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2021

Liu, H., Mohd Hasrizam Che Man, Ng, B. F. & Low, K. H. (2021). Airborne collision severity study on engine ingestion caused by harmless-categorized drones. AIAA Scitech 2021 Forum, 1-9. <https://dx.doi.org/10.2514/6.2021-1263>

<https://hdl.handle.net/10356/147372>

<https://doi.org/10.2514/6.2021-1263>

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Airborne Collision Severity Study on Engine Ingestion caused by Harmless-categorized Drones

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The drone weight less than 250g is often treated as a 'harmless' category by many authorities such as EASA (European Aviation Safety Agency) and CAAS (Civil Aviation Authority of Singapore). Is this small drone really safe and does not affect the operation of commercial aircraft? This paper is devoted to presenting a Finite Element Method (FEM) simulation method to analyze the performance of the commercial aircraft engine under the collision of the harmless categorized drone with a weight of 250g. The damage levels of the fan blades and compressor blades during the drone collision process are both investigated. Besides, another type of drone with a much higher weight (750g) is also analyzed to give a comparison study. The result shows no apparent damage to the aircraft engine fan blades, IG, and LPC blades for the drone of MAVIC MINI, while some damage can be detected for the engine fan blades under the impact of the drone of MAVIC Pro.

I. Introduction

Due to the development of manufacturing technology, more and more lightweight drones with small weight can be fabricated, which has gained extensive popularity around amateurs [1, 2]. These small drones are often used for aerial photography, and they may consciously or unconsciously intrude into the restricted airspace area like the airport. There are a lot of cases of unauthorized drones intruded into the airport area, such as the drone incident in Gatwick airport in December 2018 [3]. Because of unclear risk posed by the presence of unauthorized drones in the airport area, the common measure taken by airport management is shutting down the runway operation, which may disrupt the airport operation and even result in diversion, delay, and cancellation of flights [4-6]. Hence, it is urgent to present a method to evaluate the damage level of aircraft caused by UAV (unmanned aerial vehicle) airborne collision [7].

Concerning this problem, many academic works have been conducted all over the world. A group of researchers has performed the outdoor experiment of drone impacting onto a windscreen of commercial aircraft for the first time [8]. The UAS airborne collision severity evaluation was carried out by Olivares et al. [9, 10] to estimate the damage level of different components of commercial aircraft. Besides, Bayandor et al. [11, 12] compared the damage induced by the bird strike and drone strike and demonstrated that the drone impact would cause much more serious damage, and some detailed analyses were also carried out in their works. Meng et al. [13] performed the UAV collision ground test by using a drone impacting on the commercial airliner horizontal stabilizer section and also simulated the dynamic response of this primary component under UAV collision.

By learning from bird strikes, it is found that the most severe case might happen as the bird is ingested into the aircraft engine. Accordingly, the most serious hazard posed by UAVs presence in airport area is the mid-air collision of a drone with an aircraft engine. Such a case can lead to engine shutdown for contained or uncontained engine

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failure, which caused injuries or even fatalities to pilots, cabin crews, and passengers. Therefore, special attention should be paid to the drone ingestion into the aircraft engine. Only related work on this topic is carried out by D'Souza et al. [14], who had simulated and analyzed the dynamic process of drone ingestion into the engine of commercial aircraft. Besides, the damages of the fan blades, container ring, and nosecone caused by the drone ingestion were also investigated in detail in their work.

To better guide our study on drone ingestion into an aircraft engine, some literature on the bird strike on aircraft engines is reviewed firstly. For instance, Meguid et al. [15] classified the 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. [16] treated the bird as Smoothed Particle Hydrodynamics (SPH) particles and analyzed the influence of bird shape, bird impact location, and impact timing on the deformed shape of the fan blade. With the aid of the same simulation method, Zhang and Fei [17] detected the influence of bird geometry and impact orientation on the bird striking onto a rotary jet-engine fan. Other related work about bird strikes also can be found in Refs. [18-22]. However, most of these studies are only focused on the damage of engine fan blades resulted from a bird strike. The significant problem is that a large amount of debris would generate during the bird/drone impacting, which may go inside the low-pressure compressor (LPC) and high-pressure compressor (HPC) core and result in the damage of the compressor blades.

Besides, the other important issue is to determine which categorized drone can provide no risk to the operation of manned aircraft. As shown in Table 1, the categorization comparison weight of the bird and drone. It is clear that the weight of the bird is larger for each category, which is attributed to the fact that the stiffness of the drone is larger than that of the bird. Another difference is that the bird strike incident is often happened for multiply birds, while the drone collision incident has commonly occurred for only one single drone. In previous studies, the weight and energy thresholds for falling UAVs were studied by Low et al. [23, 24], who suggests that the 255 g weight threshold is safe for UAVs operating at 200ft.

Recently, many authorities require drone owners to register their drone information on certain websites, and the owners also needed to be trained to get the license for drone operation [1]. As a starting point, the weight of drone with 250 g maximum mass limit is proposed to be used for the 'Harmless' category [1, 25], i.e., the drone larger than 250 g is required to register and should be approved before each operation. In comparison, no registration is needed for the drone lower than 250 g. The present paper aims to study the damage level of the commercial aircraft engine caused by the drone with a weight of 250 g and to demonstrate whether it is reasonable by setting the 250 g as the weight threshold for the drone registration.

Table 1 Categorization for birds and drones.

Bird [26]		Drone [1]	
Category	Weight (kg)	Category	Weight (kg)
Large	>3.65	Large	>3.5
Medium	1.85-3.65	Medium	1.5-3.5
Small	<1.85	Small	0.25-1.5
-	-	Harmless	<0.25

In this work, not only the damage of engine fan blades but also the influence of debris on engine compressor blades during the drone collision process is analyzed by using FEM simulation. There are several parameters that may affect the dynamic process of the engine, such as the relative speeds between the aircraft and the drone and the position of the collision on the aircraft. Particularly, the damage level of engine fan blades and compressor blades caused by the drone with 250 g will be studied carefully to detect whether it is safe for the operation of this type of UAVs.

II. Simulation Model

A. Drone Model

Based on the data statistics of a bird strike, it is found that CFM-56 is an engine type with the highest cases involved in bird strike incidents. Hence, our focus is on the collision between the drone and the CFM-56 engine for the following studies. Besides, DJI MAVIC MINI (MAVIC MINI), whose weight is lower than 250 g is chosen, and a much bigger drone DJI MAVIC Pro Platinum (MAVIC Pro), is also selected to give a comparison study. The

dimension of MAVIC MINI and MAVIC Pro are $160 \times 202 \times 55$ mm, and $198 \times 83 \times 83$ mm, respectively, and the weight of these two drones are, respectively, 0.249 kg and 0.743 kg.

The software ABAQUS dynamic/explicit is adopted for the numerical simulation of a drone collision. Most drone parts have meshed as hexahedron with C3D8 element type, and shell element type S4 is also employed for the main body and arm parts. For the main body, the front part is refined with a minimum element size of 0.75 mm and a maximum element size of 2.5 mm. The average element size with about 1.5~2.5 mm is adopted to mesh the other parts of the UAV, and the total element number for MAVIC MINI and MAVIC Pro drones are about 192,556 and 209,856, respectively. The detailed FE models and material settings for each part of these two selected UAVs are presented in Fig. 1.

Fig. 1. FEM model and material distribution of (a) MAVIC MINI and (b) MAVIC Pro.

B. Engine Model

For the engine model, CFM-56 with 36 fan blades and a fan disc, as well as inlet guide vane (IGV) and stage-1 low-pressure compressor (LPC) with a total of 64 blades are established for collision simulation, as presented in Fig. 2. The external and internal radiuses for the fan blades are $R_{ex}=1,807$ mm, and $R_{in}=644$ mm, respectively, while the internal and external radiuses are, respectively, 791mm and 1,013mm for the stage-1 of the compressor blades. The hexahedral element C3D8 is adopted to mesh all engine components. The whole engine model is divided into 266,740 elements. Besides, some engine fan blades that would have contact with UAVs during the collision process are refined, as shown in Fig. 3.

Fig. 2. Geometry model for commercial aircraft engine: (a) whole aircraft engine assembly; (b) exploded view of the engine core.

Fig. 3. FE model of UAV-engine assembly system for UAV ingestion simulation (in which the first three fan blades mesh refined are shown).

C. UAV-engine Assembly System

The UAV-engine system, including the engine components and UAV, is depicted in Fig. 3. Their materials used for each aircraft engine and drone parts are listed in Table 2 and Table 3, respectively, whose detail parameters are derived from Ref. [14]. The contact behaviour among the UAV and engine is simulated by the surface to surface contact with a friction coefficient of 0.41. The take-off flight phase with an initial forward speed of 92.6 m/s and rotation speed 314.2 rad/s (3000 RPM) is adopted to analyze the severity level of the aircraft engine impinged by UAV. The boundary condition is defined by fixing the translational movement of the fan blades, blade disc, and compressor blades, but their rotational movements are released.

Table 2 Material type for each aircraft engine part.

Engine Parts	Material
Fan blades	Titanium Alloy (Ti-6Al-4V)
Fan disc	Titanium Alloy (Ti-6Al-4V)
IGV	Titanium Alloy (Ti-6Al-4V)
LPC	Titanium Alloy (Ti-6Al-4V)

Table 3 Material type for each drone part [14].

Drone Parts	Material
Drone main body	Polycarbonate polymer
Arms	Polycarbonate polymer
Battery	Lithium Polymer (Li-Po)
Motor (Rotor)	Aluminum Alloy (A520-F)
Motor (Stator)	Steel Alloy (AISI 4030)
Propeller	Nylon

III. Simulation Results

In this section, the dynamic response and damage level of the CFM-56 engine subjected to the impact by MAVIC MINI and MAVIC Pro are analyzed. The drone collision position could significantly affect the dynamic response of the CFM-56 engine, as shown in Fig. 4. We use the percentage along the fan blade to define the collision position, as presented in Fig.4. Here, the 15%, 50%, and 75% collision positions are considered, and only the first stage of the IGV and LPC compressor blades are taken into account for the preliminary study.

Fig. 4. Schematic diagram of different drone collision positions.

A. Debris size

The collision process of the aircraft engine impacted by MAVIC MINI under collision position 15%, 25% and 75% are presented in Fig. 5 and Fig. 6, respectively, at different time steps. It is found that the engine fan blades will cut the drone into much small debris, and some debris would go inside into the engine core and impact with IGv and LPC blades for the collision position 15%. The whole collision process has lasted about 3ms. At the time of 2ms, the drone is wholly ingested into the engine fan blades, and it begins to impact the IGv blades of the engine core. Due to the residual velocity of the drone debris, the debris close to the engine core will be ingested into the compressor core for the collision position 15%. However, almost no damage to the engine core can be detected for MAVIC MINI because the debris size is very small to lead the damage to the IGv and LPC blades. Moreover, almost no damage can be found for the fan blades under the collision position of 15%.

Fig. 5. Dynamic response of fan blades and compressor core under the drone collision position 15% (MAVIC MINI).

Fig. 6. shows dynamic response of the engine fan blades, IGV and LPC blades from impact with drone MAVIC MINI. For the collision position 50%, one can also find that the drone will be cut into much debris and all debris will be ingested into the fan blades at 2ms as shown in Fig. 6. (a). However, no debris is ingested into the compressor core because the collision position is far away from the engine core, and this debris will be moving outside of the engine directly through the bypass channel. The same observation can be seen for the collision position of 75%, where none of the drone debris being ingested in the engine core at 2ms, as shown in Fig. 6. (c). Besides, not much significant damage can be detected for the fan blades because the weight of MAVIC MINI is light, and the debris of the drone is small.

Fig. 6. Dynamic response of fan blades and compressor core under different drone collision position (MAVIC MINI): (a) and (b) collision position of 50%, (c) and (d) collision position of 75%.

To show the size of debris much more clearly, we collect the debris of the drone during the collision process under the collision position 50% and give a statistic of their sizes and weights as presented in Table 4. Here, both the debris of MAVIC MINI and MAVIC Pro are analyzed to give a comparison. It can be found the average debris size for the take-off flight phase is 16 mm, and the average weight is 2.4g for MAVIC Pro, while debris with 8 mm size and 1.4 g weight is found for MAVIC MINI. It is also can be concluded that the debris size and weight of MAVIC MINI are much smaller than that of MAVIC Pro, which may lead to smaller damage to the aircraft engine core.

Table 4 Debris size for different drone types.

Drone	Size (mm)	Weight (g)
MAVIC MINI	8	1.4
MAVIC Pro	16	2.4

B. Damage of Fan Blades

In this subsection, the damage of fan blades caused by the strike of MAVIC MINI and MAVIC Pro are compared. As shown in Table 5, it is evident that one fan blade is slightly damaged (i.e., nick and notch), while the IGV and LPC blades are both un-damaged when the engine is impacted by MAVIC MINI at collision position 15%. Besides, for the collision position 50%, and 75%, one can detect the nick and notch damage for two fan blades for the collision of MAVIC MINI. In a word, the damage of engine fan blades and engine cores are not so significant when the CFM-56 engine is impacted by the drone of MAVIC MINI with a weight of 250g.

In addition, the number of damaged fan blades for MAVIC Pro with different collision positions is also concluded in Table 6 to give a comparison. It can be observed that several fan blades are severely damaged with material loss and large bending for all collision positions. For 15% collision position, three fan blades are significantly deformed, and 5 and 6 fan blades are found to be greatly bending for the collision position of 50% and 75%. Especially, the size of the damaged area is the largest for the collision position 75%, followed by 50% and 15% collision positions, respectively. This phenomenon indicates that the damage of fan blades becomes larger as the collision position is closer to the tip of the fan blade. By comparing Tables 5 and 6, it is demonstrated that the damage of fan blades is larger for MAVIC Pro, illustrating the damage level of fan blades is larger when the weight of the drone is larger.

Table 5 The number of damaged blades for different drone collision position simulations (MAVIC MINI).

15%	50%	75%

1 blade damage (nick)	2 blades damage (nick and notch)	2 blades damage (nick)

Table 6 The number of damaged blades for different drone collision position simulations (MAVIC Pro).

15%	50%	75%

3 blades damage (material loss)	5 blades damage (material loss and large bending)	6 blades damage (material loss and large bending)

IV. Conclusion Remarking and Future Works

In this study, the statistics of debris size and weight are carried out for the 50% collision position case, which suggests that MAVIC MINI would lead to much smaller debris size and weight by comparing with MAVIC Pro. Besides, no damage to compressor blades is found for the drone of MAVIC MINI. Some damage of fan blades and compressor blades can be found for MAVIC Pro, which required the engine to be repaired before allowed for the next flight. These results seemingly indicate that setting a 250 g drone did not cause an immediate effect on the operation of commercial aircraft. However, nick to the fan blades caused by MAVIC Mini collision might lead to fatigue failure and reduced overall life span of the engine fan blades. Hence, the 'harmless' drone category should get ATC approval to be operating near to airport airspace to ensure the safety of aircraft operation not to be compromised.

It is also should be noted that this conclusion is obtained based on the preliminary numerical analyses, in which the influence of drone collision on the damage of all stages of LPC and HPC is not taken into account. As shown in Fig. 7, there are four stages of LPC and HPC in the CFM56-5B engine, and the debris may be ingested into the engine core to cause the damage of these stages [27]. Besides, the drone position may also lead to much more severe damage to the engine fan blades, which has been reported in our previous work [28].

Fig. 7. Whole engine model with the fan blade, LPC, and HPC compressor blades [27].

Acknowledgements

This research is supported by the Civil Aviation Authority of Singapore and the Nanyang Technological University, Singapore under their collaboration in the Air Traffic Management Research Institute. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not reflect the views of the Civil Aviation Authority of Singapore. The authors would like to acknowledge Mr Thanaraj for his help in preparing the 3D CAD drawings of the drones.

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