Research Article

Collision Analysis of the Motor and Camera in Light and Small UAVs Based on Experiment and Simulation

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For unmanned aerial vehicles (UAVs), their motor and camera are rigid components that are most likely causing damage in the event of a collision. Therefore, in the research of UAVs collision simulation, establishing accurate motor and camera FE models is the key step. Kinetic material tests were conducted for 7075 aluminum alloy, and an accurate material model was obtained. A test of motor and camera strike on plates was developed, and the dynamic response of the plates was obtained to verify the numerical method of UAV motor and camera strike on plates. Based on these, accurate FE models of motor and camera were established. In addition, the motor and camera were divided into element models with different sizes, and the influence of element size on calculation accuracy and efficiency was investigated. It is indicated that when the average size of the motor grid is less than 1.25 mm and the average size of the camera grid is less than 1 mm, a good balance could be achieved between calculation accuracy and calculation efficiency. Through comprehensive consideration, a 1.25 mm and a 1 mm mesh model were selected for the motor and the camera, respectively, to establish their finite element model which was then employed in the simulation of motor and camera strike on plates. The simulation results showed that the strain-time curve peak of the aluminum plate impacted by the motor had an error of 9.5% with the experimental result and that by the camera had an error of 9.7% with the experimental result. At the same time, the influences of speed and collision angle were investigated. It is indicated that the greater collision angle of the motor, the smaller collision angle of the camera, and the greater impact speed of both cause greater damage to the aluminum plate. The FE modelling method and collision simulation method of motor and camera proposed in this paper can greatly save the resources for testing the UAV performance through the practical structural strength test, especially for light and small UAVs.

1. Introduction

Unmanned aerial vehicles (UAVs) are widely used in many fields, such as recreation [1], emergency rescue [2, 3], environment monitoring [4], power line inspection [5], aerial mapping [6], military defense [7, 8], and agricultural plant protection [9] today, with sales expected to 82.1 billion US dollars by 2025 [10]. To address a broad range of safety challenges, researchers have designed aircraft control schemes [11–13], collision avoidance algorithms [14, 15], collision avoidance systems for UAVs [16, 17], and formation control for swarm UAV systems [18–20]. Although the above mea-

sures can reduce the risk of collision events, the collision of civil UAVs causes damages from time to time. From 2010 to 2016, the European Aviation Safety Agency (EASA) reported three collisions between noncommercial aircraft and UAVs [21]. The occurrence of these collisions has sparked widespread concern about the safety of UAVs. The Federal Aviation Administration (FAA) systematically studied the effects of rotor configuration and fixed-wing configuration on civil aircraft and commercial aircraft [22–24]. FAA established the CAD models for UAVs through reverse engineering and the UAV finite element model through building block method. The usability of the finite element

TABLE 1: The types of UAVs.

Type of UAV	Empty weight	Maximum take-off weight
Micro	<0.25 kg	—
Light	0.25 kg~4.0 kg	<7.0 kg
Small	4.0 kg~15 kg	7.0 kg~25 kg
Medium	>25 kg	25 kg~150 kg
Large	—	>150 kg

model was verified by the horizontal plate impact test. Based on the finite element model of UAV, the UAV-aircraft collision was simulated. In addition, the FAA drafted regulations related to UAV control [25] and issued a series of research reports on UAV impact in 2017, where the fourth part of the report [24] conducted the numerical simulation and damage assessment of the UAV impact. Besides, EASA, British Civil Aviation Authority, etc. also set up a research team to assess the risk of collision between UAVs and aircraft with experimental and numerical methods [26, 27].

Currently, there are two main methods for assessing the safety of UAV collisions, i.e., experimental and simulation. Since the experimental method has many disadvantages such as the complexity and diversity of setting collision scenarios, the long test period, and the limited test conditions, the simulation method has become a more convenient and efficient tool to simulate and reproduce the UAV impact process, especially the high-speed impact. Georgiadis et al. [28] believe that as long as the results have been verified by representative aircraft structures, the bird strike test can be replaced by appropriate numerical analysis, so as to improve the aircraft safety in design and significantly reduce the test cost [29]. Reference [30] determined the injury levels caused by the impact of drones dropped from various heights in free drop modelling and impact experiments. The collision mechanism of the unmanned aerial vehicle (UAV) against the glass panel was elucidated, and the collision impact force representing the collision threat by the UAV was investigated through experiments and numerical simulations [31]. The vital damaged parts, damaging process, and failure mode of the UAV structure in the crash test were accurately characterized in the collision simulation [32]. Thus, the UAV modelling and collision simulation was verified to exhibit feasibility.

In the “Interim Regulations on Unmanned Aerial Vehicle Flight Management,” the weight standards were employed by China as the major indicators and integrated other performance indicators of UAVs for the classification of micro-, light, small, medium, and large UAVs [33, 34]. The types of UAVs are listed in Table 1. Light and small UAVs were defined as UAVs whose empty weight was more than 0.25 kg but no more than 15 kg. According to this standard, most civilians used UAVs that were included in light and small UAVs [35]. Therefore, it is necessary to analyze the collision performance of light and small UAVs. And reference [36] pointed out that the densest and heaviest parts, which pose the biggest risk of penetration upon impact, are the motors, battery pack(s), and the camera as a typical payload. To the best of our knowledge, typical payload collision

problems for light and small UAVs with accurate Finite element (FE) models for motors and cameras have not been considered widely.

Motivated by the above facts, this paper investigates the accurate FE modelling problem for motors and cameras of light and small UAVs with collision conditions. Kinetic material tests were conducted for 7075 aluminum alloy, a widely used material in electric motors and cameras. And an accurate 7075 aluminum alloy material model was obtained for simulation. An air cannon system was designed, and impact tests were conducted to simulate the high-speed collision of UAVs and assess the resulting damage. An explicit FE method was adopted to build the FE models of UAV motor and camera [37], and the accuracy of models was verified by a comparison between numerical and experimental results. In addition, the effect of different mesh sizes of the UAV motor and camera on the computational accuracy and efficiency was also investigated. Compared with the previous results, the main contributions of this paper are twofold. Firstly, accurate FE models of motors and cameras of light and small UAVs with collision conditions were built to solve typical payload collision problems for light and small UAVs. In [38, 39], the model of camera was only built by the scanning inverse modelling method as an entirety. In [40–42], the camera and four motors were just assumed to be made of a single material, 6061-T6 aluminum alloy. The accurate FE models of UAV motors and cameras could help the establishment of an accurate UAV finite element model, and the modelling method can be referred to in future UAV collision studies. Secondly, material parameters of 7075 aluminum alloy, which was used for motors and cameras in DJI MAVIC 2 (a UAV version used in test), were obtained by conducting kinetic material tests at low and medium strain rates with the DNS-100 electronic universal testing machine and high-speed hydraulic servo testing machine. The accuracy of material parameters was verified by comparing numerical and experimental results. And these parameters can be referred for material modelling in numerical analysis and verification.

The rest of this paper is organized as follows. In Section 2, the material tests and air cannon tests were designed, and the results of tests were shown. FE models of motors and cameras were built in Section 3. In Section 4, the element scale and computational efficiency of the model were analyzed. In Section 5, the strain curves for motor impact from numerical and experimental results were compared. In Section 6, the influences of the speed and collision angle on the simulation results were investigated. Finally, the conclusions are drawn in Section 7.

2. Experimental Design

The camera and motor (as shown in Figure 1) studied in this paper is from the DJI Mavic2, which is a consumer-grade light and small UAV, as shown in Figure 2.

2.1. Material Testing. The main materials present in the motor and camera of the MAVIC2 UAV include polycarbonate and aluminum alloy 7075-T6. In this paper, kinetic

FIGURE 1: Motor and camera from DJI MAVIC2. (a) Motor from DJI MAVIC2. (b) Camera from DJI MAVIC2.

FIGURE 2: DJI MAVIC2.

material tests with low to medium strain rates were conducted specifically for aluminum alloy. As the collision between the motor and the camera plate was a low-speed collision, the strain rate was set to be not higher than 100 s^{-1} , so only the quasistatic and low to medium strain rate experiments were conducted, with the strain rates being 0.001 s^{-1} , 0.1 s^{-1} , 1 s^{-1} , 10 s^{-1} , and 100 s^{-1} , respectively. The quasistatic tensile test was performed on a DNS-100 electronic universal testing machine, and the dynamic tensile test was performed on a high-speed hydraulic servo testing machine (as shown in Figure 3), subjecting to the standard *metallic materials-tensile test at ambient temperature* (GB/T 228-2002). The Johnson-Cook constitutive model [43] was selected for the 7075-T6 aluminum alloy, which reflects the tensile and compressive properties of the material at different strain rate levels:

$$\sigma = (A + B\epsilon^n)(1 + C \ln \dot{\epsilon}_e^*)(1 - (T^*)^m), \quad (1)$$

where σ is the equivalent strain, B is the strain hardening modulus, n is the hardening index, A is the reference strain rate and the yield stress at the reference temperature, ϵ is the equivalent plastic strain, C is the strain rate sensitivity factor, $\dot{\epsilon}_e^* = \dot{\epsilon}_e / \dot{\epsilon}_0$ is the dimensionless strain rate, $\dot{\epsilon}_e$ is the equivalent strain rate, $\dot{\epsilon}_0$ is the reference strain rate, $T^* =$

$(T - T_t)(T_m - T_t)$ is the dimensionless temperature, where T_m is the material melting point, T_t is the reference temperature, and m is the temperature sensitivity factor. As this research focuses on low-speed collision, the temperature change during the collision was very small, so the effect of temperature change on the equivalent strain was not measured, and only the first and second terms of the J-C model were used. During the collision, most of the material failure resulted from the stretching caused by displacement in the collision region [44]. Therefore, the maximum tensile strain was used as the criterion for finite element mesh failure. The parameters of aluminum alloy 7075-T6 obtained by the experiment are as shown in Table 2.

2.2. Air Cannon Test

2.2.1. Introduction to the Air Cannon Test. FAA establishes the FE model of UAV by building block and verifies the reliability of the FE model by the part level plate impact test. Yu et al. have conducted a test of motor strike on the plate to validate the numerical simulation method of a UAV strike on blades [38]. Similar experiments were conducted to verify the numerical simulation method of motor and camera impacting target plates in this paper. In this research, an air cannon system was used for accelerating the UAV motors and cameras to collide with the target plates. The air cannon system mainly consists of an air tank, an air chamber, and a gun barrel, as shown in Figure 4. It works by loading the sabot and projectile into the barrel before firing. The air chamber is then filled once using an air compressor. The pressure value in the air tank is monitored by means of a pressure gauge on the tank, and the filling stops when the prescribed air pressure is reached. When firing, the airtight valve of the gas chamber is opened, and the high-pressure air in the gas tank will push the sabot and the projectile to accelerate along the barrel. A device at the exit of the barrel blocks the movement of the sabot, thus separating the sabot from the projectile. After separation of the sabot from the projectile, the impact speed of the projectile is measured by a laser sensor.

FIGURE 3: (a) DNS-100 electronic universal testing machine. (b) INSTRON VHS 160 high-speed testing system.

TABLE 2: Constitutive parameters of the aluminum alloy.

Material	Density, ρ (kg/m ³)	Young modulus, E (MPa)	Poisson's ratio, ν	A (MPa)	B (MPa)	n	C	$\epsilon_{\max}$
7075-T6	$2.7E+3$	$7E+4$	0.33	297	381	0.718	0	0.23

FIGURE 4: Schematic diagram of the air cannon system.

FIGURE 5: Aluminum plate mounting frame.

FIGURE 6: Schematic diagram of the strain gauges attached to the aluminum plate.

FIGURE 7: (a) The moment of impact between motor and aluminum plate. (b) The moment of impact between camera and aluminum plate.

FIGURE 8: (a) Damage of aluminum plate after the motor impact in the test. (b) Damage of aluminum plate after the motor impact in the simulation. (c) Damage of motor after the motor impact in the test.

FIGURE 9: (a) Damage of aluminum plate after the camera impact in the test. (b) Damage of aluminum plate after the camera impact in the simulation. (c) Damage of camera after the camera impact in the test.

FIGURE 10: Three views of the motor's geometric model.

FIGURE 11: Three views of the camera's geometric model.

TABLE 3: Constitutive parameters of materials.

Material	Density, ρ (kg/m ³)	Young modulus, E (MPa)	Poisson's ratio, ν	A (MPa)	B (MPa)	n	C	$\varepsilon_{\max}$
Copper	$8.93E+3$	$1.15E+5$	0.31	85	308	0.54	0	0.23
7075-T6 aluminum	$2.7E+3$	$7E+4$	0.33	297	381	0.718	0	0.23
2024-T3 aluminum	$2.78E+3$	$7.24E+4$	0.33	369	684	0.73	0	0.19
Steel	$7.85E+3$	$2.1E+5$	0.3	497.75	647.15	0.393	0	0.064

TABLE 4: Constitutive parameters of polycarbonate.

Material	Density, ρ (kg/m ³)	Young modulus, E (MPa)	Poisson's ratio, ν	K (MPa)	N	EPSF
Polycarbonate	$1.19E+3$	$2.34E+3$	0.38	$1.14E+2$	0.19	3.0157

TABLE 5: Element detection standard.

Quality parameter	Allowable min	Allowable max
Element size	0.8 mm	6 mm
Aspect ratio	—	5
Quad angle	40°	140°
Triangle	30°	120°
Warp angle	—	10°
Jacobian	0.6	—
Time-step	1E-7S	—

FIGURE 12: Simulation of bolt with NRB.

In the experiment, the target plate was a 2024-T3 aluminum alloy with dimensions of 600 mm $\times$ 600 mm $\times$ 2 mm and was bolted to the frame, as shown in Figure 5. During the experiment, the collision process was recorded by two high-speed cameras, both located on the side of the target plate.

During the experiment, dynamic strain gauges were employed to the back of the impact point of the target plate to measure the strain response of the target plate. The strain gauges were prone to failure under high-speed impact loads, resulting in data loss. To obtain a complete dynamic response for the deformation, a set of strain gauges with the same size were arranged at six different positions, as shown in Figure 6. Positions 1, 2, and 3 were along the vertical direction, and positions 4, 5, and 6 were along the horizontal direction, at distances of 100 mm, 150 mm, and 200 mm from the center, respectively.

In the experiment, the impact speed of the motor and camera was recorded by a laser velocimeter, and their collision angle upon impact with the target plate was recorded by a high-speed camera.

FIGURE 13: Simulation of hinge with NRB and joint.

2.2.2. Analysis of the Experimental Results. In the experiment, the impact speed of the motor and camera was recorded to be 89 m/s and 117 m/s, respectively. The collision angle of the motor and camera was recorded to be 36° and 32°, respectively. The moments of impacts are shown in Figure 7.

When the motor or camera hit the aluminum plate at high speed, the strain gauges and the wires connected to the strain gauges were easily pulled off, resulting in a lack of strain data. In particular, at positions 1 and 4, the strain gauges were quickly pulled off due to the proximity to the impact point and the violent deformation of the plate. In this experiment, strain data was only available for strain gauges at positions 3 and 6. As the positions 3 and 6 are symmetrical concerning the impact position, their strain response curves are essentially the same.

The damage patterns after the motor impact are shown in Figure 8. The motor did not pass through the aluminum plate but still caused a quadrilateral opening and large cracks in the aluminum plate. As can be seen, the motor retained its basic shape after impact, but the direct impact surface of the motor had a large deformation, and the hollow base of the motor had a large deformation, indicating its weak impact resistance. The drive shaft of the motor was bent but did not break.

The damage patterns after the impact of the camera are shown in Figure 9. The camera passed through the aluminum plate, causing a large quadrilateral opening and large cracks in the aluminum plate. As can be seen, the camera had a large deformation at the direct impact position, while the rest of the camera parts kept their original shape, and all the connections of the camera were broken, indicating the weak impact resistance of its screws.

3. Motor and Camera Modelling

3.1. Geometric Model. The motor and camera were mapped using vernier callipers and electronic protractors to establish their 3D model in the CATIA software, as shown in Figures 10 and 11.

FIGURE 14: The connection of CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK.

FIGURE 15: The connection of CONTACT_TIED_SHELL_EDGE_TO_SURFACE.

FIGURE 16: (a) The moment of impact between motor and aluminum plate in the simulation. (b) The moment of impact between camera and aluminum plate in the simulation.

3.2. Material Parameters. We have measured the parameters of aluminum alloy 7075-T6 by tensile tests, with the results shown in Table 3. The parameters of polycarbonate [45], copper [46], and steel [47] are shown in Tables 3 and 4.

3.3. Types of Elements. The motor and camera were discretized in the HyperMesh software, where solid cells were used to represent all parts of the motor and the internal parts of the camera, and shell cells were used to represent the camera housing. As the internal parts of the motor and camera had little influence on the collision process, monolithic modelling was used. The smaller the mesh size, the higher the accuracy of the numerical solution, and the longer the solution time, so an appropriate mesh size is needed to balance computational accuracy and computational efficiency. Therefore, this paper places certain restrictions on the element quality, and the grid checking criteria are shown in Table 5.

Hughes-Liu ($ELFORM = 1$) was chosen as the formula for the integration algorithm for the shell cell [48–50]. In two-dimensional cells, triangular cells exhibit higher stiffness than quadrilateral cells, as the number of triangular cells is always limited to 5% of the total number of cells to

ensure computational accuracy. In motors where only one layer of cells can be divided due to the thinness of the layers, the full integral cell algorithm ($ELFORM = 2$) was used to represent the bending stiffness.

3.4. Connection Modelling. A formal connection of NRB was used in the finite element model of the motor to model the bolted connection, enabling a more detailed connection structure for the MAVIC2 UAV motor.

- (i) * **CONSTRAINED_NODAL_RIGID_BODY**: for the two bolt holes of the bolted connection, the two bolt holes were modelled together in both 3D modelling and finite element modelling, the center point of the bolt hole was retained as a separate node, and the mesh nodes in the bolt hole wall area within or of the bolt hole were connected to the bolt hole by **CONSTRAINED_NODAL_RIGID_BODY** to the retained central independent node, as shown in Figure 12
- (ii) **NRB+Joint** [23, 24]: the connection between the camera and the head was hinged to allow the camera

TABLE 6: Motor and camera models with different element sizes.

Element size (mm)	Motor	Camera
0.1
0.25
0.5
0.75
1
1.25
1.5		

TABLE 6: Continued.

Element size (mm)	Motor	Camera
2
2.5
3

FIGURE 17: Relationship between calculation time, error, and element size for motor impact.

FIGURE 18: Relationship between calculation time, error, and element size for camera impact.

to rotate freely, and a combination of NRB and Joint was used. For the two studs of the hinge connection, the studs were modelled separately in both 3D and finite element modelling, the center of the bolt hole was retained as an independent node, and the mesh nodes in the stud wall area were connected to the retained center independent node via `CONSTRAINED_NODAL_RIGID_BODY`. After modelling the top and bottom round holes of the hinge connection separately, the center points were then connected with `CONSTRAINED_JOINT_REVOLUTE` to form an NRB+Joint form to represent the bolt connection junction, as shown in Figure 13

- (iii) `CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK` was used to simulate the connection between the stud and the camera housing. `CONTACT_TIED_SHELL_EDGE_TO_SURFACE` was adopted to simulate the connection between the camera lens cover, the base plate, and the housing, as shown in Figures 14 and 15

3.5. Contact Modelling. Contact modelling is a very important part of explicit dynamics analysis, where friction and contact forces between different components can have a significant impact on the simulation results. LS-DYNA offers a number of different contact algorithms.

As the location of the possible contact between the motor and the camera's own components during the collision with the aluminum plate cannot be predicted, `*CONTACT_AUTOMATIC_SINGLE_SURFACE` was chosen as the most suitable contact modelling for the detection of possible contact between the motor and all the camera's components during the collision. This contact algorithm only requires the definition of the slave contact surface, and the program will automatically detect all external surface nodes in the model at each time-step to detect if penetration behavior has occurred and apply the correct contact force to avoid penetration. The contact force is proportional to the stiffness of the contact and is estimated according to two different methods, i.e., the penalty function-based method and the soft constraint method.

The penalty function-based method is the default method used in LS-DYNA contact cards for contact stiffness calculations. The calculations depend on the material model and the size of the parts in the contact list. So, the penalty function-based method is a good choice when the parts in the contact are made up of similar materials. If very hard materials (e.g., metals) are in contact with softer materials (e.g., foams), there is a possibility of contact failure. Then, since the segment-based soft constraint method depends on the global time-step and the mass of the nodes in the contact segment, it is a good choice for dealing with contacts between materials with different stiffness properties. As the material properties of the parts of the MAVIC2 motor and camera vary considerably, the segment-based soft constraint method (`SOFT = 2`) contact algorithm was chosen, and warp segment checking (`SBOPT = 3`) was enabled.

FIGURE 19: Comparison of the strain curves for motor impact.

The contact between the motor, camera, and aluminum plate was modelled using `*ERODING_NODES_TO_SURFACE` to simulate the erosion occurring between the motor, camera, and aluminum plate.

3.6. Loads and Boundary Conditions. In the air cannon tests, the aluminum plate was mounted in such a way that it could be equated to a square fixed boundary condition. So, the plate was simplified to a 550 mm × 550 mm plate in the simulation model, and fixed boundary conditions were applied around the plate. The material used for the plate was a 2024-T3 aluminum alloy, and the Johnson-Cook material model was used, with the parameters shown in Table 3 [51]. The plate was meshed using hexahedral solid cells with a mesh size of 1 mm in the impact area and 3 mm in the rest of the area. A total of 151392 solid cells were divided in the plate. According to the test conditions, the impact speed of the motor was 89 m/s, and the collision angle was 36°. The impact speed of the camera was 117 m/s, and the collision angle was 32°. Their respective calculation model was established, as shown in Figure 16.

4. Element Scale and Computational Efficiency Analysis

This chapter investigates the convergence of meshes for the motor and camera. Elements density is an important factor affecting the accuracy of numerical calculation. In general, as the mesh density increases, the accuracy of numerical calculation will increase, but the storage space and computational time will also be greatly increased. Therefore, the balance between computational accuracy and efficiency should be considered in meshing, and it is necessary to verify the independence of the element size. Element independence means that when the number of elements is limited, the computational results do not change significantly with the increase in the number of cells when the cell model reaches a certain order of magnitude. In order to find a range of mesh sizes with less computational error and shorter computational time, we modified the mesh sizes of the motor and camera by dividing the mesh sizes of the camera into 0.1 mm, 0.25 mm, 0.5 mm, 0.75 mm, 1 mm, 1.25 mm,

FIGURE 20: Comparison of motor impact when $t = 0.25$ ms. (a) Result in test when $t = 0.25$ ms. (b) Result in simulation when $t = 0.25$ ms.

FIGURE 21: Comparison of motor impact when $t = 0.4$ ms. (a) Result in test when $t = 0.4$ ms. (b) Result in simulation when $t = 0.4$ ms.

FIGURE 22: Strain nephogram during collision between motor and aluminum plate.

1.5 mm, 2 mm, 2.5 mm, and 3 mm, and the mesh sizes of the motor into 0.25 mm, 0.5 mm, 0.75 mm, 1 mm, 1.25 mm, 1.5 mm, 2 mm, and 2.5 mm as shown in Table 6. The finite element simulation of the part impacting the aluminum plate was carried out, and the peak stress-strain curve obtained from the simulation was compared with the experimental results in terms of calculation error and calculation efficiency. The results are shown in Figures 17 and 18. When the motor element size was 0.1 mm, the calculation time was too long, when the motor size was 3 mm, the element distortion was too severe, and no effective results were obtained, which are not displayed in the following figures.

The average size of the element of the motor should be less than 1.25 mm in order to make the error be less than 10%.

In order to make the error between simulation and experiment less than 10% for camera impact, the average size of the element of the camera should be less than 1 mm, so that the calculation time could be shorter and the calculation efficiency and accuracy could be guaranteed.

5. Simulation Analysis of Motor-Camera Collision Process

Based on the conclusions of the previous section, we chose an element size of 1.25 mm for the motor and 1 mm for the camera to simulate the high-speed collision.

The high-speed camera shows that when $t = 0.25$ ms, the motor impacted the aluminum plate to the maximum extent, when $t = 0.4$ ms, the motor was still stuck on the aluminum plate, and the remaining speed of the motor was 0, showing a critical failure state, which was consistent with the experimental results. The comparison of the strain response of plate at position 3 between the simulation result and experimental result is shown in Figure 19. From the figure, an obvious peak could be found in both the experimental result and simulation result, and the peak value in the latter is 9.5% smaller than that in the former. The overall trend of the simulation results agrees well with the experimental results. The simulation results were compared with

FIGURE 23: Deformation of aluminum plate during collision between motor and aluminum plate.

the experimental results to analyze the effect of the motor on the damage pattern of the aluminum plate, which were all broken in the results, with similar quadrilateral notches, and the size of the notches was the same. The experimental result showed that the motor base and drive shaft were deformed to a greater extent, in agreement with the predicted results. The strain and damage morphology of the above simulations agree well with the experimental results, indicating that the numerical simulation method is reasonable for analyzing the motor impact process.

The strain nephogram, deformation and stress nephogram, and strain-time curve of the collision between motor and aluminum plate are shown in Figures 20–24.

The high-speed camera showed that when $t = 0.1$ ms, the camera impacted with the aluminum plate to a greater extent,

but the aluminum plate did not break; when $t = 0.3$ ms, the camera penetrated the aluminum plate completely, which was consistent with the experimental results. The comparison of the strain response of the plate between the simulation result and the experimental result at position 3 is shown in Figure 25. An obvious peak could be found in both the experimental result and the simulation result, and the peak value in the former is 9.7% larger than that in the latter. The overall trend of the simulation results agrees well with the experimental results. The effect of the camera on the impact damage pattern of the aluminum plates was analyzed, which were all broken in the results and had similar quadrilateral notches. The experimental result showed that the camera was broken at all joints, which was in agreement with the predicted results. The strains and damage patterns from

FIGURE 24: Stress nephogram during collision between motor and aluminum plate.

FIGURE 25: Comparison of the strain curve for camera impact.

FIGURE 26: Comparison of camera impact when $t = 0.1$ ms. (a) Result in test when $t = 0.1$ ms. (b) Result in simulation when $t = 0.1$ ms.

FIGURE 27: Comparison of camera impact when $t = 0.3$ ms. (a) Result in test when $t = 0.3$ ms. (b) Result in simulation when $t = 0.3$ ms.

FIGURE 28: Strain nephogram during collision between camera and aluminum plate.

FIGURE 29: Deformation of aluminum plate during collision between camera and aluminum plate.

FIGURE 30: Stress nephogram during collision between camera and aluminum plate.

TABLE 7: Simulation results of motor impact.

	Collision gesture	Damage of the aluminum plate	Damage of the motor
Collision angle 0°			
Collision angle 60°			
Collision angle 90°			
Impact speed 110 m/s			
Impact speed 70 m/s			

TABLE 8: Simulation results of camera impact.

	Collision gesture	Damage of the aluminum plate	Damage of the camera
Collision angle 0°
Collision angle 60°
Collision angle 90°
Impact speed 150 m/s
Impact speed 100 m/s

the above simulations were in good agreement with the experimental results, indicating that the numerical simulation method for the camera impact analysis was reasonable.

The strain nephogram, deformation, and stress nephogram of the camera and aluminum plate are shown in Figures 26–30.

6. Influences of the Speed and Collision Angle on the Simulation Results

In this chapter, the motor and camera finite element models established in the previous section were used to investigate the influences of the speed and collision of the motor and camera on the simulation results. The simulation results of motor impact are shown in Table 7.

For the collision between the motor and the aluminum plate, the collision angle was set as 0°, 60°, and 90°, and the impact speeds were set to 110 m/s and 70 m/s.

At a certain speed, the greater the collision angle, the greater the breakage caused to the plate. Also, the larger the speed of the motor, the greater the damage to the aluminum plate for a certain collision angle.

For the collision between the camera and the aluminum plate, collision angle was set to 0°, 60°, and 90°, and impact speed was set to 150 m/s and 100 m/s. The simulation results of camera impact are shown in Table 8.

At a certain speed, the smaller the collision angle, the greater the breakage caused to the plate. Also, the faster the speed of the camera, the more the damage to the aluminum plate and the more severe the breakage of the camera itself.

7. Conclusion

The research results indicate that the mass blocks with more concentrated masses such as motors and cameras in UAVs cause more damage to other objects. So, the establishment of accurate finite element models of motors and cameras is vital for establishing an accurate model of the whole UAV when studying UAV collision problems. The motor and camera finite element models have been established through modelling methods. The conclusions obtained in this paper are as follows.

- (1) The DNS-100 electronic universal testing machine and high-speed hydraulic servo testing machine were

used to conduct kinetic material tests at low and medium strain rates on 7075 aluminum alloy, a widely used material in electric motors and cameras. The Johnson-Cook constitutive model which can reflect the tensile and compressive properties of materials at different strain rate levels was selected. An accurate model of describing 7075 aluminum alloy materials is obtained for simulation

- (2) An air cannon system was designed and applied to conduct the collision experiment. Before the experiment started, the motor and camera were placed inside the gun barrel with the sabot, and the air chamber was inflated by an air compressor. When the specified air pressure was reached, the inflation was stopped, the air valve was opened, and the high-pressure gas pushed the motor, camera, and sabot to accelerate in the barrel. When reaching the exit of the barrel, the sabot was blocked by a specific device. The motor and the camera hit the aluminum plate. During the experiment, a high-speed camera was used to record the deformation during the collision, and the strain on the aluminum plate was recorded by means of strain gauges attached to the back of the plate. The air cannon system can be used to simulate the high-speed collision of UAVs and assess the resulting damage
- (3) The effect of different mesh sizes of the UAV motor and camera on the computational accuracy and efficiency was investigated. When the average size of the motor mesh was less than 1.25 mm and the average size of the camera mesh was less than 1 mm, a good balance could be achieved between computational accuracy and computational efficiency
- (4) The simulation of the motor and camera impacting the aluminum plate was carried out, and the simulation result was compared with the experimental result. The comparison showed that the peak value of the strain-time curve in the motor impact simulation had an error of 9.5% with the experimental result, and the peak value of the strain-time curve in the camera impact simulation had an error of 9.7% with the experimental result, which was in great agreement. The finite element model of the motor and camera obtained by the modelling method in this paper was accurate, and thus, the modelling method can be used in future UAV collision studies
- (5) For the strike between the motors and aluminum plate, the greater collision angle and larger speed of the motor cause greater breakage to the plate. Likewise, the smaller collision angle and larger speed of the camera cause greater breakage to the plate
- (6) The damage caused by the UAV battery in UAV collisions is also severe, which is a potential direction in future research. This can be tested by shelling the aluminum plate in this research to obtain an accu-

rate finite element model and also to study the classification of its fire risk level

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

Conceptualization was done by Yongjie Zhang and Zhiwen Li; methodology was done by Yongjie Zhang, Zhiwen Li, and Bo Cui; Modelling and analysis were done by Zhiwen Li, Yingjie Huang, and Bo Cui; test and validation were done by Yongqi Zeng and Yazhou Guo; data curation was done by Yongqi Zeng and Yingjie Huang; writing—original draft preparation—was done by Yongjie Zhang and Zhiwen Li; writing—review and editing—was done by Bo Cui; supervision was done by Zhang Yongjie; project administration was done by Zhang Yongjie; funding acquisition was done by Zhang Yongjie. All authors have read and agreed to the published version of the manuscript.

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