 knots exceeds that of bird weighing 4 pounds. Hence, the scope of the current study included 'Small', 'Medium' and 'Large' only as the 'Harmless' classification has been studied by [9].

TABLE 1 EASA 'OPEN CATEGORY' CLASSIFICATIONS [6].

Classification	MTOM
Large	3.50 kg
Medium	1.50 kg
Small	0.50 kg
Harmless	0.25 kg

The Civil Aviation Authority (CAA) performed an initial assessment to understand the risk and likelihood of an unintentional collision between a drone and manned aircraft [10]. The findings from CAA's assessment indicated that drones that weight typically 2 kilograms (kg) or lower have an increased tendency to be within the same proximity as an aircraft. This is usually due to the incompetency of drone operators flouting aviation regulations. Figure 1 depicts the trend of the approximate cost of a drone with its mass.

Figure 1. Drone cost with mass [6]

III. COMPUTATIONAL MODELLING

It is crucial to understand the computational modelling on ABAQUS as it was chosen as the FEA solver for this

study. It was observed that explicit dynamic analysis is more efficient in treating non-linearities and complexities than implicit dynamic analysis with its reduced computational cost and conditional stability [11, 12]. Thus, the ABAQUS/Explicit module will be chosen, and explicit dynamic analysis will be performed for the simulation of collision between UAV and aircraft engine in this study.

A. Explicit Dynamics Analysis

ABAQUS/Explicit uses an explicit algorithm solver. For an explicit dynamic analysis, the central-difference method is used. The computational cost for every increment is relatively lower as it is not required to solve the equilibrium equations. Furthermore, time incrementation for a simulation is automatically adjusted by the software. This is achieved by controlling the stability limit of the central-difference method. In addition, explicit solvers are preferred for finite element problems with high non-linearity and velocities. The governing equations for the central-difference integration operator are as follows [13]:

$$\dot{u}^{(i+\frac{1}{2})} = \dot{u}^{(i-\frac{1}{2})} + \frac{\Delta t^{(i+1)} + \Delta t^{(i)}}{2} \ddot{u}^{(i)} \quad (1)$$

$$u^{(i+1)} = u^{(i)} + \Delta t^{(i+1)} \dot{u}^{(i+\frac{1}{2})} \quad (2)$$

Where, $\dot{u}$ and $\ddot{u}$ represents the velocity and acceleration, respectively, whereas the superscript (i) is the increment. Thus, (i-1/2) and (i+1/2) refer to the middle values of increments. The computational advantage of the explicit solver is attributed to the diagonal element mass matrices which are used [13].

$$\ddot{u}^{(i)} = M^{-1} \times [F^{(i)} - I^{(i)}] \quad (3)$$

In the equation above, M^{-1} is the inverse of the mass matrix, F refers to the vector of applied forces, and I refer to the vector of internal forces. Furthermore, it is important to note that the central difference operator must be defined as an initial mean velocity. Thus, the following initial conditions of acceleration and velocity are zero when time, $t = 0$, resulting in the following equations [13]:

$$\dot{u}^{(+\frac{1}{2})} = \dot{u}^{(0)} + \frac{\Delta t^{(1)}}{2} \ddot{u}^{(0)} \quad (4)$$

$$\dot{u}^{(-\frac{1}{2})} = \dot{u}^{(0)} - \frac{\Delta t^{(0)}}{2} \ddot{u}^{(0)} \quad (5)$$

Lastly, the stability limit in the explicit integration operator ensures the analysis to be conditionally stable. The stability limit, Δt is computed using the characteristic element dimension, L_e , Lamé's constants, λ and μ and density, ρ as shown [13]:

$$\Delta t \leq \frac{L_e}{\sqrt{\frac{\lambda + 2\mu}{\rho}}} \quad (6)$$

IV. NUMERICAL MODELLING AND SIMULATION

A. Dimensional Analysis on Commercial UAVs

The purpose of the dimensional analysis was to identify and obtain data on the common geometries and dimensions of the UAVs and their components. With reference to the classifications in TABLE 1, 10 quadcopter UAVs from the

'Small' class, 19 from 'Medium' class, and 10 from 'Large' Class were studied. Following the flowchart in Figure 4, the mean maximum take-off mass (MTOM) was analyzed to be 0.445 kg, 0.98 kg, and 2.039 kg for the 'Small', 'Medium', and 'Large' class datasets, respectively. Next, 0.5 kg, 1 kg, and 2 kg were set as the designated MTOM values for the modelling of the UAVs.

It is shown in Figure 2, 5 quadcopter UAVs close to the designated value selected for further analysis. A trend was observed such that these quadcopters shared similar components, having the main body, battery, motors, and camera. Additionally, the UAV's arms were at an angle of 45 degrees from the vertical axis of the main body for quadcopters (b) and (d) in Figure 2. As such, these considerations were incorporated in this study.

B. Prediction of Estimated MTOM

For an accurate representation of the 3 classes and designated MTOM values, dimensions were chosen based on the mean dimensions of UAV data gathered. Subsequently, the Multiple Linear Regression (MLR) analysis was executed to have a prediction of the estimated MTOM of the quadcopter UAV [14]. This was to verify that chosen dimensions were near the designated MTOM value before modelling. The complete framework of the UAV

dimensional analysis with MLR prediction is illustrated in Figure 4.

Figure 2. Selected Quadcopters for Further Analysis.

Figure 3. Scatter Plot and Dimensional Analysis of 39 Quadcopter UAVs

Figure 4. UAV Dimensional Analysis Flowchart

Figure 3 depicts the correlation of dimensions for the 3 UAV classes. Hence, length, width, and height dimensions were assigned as independent variables, whereas the MTOM was the predictor variable. Finalized dimensions were 267×267×63 mm, 330×330×90 mm, and

412.5×412.5×112.5 mm for the classifications of 'Small', 'Medium', and 'Large' respectively. Using MLR, the predictions for estimated MTOM were 0.44 kg, 1.039 kg, 2.023 kg.

C. FEA Modelling

Generalized quadcopter UAVs were modelled using SolidWorks with the dimensions obtained in the dimensional analysis. Using complicated curves and fillets in the geometry of the quadcopter UAV was refrained to ensure an accurate and structured mesh [19]. Based on a study of engine ingestions due to bird strikes, it was highlighted that the CFM-56 engine has a high probability of bird ingestion events [20]. This is primarily due to its large inlet area and involvement in frequent bird-strike events. As such, this study will focus on UAV collisions with the CFM-56 engine. In addition, the fan blades of the engine model will include the refined and unrefined mesh in simulations.

(a) CFM-56 Engine Model for Simulation

(b) Mesh Refinement for 13 Fan Blades

Figure 5. Engine Model and Mesh Refinement of Fan Blades

The discretization of the UAV components was carefully performed on the Mesh module of ABAQUS. Thin-walled structures such as the main body, arms and camera brackets of the UAV meshed with S4 shell element type. In contrast, the battery, motors, and camera components meshed with C3D8 hexahedral element type. The computational cost of the simulation heavily depends on the mesh size. As such, it was crucial to select regions in the mesh that had to be finer for accurate results.

Thus, UAV components were initially given global mesh size, and local meshing with bias was used at regions close to the impact. The forward section of the UAV main body was refined for this reason. The refinement with a minimum element size of 2.0 mm and maximum element size of 3.25 mm was used. The average element size of approximately 1~2 mm was adopted to mesh the remaining UAV

components. The total quantity of elements for the UAV assembly is about 201,997.

The CFM-56 engine was modelled with its 36 fan blades, disc, shrouds, shaft, nose, and containment ring for simulation. The meshing of 13 fan blades was refined due to its proximity to the UAV collision. This was to ensure the accuracy of the FEA analysis and simulation. Thus, the unrefined fan blades had minimum and maximum element sizes of approximately 2.387 mm and 11.935 mm, respectively. The refined fan blades had minimum and maximum element sizes of approximately 1.465 mm and 7.326 mm, respectively. The total quantity of elements for the engine is about 456,591. The CFM-56 engine model and the refinement of the fan blades are depicted in Figure 5.

D. FEA Boundary Conditions

The various UAV impact scenarios and boundary conditions used in the simulation will be discussed in this section. Based on the A31X and A32X aircraft performance data published in EASA's report, maximum aircraft velocities of 250, 200 and 145 knots were used to represent the flight phases of the aircraft of approach, climb, and for take-off, respectively [21]. Additionally, these flight phases were also adopted; engine rotational speed will be varied with 5000, 4000 and 3000 RPM to represent engine full throttle and its variations [22]. The impact scenarios used in this study are presented as an engine ingestion simulation matrix in TABLE 2

TABLE 2 ENGINE INGESTION SIMULATION MATRIX

UAV Mass	Flight Phases	Engine Speed (RPM)	Collision Speed (Knots)
0.5 kg	Take-off	5000, 4000 and 3000	145
	Climb	5000, 4000 and 3000	200
	Approach	5000, 4000 and 3000	250
1.0 kg	Take-off	5000, 4000 and 3000	145
	Climb	5000, 4000 and 3000	200
	Approach	5000, 4000 and 3000	250
2.0 kg	Take-off	5000, 4000 and 3000	145
	Climb	5000, 4000 and 3000	200
	Approach	5000, 4000 and 3000	250

TABLE 3 FINALIZED UAV MASS IN ABAQUS SOFTWARE

Small UAV	Medium UAV	Large UAV
0.505 kg	1.08 kg	2.00 kg

It is notable that the engine's translational movement is restricted with only the rotation of the fan blades, disc and shaft permitted. The UAV hovers towards the engine, assigned with the maximum velocities and gets ingested by the engine. In this study, the UAV is assumed to impact the aircraft fan blades at an angle of 10 degrees. Thus, the velocity components were resolved accordingly for the UAV.

Furthermore, the interaction of the UAV components with the fan blades was modelled using general contact with contact pairs specified. The surface-to-surface contact

algorithm is used in the analysis of the contact pairs together with a frictional factor of 0.41. This was chosen based on the frictional coefficients for titanium alloy in a tribology study [23]. Finally, the actual weights of the 3 UAV modelled in ABAQUS for the simulation are shown in TABLE 3.

E. Material Models

In this study, the Johnson-Cook constitutive model was selected for the Ti-6AL-4V material. The CFM-56 fan blades are modelled with titanium alloy (Ti-6AL-4V). In contrast, the linear elastic-plastic material model is adopted to understand the failure and damage characteristics of the cast aluminium alloy, AISI 4030 steel alloy, nylon, and lithium-polymer (Li-Po). Additionally, the density, elastic modulus, and Poisson's ratio for the titanium alloy are defined as 1755 kg/m³, 114 GPa, and 0.33, respectively [24].

Figure 6. Material Type for UAV Components

Materials used in the modelling of the UAV components are depicted in Figure 6. Required material parameters for UAV components were based on the collision severity study by FAA/ASSURE and listed in TABLE 4. In addition, the Ti-6AL-4V properties and Johnson-Cook (J-C) constitutive model parameters are listed in TABLE 5. Concurrently; the J-C damage initiation criterion was also specified with the constitutive model. The determination of the 5 damage constants requires extensive testing with variations in strain-rates, stresses, and temperatures.

The J-C plasticity model was adopted for the Ti-6AL-4V fan blades for its accuracy in capturing the elastic and plastic characteristics, strain-rate, and temperature variations of the material [25]. With reference to TABLE 5, J-C parameter *A* refers to the yield strength at low stressing rates, *B* and *n* are constants based on isotropic strengthening during strains, *m* accounts for thermal softening, and θ_{melt} is the material's melting temperature. The J-C damage parameters, d1 – d5 used in this study are listed in TABLE 6 [25].

TABLE 4 ELASTIC-PLASTIC MATERIAL PARAMETERS (IN MPA)

Material	Yield Stress, σ_y	Ultimate Tensile Stress, σ_{UTS}	Ultimate Tensile Strain, ϵ_{UTS}
Cast Aluminium [6]	170	330	0.14
Polycarbonate [6]	50	50	0.5
Steel Alloy [6]	460	560	0.215
Nylon [6]	105	130	0.25
Li-Po [26]	30	55	0.375

TABLE 5 JOHNSON-COOK MATERIAL PARAMETERS (TI-6AL-4V)

A (MPa)	B (MPa)	m	n	θ_{melt}
1098	1092	1.1	0.93	1903

TABLE 6 JOHNSON-COOK DAMAGE EVOLUTION (TI-6AL-4V)

d1	d2	d3	d4	d5
-0.09	0.25	0.48	0.014	3.87

V. NUMERICAL SIMULATIONS

A. UAV Impact Force on Blades

The peak value of impact force exerted on the fan blades for the variations in UAV mass, impact speed and rotational speed of the fan blades are presented in TABLE 7.

TABLE 7 PEAK VALUE OF IMPACT FORCE FOR CASES (IN kN)

UAV Mass (kg)	Impact Speed (Knots)	Rotational Speed of Engine Blades		
		3000 RPM	4000 RPM	5000 RPM
0.5	145 Knots	140	182	205
	200 Knots	118	150	165
	250 Knots	85	130	154
1.0	145 Knots	150	212	275
	200 Knots	130	165	234
	250 Knots	96	150	218
2.0	145 Knots	180	229	345
	200 Knots	150	195	310
	250 Knots	128	170	300

Results highlighted that the peak value of impact force is expected to be larger at maximum conditions. However, it is still case-dependent on the UAV trajectory and point of collision with the engine model. Additionally, case dependency also attributes to the fan blades impacting different UAV components in each scenario. As such, this is likely to contribute to variations in impact forces on the fan blades. Shown in TABLE 7, UAV speed of 145 knots and rotational speed of 5000 RPM resulted in the most critical impact force exerted by the 2 kg UAV. Specifically, Fan Blade 27 was the blade impacted with the highest peak impact force of the UAV, as shown in Figure 7.

Figure 7. Force – Time Plot for Most Critical Case (2 kg, 145 knots and 5000 RPM)

Figure 8. Contact Force – Impact Speed Plot (0.5 kg)

Further analyses performed on the peak values of impact force for the various cases revealed trends. It was seen that the peak contact force was proportionally higher at increased rotational speed, with the greatest recorded in 5000 RPM simulations.

This trend was also similarly observed for all MTOM values of UAVs chosen for this study. Figures 8-10 illustrate this behavior of proportionality.

Figure 9. Contact Force – Impact Speed Plot (1 kg)

Figure 10. Contact Force – Impact Speed Plot (2 kg)

Figure 11. Collision Sequence for Most Critical Case (2 kg, 145 knots and 5000 RPM)

The collision sequence for the most critical case is depicted in Figure 11. At the time step of 2.56 milliseconds, Fan Blade Rad 27 faces its first collision with the UAV. In this instance, the UAV camera directly collides with Fan Blade Rad 27. At this critical time of 2.56 milliseconds, the peak impact force was observed to be approximately 345kN. Fracture of Fan Blade 27 was observed due to a head-on collision with the UAV camera.

Similarly, it was analyzed that the peak values of impact force were proportionally higher at increased MTOM values, with the greatest recorded in 2kg UAVs. Figures 12-14 illustrate this behavior for the rotational speeds of engine blades chosen for this study.

Figure 12. Contact Force – Impact Speed Plot (3000RPM)

Figure 13. Contact Force – Impact Speed Plot (4000RPM)

Figure 14. Contact Force – Impact Speed Plot (5000RPM)

B. Blade Fracture

Subsequently, the bolded values in red shown in TABLE 7 were critical simulation cases that had severe blade fracture resulting in partial blade detachment. For instance, the case of mass 1kg, aircraft speed of 145 knots and engine rotational speed of 5000 RPM resulted in a portion of Fan Blade 30 is severely fractured. This phenomenon is depicted in Figure 15. Having analyzed the 4 cases that resulted in this phenomenon, it was observed that this was due to the head-on collision of the UAV camera with the fan blade.

The stress contours and fracture to the fan blades are depicted for these critical scenarios in Figures 16-17. It was observed that severe fracture to the fan blades was present in these scenarios. For instance, the case of mass 1kg, aircraft speed of 145 knots and rotational speed of 5000 RPM resulted in high stress contours close to the UAV impact, particularly near the blade fracture region of Fan Blade 30. Similarly, the case of mass 0.5kg, aircraft speed of 200 knots and rotational speed of 5000 RPM had a portion of fan blade fractured and dislodged with high stress contours close to the UAV impact, particularly near the blade fracture region of Fan Blade 27.

Figure 15. Fracture of Fan Blade for case 2 kg, 145 knots and 5000 RPM.

Figure 16. Blade Fracture for Case 1 kg, 145 knots and 5000 RPM.

Figure 17. Blade Fracture for Case 0.5 kg, 200 knots and 5000 RPM.

VI. CONCLUSION

In this study, the collision severity of a generalized UAV impacting a CFM56 aircraft engine model was investigated based on FEM and Explicit Dynamic simulations performed on ABAQUS. Generalized UAVs were modelled with information of quadcopter UAVs obtained through the dimensional analysis of commercial UAVs in the market. 3 MTOM values were fixed based on the average MTOM of UAVs to represent the classifications of Small, Medium and Large UAVs with reference to TABLE 1. Subsequently, appropriate dimensions were chosen for these 3 UAV classifications using MLR analysis and predicting its corresponding MTOM value. 3 quadcopter UAVs with a finalized MTOM of 0.505 kg, 1.08 kg and 2.00 kg were modelled and simulated for collision with a CFM56 engine model. Important findings drawn from this study are as follows:

1. UAV collision at increased parameters of UAV MTOM, aircraft speed and rotational speed of fan blades result in proportionally higher contact forces for the fan blades. Additionally, 2kg, 145 knots and 5000 RPM cases were found to have the highest contact force amongst the simulated cases. A portion of the fan blade was fractured and dislodged in this configuration.
2. Simulation cases with the lowest UAV impact velocity of 145 knots led to the highest contact forces for all 3 UAV MTOM configurations. While increased UAV impact velocity was expected to result in the highest peak contact force, results from this study indicated otherwise. This could be due to the tendency of the fan blade to miss striking the UAV's camera and battery components at increased UAV velocities. In contrast, the fan blades are more likely to strike these components at reduced impact speeds due to longer impact times. However, further evaluation and assessments are crucial to ascertain this finding.
3. From the results obtained, it was deduced that simulations with a rotational speed of 5000 RPM for the fan blades were likely to result in the greatest contact forces and damage to the blades.
4. Results of the 3 quadcopter UAVs highlight that contact forces to the blades due to collision are more severe with UAV MTOM of 1 kg and above. This is more prominent in cases with the UAV camera having a head-on collision with fan blades. However, it is notable that simulations are case-dependent as trajectory of UAV and point of a collision varies for each scenario.

The methodology presented in this study is a preliminary work in evaluating the collision severity of generalized quadcopter UAVs of various MTOM values on aircraft engine blades. In addition, the influence of various UAV trajectories, component level sizing and larger UAVs might be considered in future studies for further understanding. More studies are also required to ascertain the findings acquired in this study. Study in this area is crucial as there is a rise in UAV operators, including UAV applications in airport operations, posing an increased risk to engine collision to aircraft.

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