A Review of High Precision Finite Element Modelling Methods for Light and Small UAS

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Abstract. In the dynamic mechanics analysis of light and small unmanned aerial systems (UAS), the importance of the high-precision modelling of UAS is unquestionable. Modelling can be classified into 3D geometric model modelling and finite element model modelling, of which the finite element model modelling is mainly divided into four parts: discretization, connection modelling, contact modelling and material attribute definition. This review summarizes the existing modelling methods of light and small UAS, and provides the basic methods and modelling methods for the simulation calculation of light and small UAS. Implications for practice and future research are provided.

1. Introduction

In recent years, the UAS industry has developed rapidly and has been widely used in various fields. The Association for Unmanned Vehicles Systems International (AUVSI) predicted that the market capacity of UAS would reach 4.7 million units by 2020 [1]. Light and small UAS refers to UAS with an empty weight of less than 15kg and a maximum takeoff weight of less than 25kg, which is the main body of the civilian UAS market [2]. As the UAS industry expands, the probability of accidental collision between light and small UAS and individuals or property has increased. Many research institutions have studied this problem, but due to the high experimental cost, it is impossible to test all the collision scenarios and working conditions. Therefore, the combination of experiment and numerical calculation is considered to be the most effective method, as pointed out by Georgiadis et al [3]. Among the numerical calculation methods, the high-precision dynamic modelling of UAS is the most critical part, which directly determines the accuracy of numerical calculation results.

Since 2016, the FAA, Virginia Polytechnic Institute and State University [4] and Nanyang Technological University [5] have successively carried out studies on light and small UAS collisions, and carried out dynamic modelling analysis on light and small UAS. According to FAA, the Phantom 3 UAV and Precision Hawk Lancaster UAV were selected as the research objects of their research, and the four-rotor UAV finite element model [6] and the fixed-wing UAV finite element model were respectively built [7]. Meng et al. [8] built the Inspire I UAV finite element model and studied the effect of a collision between a UAV and a civil airliner with the UAV finite element model verified experimentally. Lu et al. [9] built finite element models for five different UAVs exhibiting different qualities; they also studied the severity of collisions between five small UAVs and aircraft windshields. In the current studies, certain methods and strategies were adopted for the high-precision modeling of
light and small UAV. In this paper, the methods of establishing high-precision modelling of light and small UAS are summarized and discussed. The modelling process is mainly divided into two steps: 3D geometric model modelling and finite element model modelling. Each modeling process will be described in detail in the following sections.

2. 3D Geometric Model
In the present research, all the research institutions build the geometric model of UAS by the method of reverse engineering. Firstly, the drone is disassembled and point cloud data of the geometry of each part of the drone is obtained through a 3D scanner. Secondly, reverse engineering software, such as Imageware, PolyWorks, Rapidform, or Geomagic can be used to convert the point cloud data into a triangular mesh, and then process it as a separate CAD file for each part. Finally, the CAD file of each part is imported into the 3D software CATIA, which is then assembled to obtain the complete UAS geometric model. For example, the process of establishing a geometric model of quadcopter in the FAA's report, See Figure 1[6].

![Figure 1. CAD model development steps (Olivares & Gomez)](image)

3. Finite Element Model
Finite element modelling mainly includes the following four parts: discretization, connection modelling, contact modelling and material property definition [10]. Since the materials of different UAS vary greatly and there is no regularity, this part is not introduced in this paper. This review focuses on the other three parts in detail.

In terms of the selection of solvers, most research institutions have chosen the mainstream LSDYNA [6-7], while some have used PAM-CRASH [8]. For these two different solvers, the discretization method and standard are consistent, but there are some differences between connection modelling and contact modelling.

a) Discretization
There are three types of elements used in the finite element model of the UAV, which are one-dimensional element, two-dimensional element and three-dimensional element. The one-dimensional element includes the beam element and the discrete element. The beam element is used to simulate bolts and screws in UAS model, and the discrete element is used to simulate spring-damping connection in UAS model. Hughes-Lui (ELFORM = 1) was selected as the default element formulation for beam element [11]. The two-dimensional shell elements include quadrilateral and triangular shell elements, which can be modeled by full-integrated elements or under-integrated elements as required. The shell element is mainly used to simulate the thin-walled parts of the UAS, such as the fuselage, propeller, landing pad, circuit board and some other components. Three-dimensional element is also called solid element. The hexahedral element is mainly used in the UAS finite element model, and the default under-integrated formulation is selected. However, this element algorithm requires at least three elements along the thickness direction to properly represent the bending stiffness [7]. The solid element is used to simulate the block parts in UAS, such as camera, universal joint, motor, battery and wing of fixed wing UAS.
b) Connection Modeling

Connection modelling is of great importance in the whole UAS modelling, because the connection relationship represents the transmission mode between parts. Only by modelling the connection relation correctly can the accuracy of the transmission path be guaranteed. There are many different forms of connectivity in light and small UAS. Rotary-wing UAS mainly use screw connection and spring-damping connection, while fixed-wing UAS also use zip ties connection and welding.

Due to the different solvers used, the connection elements are modeled differently. In the finite element model of a four-rotor UAS established by Meng Xianghao based on the PAM-CRASH solver [8], all connection relationships are modeled by the TIED element with fracture model, in which the fracture model is not considered in the modelling of welding. In the finite element model of UAS established based on LS-DYNA solver [6-7], the modelling methods of different connection relations are quite different. The following explains the modelling methods of different connection relationships.

— Bolt, screw connection

There are two modelling methods for bolt and screw connections in light and small UAS, namely Spot-weld and NRB(*CONSTRAINED_NODAL_RIGID_BODY) + Beam element. Among them, Spot-weld is used for modelling non-critical bolts and screws in UAS, and NRB + Beam element is used for modelling relatively important bolts and screws.

Spot-weld: the degrees of freedom of two nodes are connected by a rigid bar. In this model, there is no need to model the bolt hole, and the bolt hole is replaced by the node at the hole center. See Figure 2 [6].

![Figure 2. Spot-weld connection (Olivares & Gomez)](image)

NRB + Beam element: a combination of rigid connectors and beam elements. In this model, two bolt holes need to be modeled separately, and the degree of freedom of the nodes around the hole is connected to the independent node at the center of the hole by *CONSTRAINED_NODAL_RIGID_BODY. Then, the beam element is used to connect the nodes in the center of the two bolt holes to establish the connection. The section size of the beam element is same with that of the bolt. See Figure 3 [6].

![Figure 3. NRB + Beam element connection (Olivares & Gomez)](image)

— Spring-damping connection

In the light and small UAS, a spring-damping system is used to connect the camera to the body. The spring-damping system was modeled using NRB+ Discrete element. This connection is similar to
NRB + Beam element modelling except that Beam element is replaced by Discrete element. See Figure 4 [6].

Figure 4. NRB + Discrete-Element connection (Olivares & Gomez)

--- Zip ties connection

In fixed-wing UAS, zip tie is a common way to connect parts to the fuselage. The shell element is used to model the zip tie separately and the material of the zip tie is given a failure model. See Figure 5[7].

Figure 5. Zip Ties connection (Olivares & Lacy)

--- Welding connection

In small and light UAS, electronic components are often welded to the fuselage. Because the solder joint is small, the solder spot is not modeled separately in the whole machine model, but connected by establishing contact model at the solder joint. Welding connections are described in detail in contact modelling.

c) Contact Modeling

Contact modelling is mainly divided into two parts, including global surface contact modelling and welding connection modelling. The global surface contact model defines the contact behavior between most parts in the finite element model of UAS. Only in the UAS model with welding connection, it is necessary to define the independent welding contact at the solder spot.

In the FAA’s report [6-7], both the rotor and fixed-wing UAS finite element models established based on LS-DYNA solver set the global surface contact model, and three independent welding contact models were set in the fixed-wing UAS finite element model. Only the global surface contact model was established in the finite element model of the four-rotor UAS established by Meng Xianghao based on the PAM-CRASH solver.

i. Global Surface Contact Modelling.

Because all surfaces of the UAS may come into contact with each other during the collision, and the location of the contact cannot be predicted. Therefore, based on LS-DYNA and PAM - CRASH solver respectively established * CONTACT_AUTOMATIC_SINGLE_SURFACE [10] and Self - Impacting
the Node to the Segment of the global surface contact model. Both of these contact algorithms only need to define the slave contact surface, and the program will automatically detect all outer surface nodes in the model at each time step to detect whether penetration behavior has occurred, and apply the correct contact force to avoid penetration. There are many kinds of materials in light and small UAS, and the elastic modulus of materials varies greatly, such as metal body and soft battery materials. Therefore, in the *CONTACT_AUTOMATIC_SINGLE_SURFACE contact model, soft constraint (SOFT=1 or 2) based on the global time step and the mass of the nodes in the contact segments is selected. In addition, surface penetration (DEPTH=13) and segment warpage checks (SBOPT=3) at nodes and edges are also enabled.

ii. **Welding Connection Modeling**

According to the position and modelling method of the welded part, the welding connection is divided into two cases, which are modeled by the keywords *CONCTACT_TIED_SHELL_EDGE_TO_SURFACE and *CONTACT_TIED_NODES_TO_SURFACE [11]. The static and dynamic friction coefficients in the welding contact model are relatively small, within the range of 0.01 to 0.05. The key *CONCTACT_TIED_SHELL_EDGE_TO_SURFACE simulates a welding connection between two parts modeled by a shell element. The contact is defined between the slave node along the edge of one part and the main surface at the corresponding location of another part. See Figure 6(a). The welding model of the solid element connected to the shell element is simulated by the keyword *CONTACT_TIED_NODES_TO_SURFACE. See Figure 6(b).

![Figure 6. Welding connection. (a)Welding of two shell element parts. (b)Welding of shell element and solid element parts.](image)

4. **Conclusion**

High precision modelling of light and small UAS is of great significance in the study of collision safety characteristics of UAS. The finite element models based on different solvers can reflect the characteristics of UAS form different degrees. Generally, the finite element model of UAS based on LS-DYAN solver is more comprehensive and accurate, and the modelling method is more detailed. This paper summarizes the methods and strategies for high-precision modelling of light and small UAS, and provides ideas for future research.

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