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Simulation Analysis of Electromechanical Coupling for Unmanned Aerial Vehicle Cabin Door System

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Abstract

In order to study the dynamic response of the unmanned aerial vehicle cabin door opening and closing system under impact load conditions, considering the flexible treatment of mechanical components, and the system's motion with different stiffness of energy-absorbing components, a rigid-flexible coupling model of the cabin door actuation system was established in LMS. Virtual. Motion. In Amesim, a control model of the motor was created. Through the Motion-Amesim co-simulation module, the dynamic module of the system was combined with the motor control module to complete the electromechanical coupling simulation and analyze the results.

Keywords

Unmanned Aircraft, Cabin Door, Electromechanical Coupling, Virtual Prototype, Dynamic Characteristics

1. Introduction

In recent years, drone technology has witnessed significant advancements and has found widespread applications across various sectors, including military, civilian, scientific research, and commercial industries. The versatility and adaptability of drones make them ideal tools for a multitude of applications. Since their inception, drones have played pivotal roles in battlefields worldwide, handling numerous complex tasks previously performed by humans and achieving more precise and outstanding results [1]. According to forecasts by the Federal Aviation Administration (FAA) in the United States, the drone industry is expected to create billions of dollars in economic value for the nation by 2030 and offer employment opportunities to thousands of individuals. This has prompted countries to invest in drone armament competitions, striving to enhance their operational capabilities, signifying the future potential of drone technology [2]. As far back as the mid-20th century, foreign scholars conducted extensive experimental research on the aerodynamic characteristics of fuselages using wind tunnel tests [3]. In recent years, both domestic and foreign scholars have conducted comprehensive research and analysis on cabin doors through the accurate, rapid, and cost-effective method of virtual prototypes [4] [5] [6], confirming the accuracy and practicality of virtual prototype approaches. Chinese scholars, such as Wu and others, improved the flow field characteristics of the fuselage and weapon separation characteristics through aerodynamic analysis, using the method of suspending thin metal strips at the front edge of the fuselage [7]. Shen and others analyzed the noise and vibration produced by the fuselage structure under intense disturbances, enhancing the service life of the fuselage under severe vibration conditions [8]. However, research on the impact of mechanical system properties on motor output characteristics concerning the fuselage is still incomplete.

2. Rigid-Flexible Coupling Dynamic Modeling of Unmanned Aircraft Cabin Door Mechanism

The unmanned aircraft cabin door opening and closing mechanism typically includes a driving mechanism where a motor drives a connecting rod, which, in turn, rotates the door, through a combination of a gearbox and a differential mechanism, creating a certain reduction ratio [9]. In the structure of the unmanned aircraft cabin door mechanism, the actuating motor is usually installed inside the fuselage, while the rotating actuator is distributed along the axis of rotation of the door, with multiple sets of structurally identical rotating actuators placed at intervals. The output torque of the motor is reduced through the gearbox, transmitted to the middle of the door’s axis of rotation, and then connected to both the left and right sides of multiple sets of structurally identical rotating actuators through transmission shafts, enabling these multiple rotating actuators to work in coordination to complete the extension and retraction motion of the outer cabin door. The mechanical part of the unmanned aircraft cabin door opening and closing mechanism described in this paper consists of basic structures such as the gearbox at the motor end, the transmission connecting rod, and the rotating actuator. The layout is depicted in **Figure 1**.

Taking into consideration that during the locking phase of the cabin door mechanism, collision forces may arise due to structural constraints, resulting in fluctuating responses at the motor end, two transmission shafts closest to the motor are designated as flexible shafts, serving as energy storage devices. They rely on their own deformation to store energy and mitigate the load fluctuations at the motor end. The remaining transmission shafts on the outer side are rigid shafts, ensuring the synchronized extension of multiple actuators. The physical representation is as **Figure 2**.

The locking collision force of the cabin door is expressed using a modified version of the Hertz collision formula in Equation (1):

$$P = \frac{2}{3}\sqrt{\frac{2mv}{A^3k}} \tag{1}$$

With the primary objective of analyzing the flexibility of major load-bearing components, in the cabin door mechanism, the flexible shaft serves as the primary component for transmitting the motor output torque, while the rigid shafts progressively transmit torque to the farthest end's rotating actuators. The central forks of the rotating actuators are responsible for transmitting forces to the cabin door, which bears external loads and undergoes deformation. Therefore, in this project, we have selected the elastic shafts, rigid shafts, the central forks of the rotating actuators, and the cabin door for flexible modeling. The material properties assigned to these components are as **Table 1**.

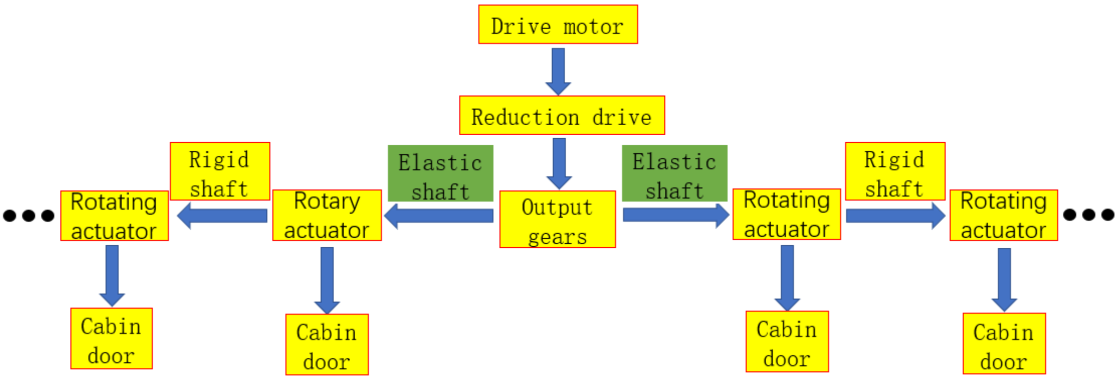

Figure 1. Layout design of unmanned aircraft cabin door mechanism.

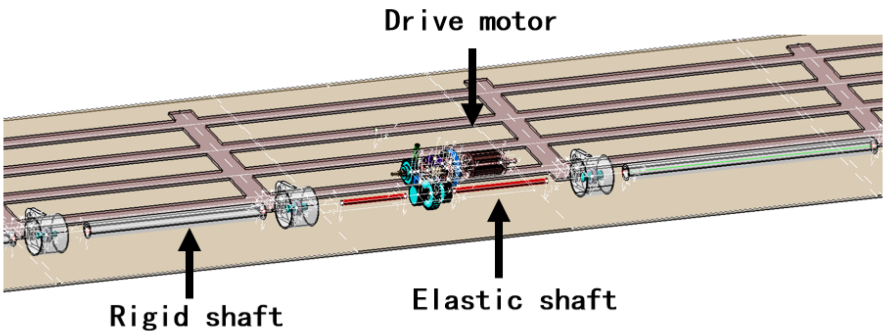

Figure 2. Physical representation of unmanned aircraft cabin door mechanism.

Table 1. Material properties.

Component name	Material
Elastic shaft	38CrMoAlA
Rigid shaft	LY12CZ
Cabin door	composite materials
central forks	300 M steel

3. Integrated Electromechanical Modeling of Unmanned Aircraft Cabin Door Mechanism

The motor drive and control system of the unmanned aircraft hatch door mechanism employ a dual closed-loop control system based on PID control law [10]. To better control the motion of the unmanned aircraft hatch door mechanism and ensure that the system reaches its final state smoothly and accurately within the specified time, the rotational speed and angular displacement of the hatch door mechanism are used as the primary control variables [11]. The rotational speed loop serves as the inner closed-loop, while the angular displacement loop serves as the outer loop. Additionally, to ensure the stability of the motor control system during operation, a saturation module is incorporated into the control loop.

Sensors continuously monitor the angular velocity and angle of the hatch door mechanism and transmit this information to the control loop. The control loop, through the action of a dual-stage PID controller, generates torque control signals, which are then sent in real-time to the motor control system. The motor control system, under the influence of these signals, produces an output torque to act on the hatch door mechanism, thereby controlling the motion of the unmanned aircraft hatch door mechanism. The operational principle of the motor drive and control loop is shown in **Figure 3**.

A purely motor control system model cannot accurately describe the mechanical dynamics of the load, while a purely mechanical dynamics model cannot accurately represent the working characteristics of the control system [12]. “1D + 3D” simulation combines an accurate motor control system model with a mechanical dynamics model, using sensor data to transfer real-time angular velocity and angle signals of the unmanned aircraft hatch door mechanism to the motor control model [13]. Based on these signals, the motor control system generates output torque to drive the motion of the hatch door mechanism through the action of PID control law. This approach overcomes the limitations of traditional methods and maximizes the advantages of both the control system model and the mechanical dynamics model. The principle of electromechanical

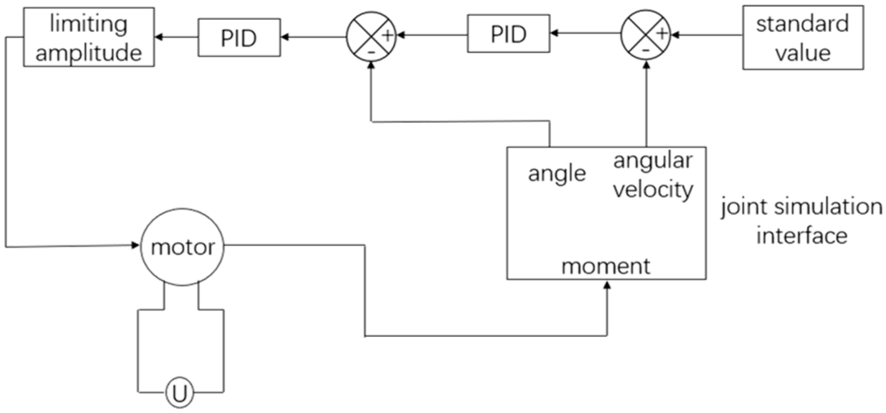

Figure 3. The operational principle of the motor drive and control loop.

integration modeling of the unmanned aircraft hatch door mechanism is shown in **Figure 4**.

4. Results

In this paper, during the cabin door motion process, the motor-driven angular velocity curve is as shown in **Figure 5**.

The wind load acting on the cabin door takes the form of a distributed load, and the total external load is set as a torque that varies with the cabin door opening angle (as shown in **Figure 6**).

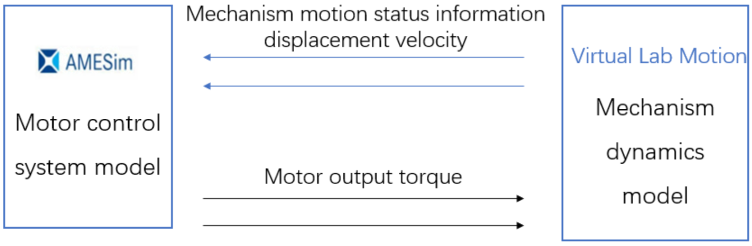

Figure 4. The principle of electromechanical integration modeling.

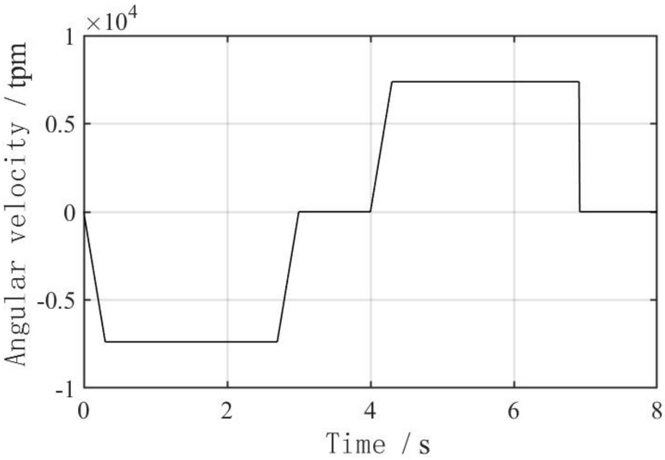

Figure 5. Motor-driven angular velocity curve.

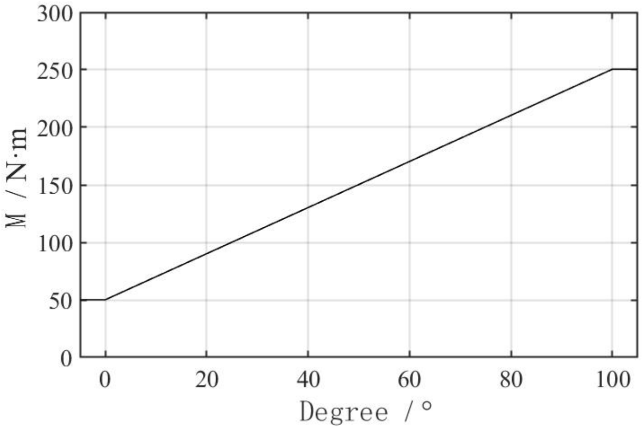

Figure 6. Wind load curve.

The number of simulation groups is set to 3, with the motor drive and external load remaining constant. The stiffness coefficient of the flexible shaft is set to 50%, 100% and 150%, respectively.

The motor output torque results for the three stiffness settings are as shown in **Figure 7**.

5. Conclusions

1) If the stiffness of the flexible transmission shaft is greater, then the motor's output torque experiences more significant fluctuations for a period of time after a collision. If the stiffness is smaller, the fluctuations are reduced. This suggests that softer transmission shafts result in smaller steady-state fluctuations in the mechanism.

2) At 50% stiffness, the maximum instantaneous motor output torque is 0.778 N·m; At 100% stiffness, the maximum instantaneous motor output torque is 0.804 N·m; At 150% stiffness, the maximum instantaneous motor output torque is 0.687 N·m. All cases experienced over 3 times overshoot.

3) Using 100% stiffness as the reference, the maximum instantaneous motor output torque is reduced by 3.2% at 50% stiffness and 14.6% at 150% stiffness.

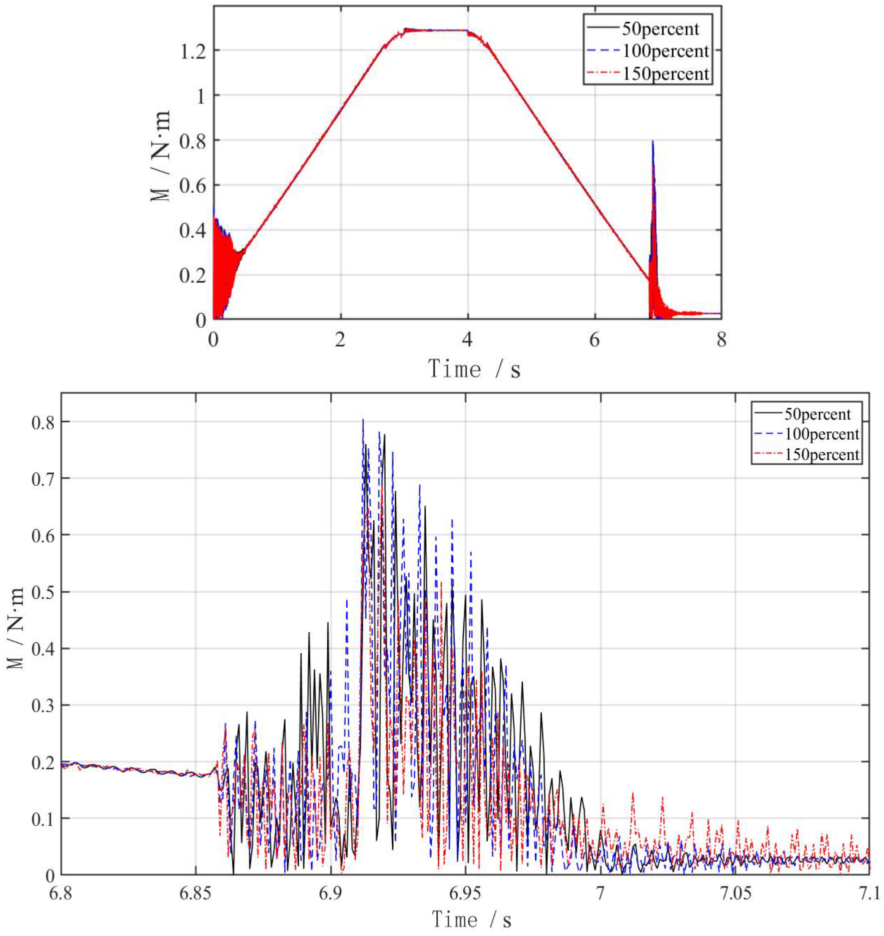

Figure 7. Motor output torque for different stiffness.

4) For the dynamic characteristics of the system at the moment of collision, the stiffness of the transmission shaft does not have an absolute linear relationship with the peak value of the motor's output torque. This peak value is not only related to the stiffness of the transmission shaft but is also influenced by factors such as motor selection, the mechanism itself, external load magnitude, etc. Therefore, the choice of shaft stiffness should consider various factors, including the motor's overshoot and the potential for shaft fracture.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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