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Preliminary Evaluation of Thrust Loss in Commercial Aircraft Engine due to Airborne Collision with Unmanned Aerial Vehicles (UAVs)

Mohd Hasrizam Che Man, Hu Liu, Bing Feng Ng, Kin Huat Low*

Abstract— This paper is devoted to investigating the influence of UAVs airborne collision with civil aircraft engine on the operation safety of commercial aircraft. The damage levels of the civil aircraft fan blades and compressor blades during the UAVs airborne collision are both evaluated based on the Finite Element Method (FEM) simulation. Besides, the percentage of the engine thrust loss can be estimated by the reduction of pressure ratio throughout the engine using Computational Fluid Dynamics (CFD) simulation. In our study, it is found that UAVs ingestion at approach flight phase has the highest UAVs debris weight of 80g which can cause most severe damage to aircraft Inlet Guide Vane (IGV) Low Pressure Compressor (LPC) blades. This thrust loss can reach up to 75% when the damage of High Pressure Compressor (HPC) blades is included in the analysis. More simulations are will be carefully carried out to check the reliability of this conclusion, in which the influence of secondary level of damage especially IGV blades debris impact on HPC blades are considered.

I. INTRODUCTION

Development of small size UAVs for low attitude airspace allows various application for personal and commercial activities like aerial photography, surveillance, inspection, and package delivery [1, 2]. Then, its number has been increased year by year due to the growing interest of usage UAVs for such application and it is estimated total number of UAVs will reach 4.7 million units by the year 2020 [3, 4].

A. Engine Ingestion Literature Review

Due to its small size and rapid deployment, some peoples are using small UAVs for aerial photography or other activities in the restricted airspace area like the airport. Recently, a lot of cases of unauthorized UAVs intruded into the airport area such as Gatwick airport drone incident in December 2018 [5]. It is reported that there are about thousands of UAV intruding accidents happened over the last ten years. Because of unclear risks posed by presence of the unauthorized UAVs in the airport area especially when aircraft in operation as depicted in Fig. 1(a), common measure taken by airport management is shutting down the runway and airport operation [5]. Disruption in airport operation could result in diversion, delay, and cancellation of flights.

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The most similar research is the bird strike which has been reported since the year of 1970s [6]. FAA statistical data have revealed that the commercial aircraft engine is the most vulnerable component during the bird strike accident and Fig. 1(b) shown cutaway of the commercial aircraft engine [7]. In real-life, the most severe accidents of commercial aircraft are happened due to the failure of the engine parts, which are the sole parts that will supply the power and thrust to the entire commercial aircraft. Thus, the dynamic response of gas turbine engine system under the bird strike has been investigated by several different researchers. For instance, Gao and Li [8] numerically and experimentally analyzed the damage performance of fan blades subjected to bird impact. Mao et al. [9] adopted the finite element method (FEM) to study the influence of different impact velocities on the impact force of fan blades during bird impacting. Apart from the FEM, the smoothed particle hydrodynamics (SPH) method is also widely adopted to examine the damage level of the fan blades under the bird strike [10-12]. Concerning the hazard caused by bird ingestion into engines, different regulations, standards, and certifications have been established for the bird and ice ingestions into aircraft engines to ensure survivability of the civil aircraft engine after impact [13-15].

Figure 1. Problems considered: (a) Presence of drone surrounding commercial aircraft (reproduced image); and (b) cutaway section of commercial aircraft engine [7].

However, these bird strike studies and regulations cannot be directly transferred to UAVs because of the different material composition and strength between birds and UAVs [16]. Concerning this problem, a few experimental and simulation works have been conducted to investigate the collision damage severity resulted from the manned aircraft struck by UAVs. For instance, a group of researchers had performed an outdoor experiment of UAV impacting onto a windscreen of commercial aircraft [17]. The airborne collision simulation between UAS and civil aircraft was carried out by Olivares et al. [18] to estimate the damage level of different components of commercial aircraft. Additionally, an experimental study on UAS airborne collision to the horizontal stabilizer was also carried out to evaluate the damage severity caused by UAV impingement [19].

However, the investigations of UAV ingestion into the engine of commercial aircraft are very limited. The only

related work that can be found was the work carried out by D'Souza et al. [20], in which the damage of the fan blades caused by quadcopter and fixed-wing UAVs was examined in detail. In their study, three flight conditions including take-off, approach, and flight below 10,000 ft were taken into account. Besides, the other related works were conducted by Bayandor et al. [21, 22] to detect the influence of different parameters on the damage level of the fan blades. In their studies, the damage of fan blades caused by the bird and drone strikes was compared, and more serious damage to the drone strike can be observed. However, all these studies have failed to reveal the influence of drone ingestion on the thrust loss of commercial aircraft engines.

B. Thrust Loss due to Engine Ingestion

Engine core can provide about 30% to total engine thrust, however the significant amount of damage to engine core can reduce almost all total engine thrust production. Engine ingestion not only caused engine shutdown and thrust loss, also lead to disruption of aircraft flight operation, injuring flight crew, or might lead to fatal accidents [23, 24]. For example, damage to the high pressure compressor variable guide vane (VGV) and stage-1 compressor blades due to the bird ingestion into the engine inner core has led the total thrust loss to both aircraft engines as experienced by US Airways Flight 1549 during take-off [23].

Almost 2 months prior to the US Airways Flight 1549, Ryanair Flight 4102 suffered multiple bird strikes while approach, which led to a dual engine failure and thrust loss. No deaths were reported, but the aircraft did sustain significant damage. There was no significant damage reported on the fan blades itself, although a considerable amount of organic material was found inside the engine core (LPC, HPC and compression chambers) which caused severe alterations in the aerodynamic profiles of compressor blades, causing partial airflow disruption [25].

Due to concern about the bird ingestion into the aircraft engine, it is required that all gas turbine engines and particularly turbofan engines should be durable to withstand the bird ingestion. For the ingestion of small and medium birds, the demonstration of structural integrity and a continued thrust level of 75% should be satisfied. For large bird (1.85 kg) ingestion, the certification regulation requires the engine can be shut down under a controlled manner with no fire, and this must be proved in a certification test on an entire engine. Besides, it also has to be proven that the engine inlet can stand a large bird impact without damage to significant components (FAR/JAR/CS 25.571, 33.76). This bird ingestion certification also can be followed for drone collision study in our future study.

However, up to the authors' knowledge, none study has been done to analyze the influence of UAVs debris ingested into the aircraft engine core from an airborne collision between a UAS and a manned aircraft. Especially, the effect of the compressor blade damage on the engine thrust production is barely reported.

Motivated by this fact, the objective of this study is to investigate the effect of UAVs debris ingested into the aircraft engine by using the commercial FEM or CFD simulations, then to have better airborne hazard severity thresholds for collisions between unauthorized UAVs and manned aircraft within the aerodrome and its impact on airport and flight operation. Furthermore, understanding the effect of collision between UAVs and aircraft engines is important for regulations and standards around manned aircraft and could provide important information to flight crews when such collision is taking place.

II. MODELING AND SIMULATION

To understand the hazard severity caused by UAVs airborne ingestion into the commercial aircraft engine, the simulation using commercial FEM and CFD software has been carried out. Firstly, the FEM models of UAVs and the civil aircraft engine are built, which will be exhibited in detail in the following sections. Then, these models are assembled to a UAV-engine system with estimated material properties, initial conditions, and boundary conditions from the established database. Besides, the fan blades and compressor blades damage are investigated under different flight phases using FEM simulation. Finally, the percentage of thrust loss is obtained by using the data pressure ratio reduction obtained via CFD simulation.

A. UAVs and Aircraft engine model

In this study, the FEM simulation of the UAV airborne collision is prepared by using ABAQUS software and solved with Dynamic/Explicit formulation. Here, DJI INSPIRE I with dimension $437 \times 453 \times 302$ mm and weight 3.50 kg are chosen to represent small UAVs [26] size category as depicted in Fig. 2. Based on the data statistics of bird strikes from Ref. [16], it is found that CFM-56 is the civil aircraft engine type involved in most bird strike incidents in U.S between 1990 until 2018. Hence, our focus in the following studies is the UAVs collision on the CFM-56 engine. All the 36 fan blades of the aircraft engine with a disc, as well as the inlet guide vane (IGV) and stage-1 LPC are established for the engine ingestion simulation, as shown in Fig. 3.

All of UAVs and engine parts are meshed as hexahedron with C3D8 element type except the UAV thin-walled structures such as the main body hull and bracket parts are meshed as shell element type S4. For the UAV main body, the front part is refined with a minimum element size of 0.75 mm and the maximum element size of 2.0 mm. The average element size with about 4~5 mm is adopted to mesh the other parts of the UAV, and the total element number is about 233,315 with detailed FE models and material settings for each part are presented in Fig. 3. The maximum and minimum element sizes for the fan blade are about 1.7 mm and 12.1 mm, respectively. A total number of 266,740 elements are meshed for the whole engine model. To ensure the accuracy of FEM simulation, the mesh size of the twelve fan blades that would contact UAVs during the collision process is refined, and the location of the first three fan blades with refined meshes is presented in Fig. 4.

B. FEA Boundary Condition

As depicted in Fig. 4, the UAV-engine system combining with the engine fan blades, blade disc, as well as compressor fan blades and the UAV are assembled. The UAVs are assumed to impact the aircraft engine fan blade leading edge at position 15% from the fan blade root. The interaction behavior between the UAV and engine is modeled as surface to surface contact algorithm with no friction. To evaluate the damage severity level that occurred to the aircraft engine during the UAV strike, the take-off and approach phases with different forward (relative) and rotation speeds are considered

Figure 2. FEM model and material distribution for UAV: DJI INSPIRE I.

Code	Material
Yellow	Polycarbonate Polymer
Blue	Lithium-Polymer (Li-Po Battery)
Green	Cast Aluminum 520.0
Red	Steel Alloy AISI 4030
Grey	Carbon Fibre

Figure 3. FEM model for civil aircraft engine: (a) isometric view; and (b) side view (internal components, IGV and LPC blades).

C. Model for Engine Thrust Loss

The engine thrust loss behavior can be analyzed based on CFD simulation. For this study, only LPC section was defined for CFD simulation as shown in Fig. 5(a) and solved using commercial software, ANSYS Fluent.

The cases being considered for the CFD analysis are as follows: i) with no blade damaged; and ii) two IGV LPC blades missing as shown in Figs. 5(c) and 5(d), based on the investigation on the aircraft accident report for Airbus A320 with engine CFM56 [7]. By using this simulation, the total pressure in front and behind the IGV LPC blades both can be obtained, and the pressure ratio can be derived by dividing the total pressure behind blades with that in front of the IGV LPC blade.

in this study.

In the simulation, by assuming the drone is hovering at the center of runway then the UAV can be defined with initial forward speeds of 92.6 m/s and 115.8 m/s (relative speed between drone to aircraft) taken from Refs. [27, 28], for the take-off and approach phases, respectively. Besides, the aircraft engine is defined with a rotational speed of 314.2 rad/s (3000 RPM) [29] for both flight phases. The fan blades, blade disc, IGV, and compressor blades are allowed to move rotationally, while no translational movement along the engine blade disc axis of rotation is adopted.

The engine pressure ratio (*EPR*) can be achieved by using the total pressure at engine inlet dividing the total pressure at engine outlet one, i.e.,

$$EPR = P_{in}/P_{out} \quad (1)$$

in which P_{in} and P_{out} denote the engine total pressure at the engine inlet and the engine low pressure turbine outlet, respectively as shown in Fig. 5(a). Similarly, the pressure ratio in each stage of the engine also can be derived by using the total pressure at behind dividing the one at the front. For instance, the pressure ratio across IGV and stage-1 LPC, PR_1 can be calculated using similar manner by taking total pressure before IGV, P_{IGV} and total pressure after stage-1 LPC, P_1 as depicted in Fig. 5(b). Then, the total pressure at the

Figure 4. FEM model of UAV-engine ingestion simulation of engine fan blades and UAV parts with mesh refinement on engine fan blades (the first three refined mesh fan blades).

engine nozzle outlet can be calculated by using the following equation:

$$P_{out} = P_{in} \times PR_1 \times PR_2 \times \dots \times PR_i \times \dots \times PR_N \quad (2)$$

where PR_i denotes the pressure ratio in the i^{th} ($i = 1, 2 \dots N$) stage, and N is the total number of stages in the engine core. Taking the IGV stage and Stage-1 of LPC for example, the engine pressure ratio can be calculated by using the following equation if there is no damage in these two stages, i.e.,

$$\begin{aligned} EPR_{no} &= \frac{P_{out_{no}}}{P_{in}} = \frac{P_{in} \times PR_{1_{no}} \times PR_{other}}{P_{in}} \\ &= PR_{1_{no}} \times PR_{other} \end{aligned} \quad (3)$$

where $PR_{1_{no}} = P_{1_{no}}/P_{IGV}$ denotes the pressure ratio of these two no-damaged stages (IGV stage and Stage-1 of LPC), and PR_{other} is the pressure ratio of other stages, which satisfies,

$$PR_{other} = PR_2 \times \dots \times PR_j \times \dots \times PR_N \quad (j = 2, 3 \dots, N) \quad (4)$$

Once some damages have occurred in these two stages, the engine pressure ratio can be re-calculated as

$$\begin{aligned} EPR_{damage} &= \frac{P_{out_{damage}}}{P_{in}} = \frac{P_{in} \times PR_{1_{damage}} \times PR_{other}}{P_{in}} \\ &= PR_{1_{damage}} \times PR_{other} \end{aligned} \quad (5)$$

in which PR_{other} is the same as the above equation; $PR_{1_{damage}}$ can be calculated by using the behind pressure $P_{1_{damage}}$ dividing the front pressure P_{IGV} , in which the pressure $P_{1_{damage}}$ was obtained by CFD simulation.

Once some compressor blades are failed, the reduction of total pressure ratio in the across aircraft engine can be

simulated and it can be used to estimate the engine thrust loss by using following equation [30]:

$$Thrust, T = \dot{m}V + A(P_{out} - P_{inlet}) \quad (6)$$

where $\dot{m}$ and V are mass flow rate and velocity at engine exhaust, A , P_{in} , and P_{out} are the area of engine inlet, the total pressure at engine inlet, and the total pressure at engine low pressure turbine outlet, respectively.

D. Material Data

The fan blades and compressor blades of CFM-56 are made of titanium alloy (Ti-6AL-4V). In this FEM simulation, the linear elastic-plastic material model is adopted to simulate the failure and damage behavior of the titanium alloy Ti-6AL-4V, aluminum alloy, steel alloy, and lithium-polymer (Li-Po) battery. Besides, density, elastic modulus, and Poisson's ratio for the titanium alloy are defined as 1755 kg/m³, 114 GPa, and 0.33, respectively [31]. Accordingly, the elements will be deleted as their equivalent tensile strain reaches the critical failure strain. In the present study the failure strain for titanium alloy Ti-6AL-4V is set as 0.15 [32].

Table 1 Elastic-Plastic material parameters used in this study (unit: MPa).

Material	Yield stress, σ_y	Ultimate tensile stress, σ_{UTS}	Ultimate tensile strain, ϵ_{UTS} (%)
Ti-6AL-4V	880	900	15.0
Aluminum Alloy	170	330	14.0
Steel Alloy	460	560	21.5
Carbon Fiber [33]	765	765	1.45
Li-Po Battery [34]	30	55	37.5

Figure 5. Models considered: (a) LPC section will be modelled in CFD [7]; (b) Location of total pressure before IGV blade, P_{IGV} and total pressure after Stage-1 LPC, P_1 ; (c) CFD domain with no blade damaged; and (d) CFD domain with two blades are missing (removed).

The material properties of UAVs are derived from Ref. [18], in which the detailed materials used for each part are listed in Fig. 2 and material properties presented in Table 1. The polycarbonate polymer is modeled as the elastic-plastic criterion. The element deletion is simulated as the plastic strain is getting larger than the maximum tensile plastic strain. Some basic mechanical parameters of battery are given as follows: density, $\rho = 1755 \text{ kg/m}^3$, Young's modulus, $E = 500 \text{ MPa}$, and Poisson's ratio, $\nu = 0.01$ [33].

III. NUMERICAL RESULTS

A. UAVs Debris size

The effect of the flight phase on the UAV's debris size and weight from UAVs collision with aircraft engine fan blades for different UAVs category hard components (i.e. motor and camera) is presented in Table 2. Fig. 6 shows kinematic series of impact between drone and fan blades.

Table 2 UAVs debris size and weight for large UAVs category at different flight phases.

Flight Phases	Debris size (mm)	Debris weight (g)
Take-Off	34	16
Approach	42	80

For the take-off flight phase, all of UAVs hard parts debris (i.e. motor and camera) are not ingested into the engine core because the high fan blades centrifugal force has pushed UAVs debris aside from being ingested into engine core.

However, due to higher aircraft speed during the approach phase, more drone debris being ingested into engine core and breaking one of the IGV blades as shown in Fig. 5(d).

Figure 6. Kinematics of the impact between the commercial aircraft engine and a UAVs for approach flight phase.

B. Engine Total Pressure

Fig. 7 shows the influence of different flight phases on the damage IGV LPC blades. IGV LPC blades damage level can be between 0% and 100%, for 0% damage level indicate no damage to IGV LPC blade and 100% damage level to represent total damage to one IGV LPC blade as depicted in Fig. 7(d).

From CFD analysis performed, the total pressure across the IGV LPC blades can be determined. The total pressure along the aircraft engine section can be calculated based on CFM56 engine data from Ref. [35] and total pressure from CFD analysis. Then the engine thrust can be estimated by using Equation (1), which can be subsequently used to estimate thrust loss, as shown in Table 3. The simulation results suggest that the flight phase will also affect the IGV blade damage and thrust loss of the aircraft engine. The most critical phase that would cause much more influence on the operation of the engine is the approach flight phase.

Besides, it is observed that the estimated thrust loss for the approach phase is 3% which is inconsistent with the report provided in Ref. [23]. The investigation by Ref. [23] found that two IGV blades ingested into the engine core can cause damage (i.e. battering and bent) to all stage-1 HPC blades and lead to 100% thrust loss.

Table 3 The percentage of blade damage and estimated thrust loss for different flight phases.

Flight Phases	Blade Damage (%)	Estimated Thrust Loss (%)
Take-Off	25	1
Approach	100	3

It means that the current study based on only damage to IGV LPC blades is not enough to determine the thrust loss due

to mid-air collision between UAVs and aircraft engines. Because HPC blades are made from a less strong material, and its high rotational velocity, it is easily damaged due to debris ingested into engine core. In Ref. [23], it is reported that the damaged IGV blades will go inside and cause all stage-1 HPC blades missing, i.e., the pressure ratio across this stage becomes 1 (mean no pressure increase). It is clearly shown that the total pressure at station P2 decreases when all stage-1 HPC blades broken is 23.3% compared to the no damage case. The thrust along the engine section is plotted in Fig. 8. The significant drop in total pressure drop at station P2 has led to thrust loss by 75%.

IV. CONCLUSION

In this paper, the UAVs airborne collision onto the aircraft engine is studied based on the FEM and CFD simulations to evaluate the thrust loss of commercial aircraft. The damage of the fan blades and IGV compressor blades can be simulated by using FEM simulation, and the percentage of thrust loss of the engine can be estimated by the reduction of pressure ratio through CFD simulation. Some important conclusions can be drawn as follows:

1. In our study, the drone ingestion happens at different flight phases would lead to different drone debris sizes and weights. The approach flight phase has the highest drone debris weight of 80g which can break one of IGV LPC blades. By considering only the damage of one IGV LPC blade, the thrust loss is about 3% for the approach phase.

2. The stage-1 HPC blades will be totally battered and bent due to the impinging by the IGV LPC blade debris ingested into the engine core. The reduction of the engine thrust would increase from 3% to 75% once the damage of the HPC blades is considered.

It is also should be noted that the HPC blades damage caused by IGV blades debris ingested into the engine core is obtained according to the accident report [23]. More detailed numerical simulation with considering all LPC and HPC stages can be carried out in future work. In addition, study influence of different drone posture to the thrust loss might also be considered in future study as complex drone posture may lead to more serious damage to fan blades as reported by Liu et al. [36]. The method presented in this work is helpful to guide us to understand the influence of UAVs ingestion on the engine thrust loss and aircraft flight operation.

Figure 7. Damage to aircraft engine IGV blades for (a) 0% damage level, and (b) 100% damage level.

Figure 8. Total Pressure across aircraft engine from CFD analysis for different cases: (a) no damage [35]; (b) All stage-1 HPC blades damage; and (c) 2 IGV LPC blades damage [23].

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