

Airborne Collision Evaluation between Drone and Aircraft Engine: Effects of Position and Posture on Damage of Fan Blades

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Abstract: The incident of unmanned aerial vehicles (UAVs) incursion into aerodrome often happens due to the popularity of drones among amateurs, and this may lead to a threat to the safety of commercial aircraft operation. Hence, it is essential to estimate the damage level of commercial aircraft caused by drone strikes. From the data analysis of bird strike accidents over the period 1990-2019, it is found that the engine part is more susceptible to be damaged by bird strikes compared to the other aircraft parts. In this paper, the damage of engine fan blades caused by the drone ingestion is simulated by using a drone (MAVIC Pro) impinging onto a typical business engine (CFM56-5B) with the aid of FEM (finite element method). It is demonstrated that the collision position and collision posture both would affect the damage level of engine fan blades significantly. More damage to fan blades can be detected for the 75% collision position, and the complex collision posture would lead to much larger damage on the engine fan blades. The results presented in this work can be used to guide the decision made on the drone incursion incidents over the aerodrome.

I. Introduction

Currently, with recent development in science and technology, unmanned aerial vehicles (UAVs) have been increasingly used in many areas. The safety regarding an airborne collision between drones and commercial aircraft has become a great concern to the public and government officials at all levels [1-3]. Focusing on this issue, many experimental and simulation works have been conducted all over the world. Olivares et al. [4, 5] did the pioneering work to estimate the damage level of different components of commercial aircraft. The UAS airborne collision severity evaluation was systematically reported in their work for the first time. Besides, a group of researchers has performed the outdoor experiment of drone impacting onto a windscreen of commercial aircraft [6]. The comparison between experimental and numerical investigations was also conducted in their studies. Meng et al. [7] analyzed the damage of the horizontal stabilizer subjected to UAS airborne collision and compared the damage level caused by the same weight of drone and bird. It is demonstrated that the drone would lead to much more serious damage due to its high stiffness components.

Unlike drone strike, bird strike has been studied extensively in the last decades and some of its information might be useful as a start point to explore damage due to drone strike with an aircraft engine. Bird strike is an airborne collision between flying birds and aircrafts, which is a major threat to flight safety in aviation as a bird strike can lead to serious structural damage [8-10]. According to the Federal Aviation Administration (FAA), it was reported that the bird strike accident had killed over 219 people and destroyed more than 200 aircrafts since 1988 [11]. Bird strikes not only result in human lives in danger but also would cause incalculable economic consequences. It is reported by many references that the commercial aircraft jet engines are the most vulnerable part under bird strikes [12], which will be analyzed in detail in Section II.

Focusing on the dynamic process and damage level of aircraft engine caused by the bird strike, many experimental and simulation studies have been carried out. For instance, Meguid et al. [13] simulated a bird with three different geometry configurations (i.e., straight and hemispherical-ended cylinders, as well as an ellipsoid) impacting onto a single fan blade by using LS-DYNA. Vignjevic et al. [14] treated the bird as SPH (Smoothed Particle Hydrodynamics) particles and analyzed the influence of impact location, bird shape, and impact timing on the deformed shape of fan blades. Besides, these numerical results were also validated by comparing with the experimental test. Similar studies were also performed by Zhang and Fei [15] to detect the influence of geometry and impact orientation of the bird on the damage of a rotary jet-engine fan under bird strikes. Other related works on the dynamic response of fan blades induced by the bird strike also can be found in the literature [16-19].

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Due to the high stiffness of drone components, the drone strike would result in much more hazard damage during the accident of drone ingestion into the engine of commercial aircraft, and the reason will be explained in detail in Section II. However, academic researches concerning this topic are very limited. Lyons and D'Souza [20] investigated the damage severity of a drone impacting on an engine fan model. The damages of the fan blades, container ring, and nosecone caused by the drone ingestion were analyzed in detail in their work. Additionally, a similar study on drone ingestion into the engine of commercial aircraft was simulated and analyzed by D'Souza et al. [21]. A limitation of their study is that the engine model used in their work is not a real engine in service. Besides, Bayandor et al. [22, 23] compared the damage level between the bird strike and drone strike and demonstrated that the drone impact would cause much more serious damage compared to bird strike, and some detail analyses were also carried out in their works. However, the drone model used in their study is a simplified model.

In this manuscript, we aim to present a simulation method for a real drone striking on a real aircraft engine. From the database sweep study done, it was found that CFM-56, P&W, and GE are the top three engine types that involve an airborne collision with bird [24], and CFM56-5B was selected in this study. In addition, MAVIC Pro is selected as the drone model to represent the middle size category of drone with weight in the range of 250g-1500g. Hence, we will concentrate on the simulation of MAVIC Pro drone impacting on the CFM56-5B engine in the following sections.

This paper is outlined as follows: firstly, a comparison study on the bird and drone strikes was performed in Section II to exhibit the similarities and differences between the bird strike and drone collision, and it is demonstrated that the engine is the most critical component to cause the catastrophic damage to the operational safety of commercial aircraft. Then, we will focus on commercial aircraft engine ingestion due to drone strikes, and the drone-engine collision model is established in Section III. Besides, the numerical simulations are carried out in Section IV to evaluate the number and size of damaged fan blade under different drone collision positions and different collision postures. Finally, some conclusions are presented in Section V.

II. Bird Strike vs. Drone Collision

As is known to all, the bird strike is a hazard incident to all aviation and would lead to serious consequences such as crashes of aircraft and human death. Even though no catastrophic consequence happens, the bird strike would also lead to high operational costs for repairing the damaged aircraft, as well as expensive insurance claims, etc. It is reported that the chance of a bird strike accident occurred is once per 2000 flights [25]. Besides, it is also estimated that the bird strike incidents occur about 10,000 times per year over the world and the cost due to these incidents can reach USD 1 billion per year [26].

Drone collision is a new hotspot in recent decades due to the rapid development of UAVs in military or civilian fields such as reconnaissance, surveillance, inspection, search and rescue operations. Especially, the UAV has gained significant popularity among amateurs, and incidents of UAV operation without permission often happen during the airspace of the aerodrome, which would greatly threaten the safety of commercial aircraft operation. To guide the study of the drone collision severity with manned aircraft, it is helpful to learn from bird strikes. In this section, the detailed similarities and differences between the bird strike and drone collision will be analyzed.

A. Similarity between bird and drone strikes

The similarity between the bird strike and drone collision incidents is that they are both happened suddenly and unpredictably. Hence, the statistical analysis of the massive data of bird strike incidents is meaningful to understand the potential effect of drone collision on aircraft operation. From the FAA statistical data, 131,032 total number of bird strike incidents reported for the period 1990-2019 [24]. Based on these data, one can figure out the damage percentage caused by the bird strike on different components of aircraft, as presented in Fig. 1. From this figure, it is found that the engine, wing and radome are the top three critical components that would be damaged under the bird strike. Moreover, the engine part is more susceptible to be damaged by comparing with the other aircraft parts. In reality, most severe accidents are happened due to the severe failure of aircraft engines, which are the only part to supply the power and thrust to the entire commercial aircraft. Hence, the problem of birds striking engine part requires careful investigation in the following statistical study.

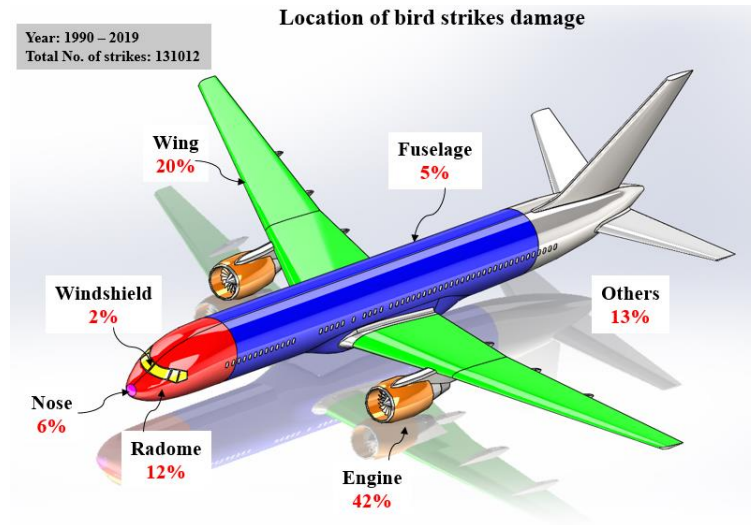


Fig. 1. Statistics of damage percentage for different locations induced by bird strike.

Next, we focus on the damage level of engine part caused by bird ingestion incidents, as shown in Fig. 2. It is seen that no damage can be found for most bird ingestion accidents, which can reach to 59%. Even though, almost 22% ingestion accidents would lead to severe damage to the engine. This severe damage to the engine may cause the thrust loss of the engine and lead to catastrophic consequences. Due to the high chance of severe damage accidents under bird ingestion, the problem of birds hit an engine requires careful investigation. In fact, many experimental and numerical analyses had been conducted to evaluate the resistance and integrity performances of engine parts under bird ingestion. Previously, this evaluation was solely dependent on experiments, and the aviation authorities require that all critical components of the aircraft should be proved by a certification test of bird strike resistance before they aircraft for operation [16]. Here, an introduction to the certification test of bird ingestion into engine is presented.

In this bird ingestion certification, it is required that all gas turbine engines and particularly turbofan engines should be durable to stand the bird ingestion. For the ingestion of birds with small and medium weights, the demonstration of mechanical integrity and a continued thrust level of 75% should be satisfied. For large bird (1.8 kg) ingestion, the certification regulation requires shut down behavior of the engine can be manipulated under a controlled manner with no fire, and this must be proved for an entire engine certification test. Besides, it also has to be proven that the engine inlet can withstand a large bird impact with no damage to significant components of the engine (FAR/JAR/CS 25.571, 33.76). This bird ingestion certification also can be followed for drone collision study in our future study.

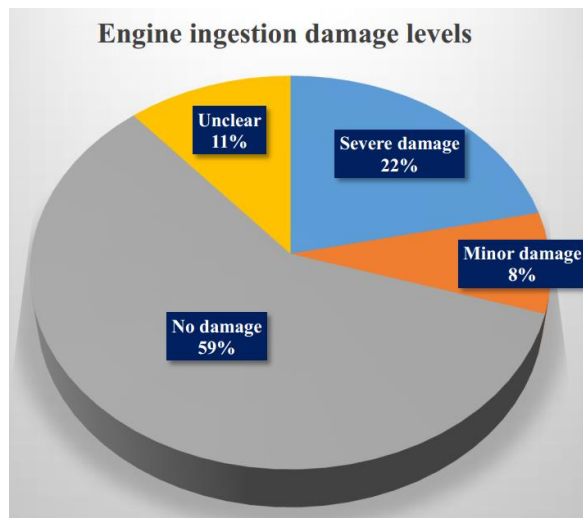


Fig. 2. Statistics of bird ingestion incidents for damage level.

B. Different scenarios between bird and drone strikes

Obviously, there are also some differences between bird and drone strikes. Firstly, the multiple bird strike is a typical feature of bird strike accidents because the birds often fly in flocks, which is a great difference from drone collision because the drone often flies in single. The statistics of bird ingestion incidents for different bird size and numbers are presented based on the data of the bird impacting on the aircraft engine, i.e., the data of engine ingestion accident, as shown in Fig. 3. It is found that there are not only engine ingestion accidents of single bird but also many accidents caused by multiple birds. From this figure, it is also found that the engine ingestion accidents are often caused by the bird with medium weight, and followed by large and small birds. Especially, the number of accidents caused by a single bird with medium weight is the largest. The number of single and multiple bird accidents are in balance for the small and large bird accidents, while the number of the accident resulted by the single birds is significantly larger than that resulted by the multiple birds for the medium bird accidents.

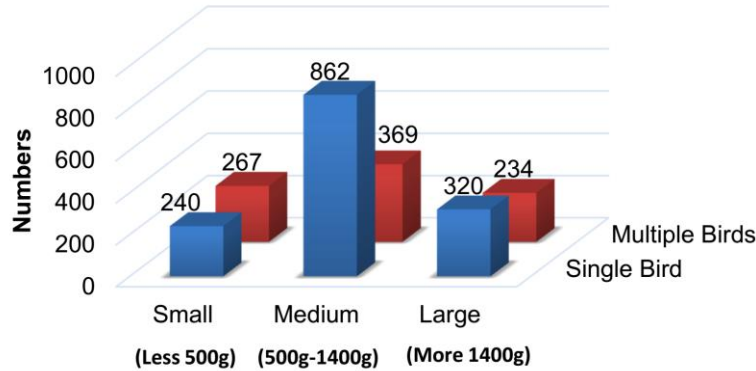


Fig. 3. Statistics of bird ingestion incidents for different bird size and numbers.

C. Different numerical methods between bird and drone strikes

In addition, it is reported that the dynamic response and damage level of the aircraft components under bird strike and drone collision are greatly different [27]. This is mainly attributed to the fact that the drone is composed of many components with higher stiffness than bird, which would cause much more damage to the aircraft during collision. Another difference between bird strike and drone collision is that the bird is made of homogeneous materials, while the drone is a typical heterogeneous material because the material in each component is made of different materials, which would incur more complexity on the simulation of collision process.

The numerical method is an important strategy for engine ingestion study, and this method has gained much more significant popularity due to its low-cost and high-efficiency by comparing it with traditional experimental studies. Especially, with the development of simulation techniques, more and more software with high precision performance are explored to simulate the impact process of bird and drone strikes. However, the numerical methods adopted for the bird strike and drone collision are significantly different due to the different compositions of birds and drones. Next, the numerical methods adopted in the bird and drone strikes simulation will be explained in detail firstly.

For the numerical method of bird strike, Lagrangian and Eulerian modeling methods are two traditional approaches. The Lagrangian formulation is a classical approach for almost all structural finite element studies. The mesh nodes are associated with the material and every node yields the material during the deformation. This method is a typical method for solid materials. However, a major problem of the Lagrangian approach is that the bird may undergo large deformation during the impact process and these large distortions of elements would result in serious hourglassing and negative volume of elements [28]. In the Eulerian numerical method, the mesh is fixed in the space and the material flows through the mesh, which can avoid the excessive element deformation in the Lagrangian formulation. This approach is widely employed for simulation the fluid materials and flow behaviors. During the simulation, each element should have a certain volume fraction of different materials, i.e., each element should be partially set with fluid material properties. A drawback of this method is that the boundary of the impactor body cannot be exactly defined, and it is related to the mesh size. Especially, only the impactor can be modeled as the Eulerian element, while the target should be treated as Lagrangian elements during the bird strike simulation, i.e., the coupled Eulerian-Lagrangian method will be adopted for this fluid-structure interaction problem. By employing this method, the dynamic process of bird ingestion into engine is widely investigated by several researchers [29, 30].

Apart from Lagrangian and Eulerian modeling methods, the smooth particle hydrodynamics (SPH) is also widely adopted to analyze the dynamic process of aircraft components impacted by birds. The SPH method is a meshless Lagrangian technique, in which the fluid behavior can be captured by using a set of discrete interacting particles [31, 32]. This method can cover the large deformation without mesh distortion problem that may meet in Lagrangian technique, and it can easily avoid the possible problem of material interface in the Eulerian technique. This method is widely used to simulate the dynamic behavior of bird ingestion [15, 18, 33]. However, a drawback of this method is lacking sharp boundary conditions that will affect the accuracy of fluid-structure interaction simulation. From the literature review of the numerical method adopted in the bird strike simulation, it can be concluded that the Lagrangian, Eulerian and SPH approaches all have their advantages and drawbacks. To choose the suitable method for different problems, the influences of specific applications, parameter setup, and software package, as well as the geometry, mass and velocity of birds all need to be carefully taken into account [16]. Recently, the Eulerian and SPH methods are much more preferred by comparing with the Lagrangian method for the simulation of bird strikes.

However, due to the high stiffness of drone components, the drone should be treated as elastic-plastic materials, and the damage criterion of the drone components becomes complex by comparing it with bird material. Besides, the drone is often made of polymer and composite materials whose properties should be defined much more properly. Due to the above two reasons, the traditional Eulerian and SPH approaches used in bird strike simulation is no more suitable for capturing the material behaviors of the drone. The components of drone are much more close to the solid materials, which can be modeled by Lagrangian finite element method. In this manuscript, the Dynamic/Explicit formulation of ABAQUS software is employed to capture the non-linear dynamic process of drone ingestion. Especially, the abundant materials in ABAQUS software can capture the plastic material properties of polymer and composite materials, which is suitable for drone collision simulation.

III. Drone-Engine Collision Model

This study will focus on the damage evaluation of a drone impinging on an aircraft engine around the airport aerodrome. The drone type of MAVIC Pro and the engine type of CFM56-5B are chosen for the simulation. The drone collision numerical simulation is prepared by using ABAQUS software and is solved with the aid of the Dynamic/Explicit formulation. Fig. 4 shows the assembly of drone and engine structures, in which the aircraft engine with 36 fan blades, as well as a blade disc and a nose cone is presented. The drone-engine assembly has a combination of plastic and metallic parts, Table 1 shows the material type defined for each part of drone and engine.

Table 1 Material properties of drone and engine [21].

Drone		Engine	
Parts	Material	Parts	Material
Drone main body	Polycarbonate polymer	Fan blades	Titanium Alloy (Ti-6Al-4V)
Arms	Polycarbonate polymer	Fan blades disc	Titanium Alloy (Ti-6Al-4V)
Battery	Lithium Polymer (Li-Po)	Nosecone	Aluminum
Motor (Rotor)	Aluminum Alloy (A520-F)		
Motor (Stator)	Steel Alloy (AISI 4030)		
Blades	Nylon		
Camera	Aluminum Alloy (A520-F)		

All engine components are meshed via the hexahedral C3D8 element with a total number of 189,366 elements. Here, the maximum and minimum sizes for the fan blade are 1.7 mm and 12.1 mm, respectively. The ten fan blades that will contact the drone are refined with a graded size wherein the contact part has the smallest sizes and the element size changes smoothly from this contact part to the tip and root parts, as presented in Fig. 4(c) which exhibits the mesh for the first 3 refined fan blades. All of drone parts are meshed using hexahedral C3D8 element type except the arm and the main body which are using shell element type S4 with 5 mm thickness. The total element number for the whole drone model is 104,928. The front main body of the drone has been refined with a minimum element size of 0.75 mm, while other surfaces are meshed with a maximum element size of 2.0 mm.

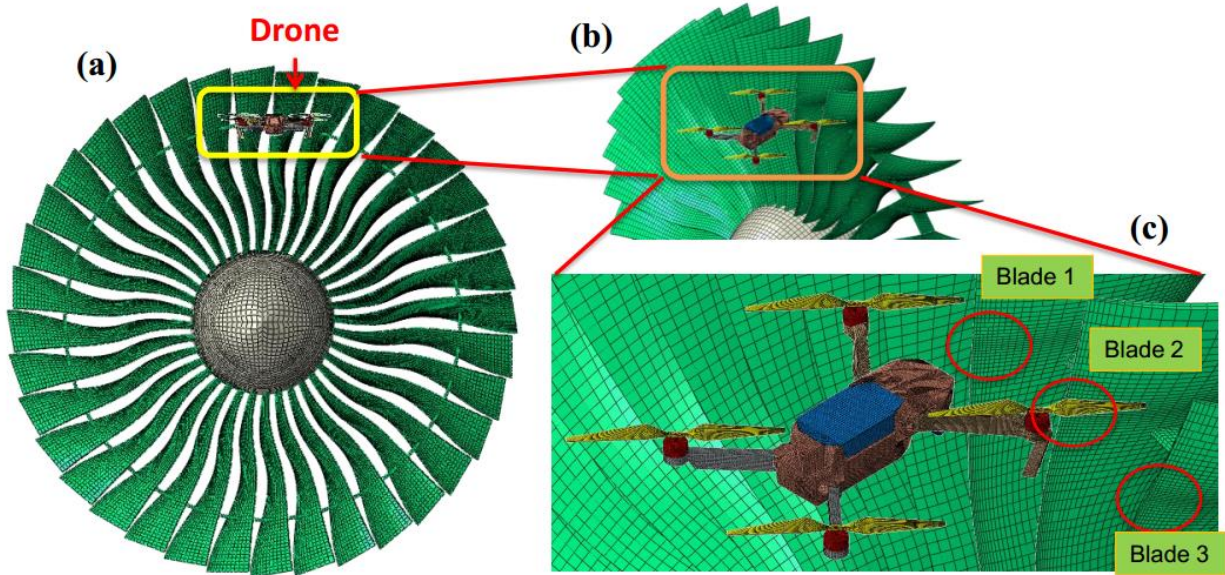


Fig. 4. FE model for drone ingestion simulation: (a) overview; (b) assembly of engine and drone; (c) mesh refinement on engine fan blades (at drone strike position).

To determine the most severe damage occurred to the aircraft engine subjected to the drone collision, the take-off phase is taken into account due to the fact that this phase has the highest forward and rotation speeds. In the simulation, the drone was defined with an initial forward speed of 92.6 m/s (by taking aircraft speed during take-off) and rotational speed of 523.6 rad/s (5000 RPM) in which the engine is running at its 100% thrust level. The fan blades, blade disc, and nose cone are allowed to be moved rotationally while no translational movement along the engine axis of rotation is employed on the whole engine parts.

IV. Results and Discussion

In this section, the influences of drone collision position and collision posture on the dynamic response and damage level of the CFM56-5B engine will be studied. This paper has three main contributions by comparing with the numerical study reported by D'Souza et al. [21]. Firstly, the drone used in D'Souza's study is about 1300g, while a lighter drone type with 750g is used in our study. Moreover, the engine adopted in D'Souza's study is not a real engine in service, while the CFM56-5B engine established in this study is a real engine. Secondly, we compare three different collision positions including 25%, 50%, and 75% which are not mentioned exactly in D'Souza's study. Thirdly, not only the common posture but also the combine postures by changing the orientations of pitch, yaw, and roll are considered in this study, while only 0° direction, 90° pitch, and 180° yaw are analyzed in D'Souza's study.

A. Effect of collision position

As presented in Fig. 5, three collision position cases including 25%, 50%, and 75% position along the fan blade are considered. The dynamic process of the drone collision under 75% collision position is presented in Fig. 6, which illustrates that the duration of the collision process is about 3ms, and some plastic deformation can be observed during the collision process.

To exhibit the damage of the fan blades much more clearly, the number of damaged fan blades is compared for different collision positions, as depicted in Table 2. It is clear that for 25% collision position, 3 blades are damaged, while 5 and 6 damage blades are found for 50% and 75% cases, respectively. Besides, the maximum sizes of the damaged fan blades are 16.5mm, 29.1mm, and 31.2mm, respectively, for the 25%, 50%, and 75% collision positions, which indicates that the 75% collision position will result in much more damage on the fan blades.

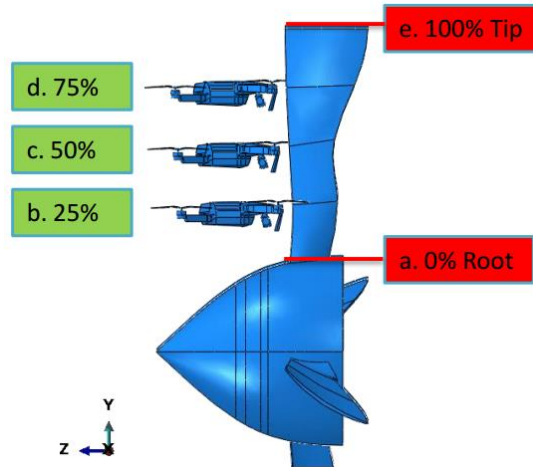


Fig. 5. Schematic diagram of different drone collision positions.

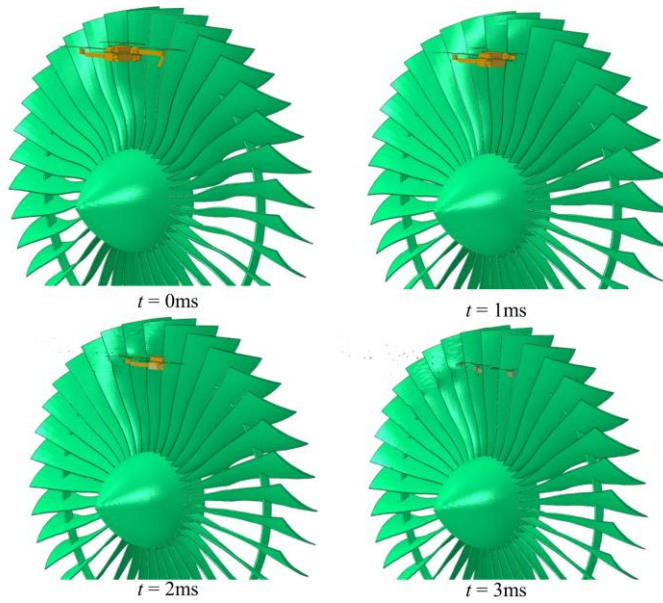


Fig. 6. Time history of drone collision process under 75% collision position.

Table 2 Number and size of damaged fan blades caused by different collision positions.

Position	25%	50%	75%
Deformed shape			
Blades No.	3 blades damage	5 blades damage	6 blades damage
Max. size	16.5mm	29.1mm	31.2mm

B. Effect of collision posture

Apart from the drone collision position, the influence of collision posture on the dynamic response and damage level of the CFM56-5B engine is also investigated. Fig. 7(a) presents the definition of the collision postures, i.e., the drone rotating along x -, y -, and z -axis to represent the pitching (θ), yawing (ψ) and rolling (ϕ) of the drone posture, respectively. These three common collision postures with only changing one angle are exhibited in Fig. 7(b), and the number and size of damaged fan blades caused by these different common collision postures are listed in Table 3. By comparing with the reference posture of $\theta = \psi = \phi = 0^\circ$, though the number of the damaged fan blades is almost unchanged, the maximum size of the damaged fan blades enlarges significantly in the common collision postures. It can be concluded that changing the collision posture would lead to much higher damage level to the fan blades by comparing with the reference posture.

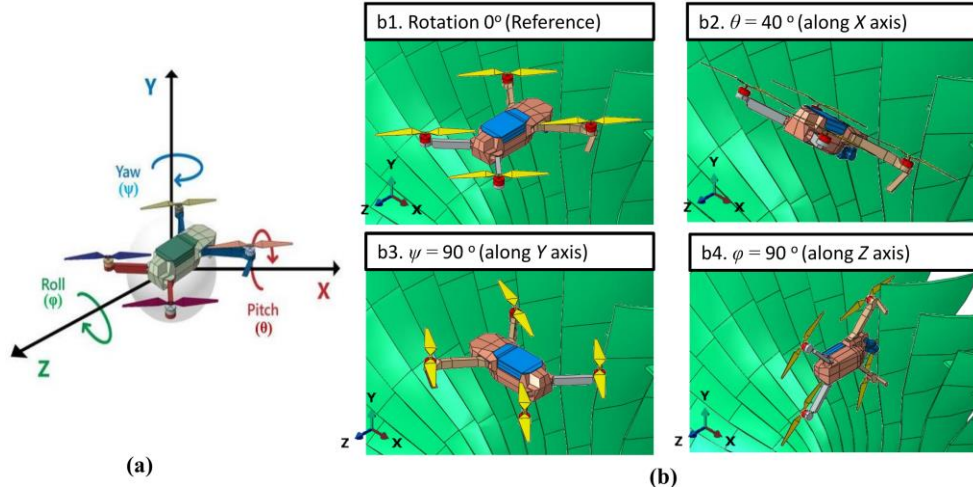
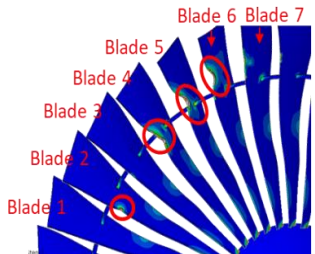
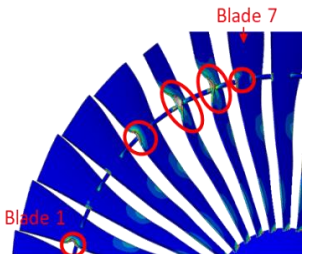
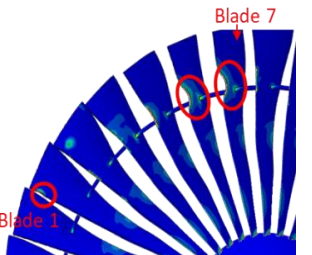


Fig. 7. Schematic diagram of different drone collision postures.

Table 3 Number and size of damaged fan blades caused by different common collision postures.

Posture	$\theta = 40^\circ$	$\psi = 90^\circ$	$\phi = 90^\circ$
Deformed shape			
Blades No.	4 blades damage	5 blades damage	3 blades damage
Max. size	75.5mm	87.1mm	73.5mm

The analysis shown in Table 3 indicates that changing the collision posture can result in much more damage to the fan blades, but this study is only limited to the common collision posture. Here, the influence of complex collision posture on the damage of the fan blades is also investigated. As shown in Fig. 8, the time history of the collision process for the drone collision posture with $\theta = 20^\circ$, $\psi = 45^\circ$ and $\phi = 0^\circ$ is given. By comparing with Fig. 6 of the reference posture, the collision process lasts 4s for this posture, indicating the duration of this posture is much larger. Besides, the number and size of damaged fan blades induced by some representative complex postures are presented in Table 4. It is evident that some complex postures would cause much more damage on the fan blades, e.g., the maximum damage size can reach to 317.0mm for the posture of $\theta = 0^\circ$, $\psi = 90^\circ$, $\phi = 45^\circ$, and seven damaged blades can be detected for the posture of $\theta = 0^\circ$, $\psi = 45^\circ$, $\phi = 90^\circ$.

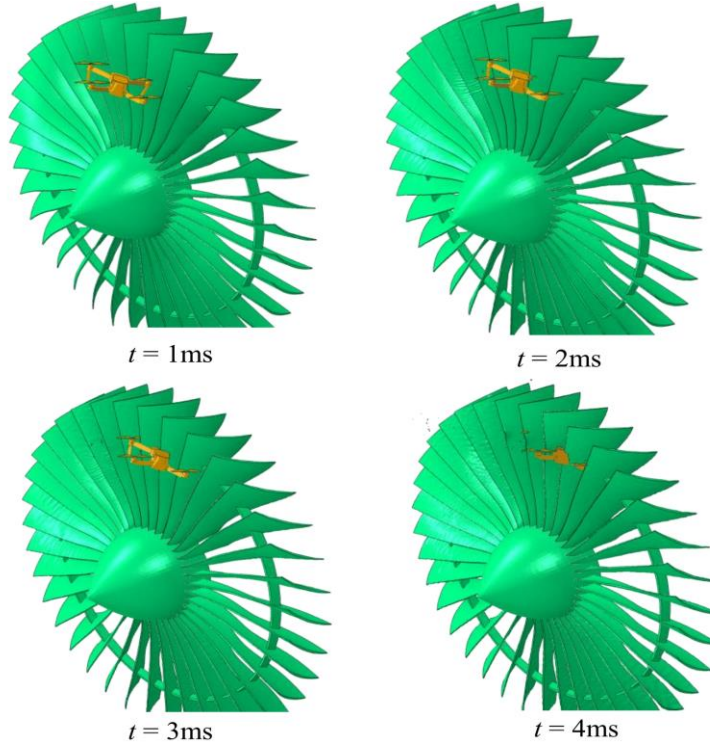
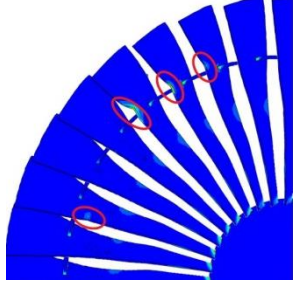
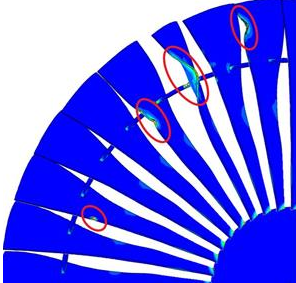
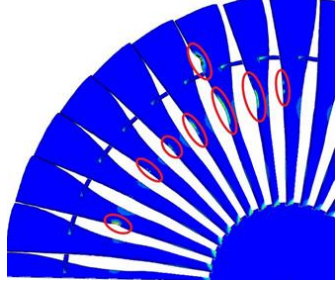


Fig. 8. Time history of drone collision process under drone collision posture $\theta = 20^\circ$, $\psi = 45^\circ$ and $\varphi = 0^\circ$.

Table 4 Number and size of damaged fan blades caused by different complex collision postures.

Posture	$\theta = 20^\circ, \psi = 45^\circ, \varphi = 0^\circ$	$\theta = 0^\circ, \psi = 90^\circ, \varphi = 45^\circ$	$\theta = 0^\circ, \psi = 45^\circ, \varphi = 90^\circ$
Deformed shape			
Blades No.	4 blades damage	4 blades damage	7 blades damage
Max. size	194.2mm	317.0mm	173.0mm

V. Conclusions

In this study, the dynamic response and damage level of commercial aircraft engine induced by the drone ingestion are investigated. By revisiting the data of the bird strike accident, one can find that the engine part is much susceptible to be damaged by comparing it with other components. With the aid of ABAQUS Dynamic/Explicit, a drone of MAVIC Pro impinging onto a typical mid-sized business engine of CFM56-5B is simulated. The damage level of the fan blades caused by different drone collision positions and different collision postures is examined in detail. It is demonstrated that the damage level in the 75% collision position is much larger than that in 50% and 25%. Changing the collision posture can result in much larger damage to the fan blades. By comparing with the common postures, the complex posture can cause more fan blades to be damaged and can lead to much larger damage sizes. Furthermore,

as reported by Hasrizam et al. [34], the debris of drone and damaged engine fan blades may be ingested into the engine core to cause the thrust loss of engine, which can be studied in detail in our future work. The present study will pave an effective way to clearly understand the damage of engine caused by the drone strike and can guide the decision-made when the drone incursion happens over the aerodrome.

Acknowledgments

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