Simulation Aided Design of Solar-Powered UAV

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Abstract. This paper describes a distributed flight dynamic simulation method. It needs reasonable computing resources, and can be applied in the design process of solar-powered UAV. A flight dynamics model is established based on the Hamilton’s principle, with the simulation model, this paper discussed the flight characteristics of the large aspect ratio flexible solar-powered UAV, and the influence of different design schemes, then proposed a simulation aided design method, which can be used to select design parameters of the solar-powered UAV, it can also provide reference for similar UAV design.

Keywords: Solar-Powered UAV; Simulation, Design.

1. Introduction
Solar-powered UAV takes the sunshine as energy source, which makes it able to realize ultra-long flight time. The power system composed of motor and propeller is not limited by the intake flow of the engine, so that it can adapt to the very-high flight environment. These aircrafts have unique application advantages in military and civil fields due to their incomparable characteristics. In recent years, driven by commercial applications, solar-powered UAV have attracted widespread attention. The solar-powered UAV platform integrates many technologies, such as aircraft design, flight control, materials, energy, propulsion and so on. There are many technical difficulties compared with conventional aircraft. Due to the limitation of energy sources, solar-powered UAV generally adopts high aspect ratio and very light structure, this makes its wing shows the characteristics of large-scale flexible deformation in flight, which will significantly change its flight dynamics and control characteristics. In terms of design and analysis methods, the small disturbance dynamic analysis model adopted by conventional aircraft is difficult to fully reflect the flight dynamic characteristics of solar-powered UAV, and the analysis results will bring potential design risks. The technology of simulation aided design is widely used in many fields in recent years. In this paper, based on the idea of simulation aided design, a nonlinear and distributed computing model of large aspect ratio flexible solar-powered UAV is established, which is used to assist the design of this new type of aircraft.

2. Modeling of Solar-powered UAV
Due to the pursuit of high lift drag ratio and lighter airframe structure, the layout design of solar-powered UAV generally adopts wing with super aspect ratio and low strength structure, which reflects the structural characteristics of large deformation in flight. In the field of aircraft design, the traditional method is generally considered that the aircraft is a rigid body or an elastic body with small deformation, and linear analysis method is used to analyze the performance of the aircraft in flight. This method cannot accurately describe the flight characteristics of this type of UAV.
The deformation of solar-powered UAV in flight is a kind of geometrically nonlinear motion. Its wing has large amount of deformation, at the same time, the force direction and reference coordinate are also changed, so the linear assumption in the conventional aero-elastic modeling is difficult to accurately describe the large-scale wing deformation of the UAV. The motion equation of solar-powered UAV needs to be established according to this characteristic, it should be different from the traditional flight dynamics model, which taking the UAV as a whole, a distributed coordinate system is adopted in the flight dynamics modeling, more calculations are needed to simulate the dynamics during the flight process. It can take into account the external wind disturbance, and then analyze the flight characteristics of this layout to verify the feasibility of design.

Based on this consideration, it is necessary to establish the local coordinate system of solar-powered UAV, which is convenient to establish the distributed simulation model. Local coordinate is a continuous coordinate system. Its origin is based on the torsion elastic center along the span wise direction, so the coordinate is constantly changing span wise. Therefore, in the local coordinate system, the kinetic energy and elastic potential energy of UAV can be expressed as a continuous integral. The expression of kinetic energy variation is as follows:

\[ \delta T = \int_{-l/2}^{l/2} \left( P \cdot \delta V + H \cdot \delta \omega \right) ds . \]  

In this formula, \( P \) and \( H \) are the generalized momentum and angular momentum of the local wing, \( V \) and \( \omega \) are the velocity and angular velocity of UAV local coordinate system respectively, \( l \) represents the wing span. Similarly, in the full span wise integration, the elastic potential energy of wing deformation can be expressed in the form of variation:

\[ \delta U = \int_{-l/2}^{l/2} \left( F \cdot \delta \gamma + M \cdot \delta \kappa \right) ds . \]  

Where \( \gamma \) and \( \kappa \) represent the local generalized strains of the wing, which can be calculated by the partial differential of linear displacement and angular displacement. And \( F \) and \( M \) are the local internal forces and internal moments.

According to Hamilton's principle:

\[ \int_0^t (\delta T - \delta U - \delta W) dt = 0 . \]

The above expression is expressed as the wingspan integral, where \( \delta W \) represents the variation of the work of non-conservative forces:

\[ \delta W = \int_{-l/2}^{l/2} \left( f \delta u + m \delta \chi \right) ds . \]

In the formula, \( f \) and \( m \) represent the sum of non-conservative forces and moments, which is defined in the local coordinate system of UAV. In this model, non-conservative force mainly includes aerodynamic force and thrust, in addition, in order to be different from the elastic force, gravity is expressed as non-conservative force. The expressions of the above forces and moments are also functions of the position \( s \).

Since the local coordinate system is a continuously changing coordinate system, in the equations established, each variable is a function of both displacement \( s \) and time \( t \). The dynamic equation established in this coordinate system has the form of partial differential equation.

In the same way as the conventional flight dynamic problems, the time derivative can be calculated by computer with the numerical integration such as Runge-Kutta method. To deal with the displacement partial derivative, the continuous position \( s \) must be discretized, and the equation of deformation is calculated approximately. In the process of discretization, the wing is discretized as small sections, the shorter the sections, the higher the accuracy of calculation, but also larger the amount of calculation is needed. Using this method, computing resources can be reasonably allocated in different stages of design. After discretization, the nonlinear aero-elasticity and flight dynamics coupled equations of solar-powered UAV can obtained in the following forms:
After discretization of the dynamic equation, the dynamic model of solar-powered UAV in the form of nonlinear ordinary differential equations is obtained, in which $x$ represents the state variables of the discretized local coordinate systems, If the wing is divided into $n$ sections, $x$ is a vector of $6n$ elements, which are used to describe the movement and deformation of the UAV. The deformation and motion process of the UAV can be obtained by solving the model together with the non-conservative force equations.

3. External Force Based on Local Coordinate System

For the established dynamic equations, it is necessary to project the non-conservative forces to the local coordinate system, including aerodynamic force, propulsion force and gravity. For the study of flight mechanics in this paper, the aerodynamic force mainly determined by the velocity of the local inflow and the aerodynamic coefficient. The aerodynamic model can be obtained by wind tunnel test or CFD calculation, which is expressed as the relationship between aerodynamic coefficient and local effective angle of attack.

In the distributed dynamic equation of solar-powered UAV, the aerodynamic force is projected in the local coordinate system of the UAV. Since the local coordinate system is based on the torsion elastic center of the wing, and the aerodynamic force of the UAV is described in the aerodynamics coordinate system, the corresponding coordinate transformation is required:

$$ f_A = L_2 L_1 f_{aero}, $$

$$ m_A = L_2 L_1 m_{aero} + L_2 y_{ac} L_1 f_{aero}. $$

Among them, $L_2$ is the coordinate transformation matrix to the aerodynamics coordinate system, $L_1$ is the transformation matrix from the aerodynamics coordinate system to the local coordinate system. At the same time, the propulsion model needs to be considered. Because of the low flight speed of the solar-powered UAV, in order to pursue high propulsion efficiency, the large-scale screw propeller or multiple distributed propellers are often used. Due to the long wingspan, the low propeller load and distributed arrangement will affect the lateral characteristics of the UAV.

Similarly, after establishing the distributed dynamic model of the UAV, the thrust and gravity are projected to the corresponding local coordinate system. This can take into account the impact of the distributed propulsion system on the flight dynamics of solar-powered UAV.

4. Simulation and Design

In this way, the distributed dynamic model of solar-powered UAV is established. Compared with the traditional flight dynamics analysis method, it can reflect the wing deformation characteristics of solar-powered UAV during flight. This model is based on the local coordinate system of the UAV.

As previously described, for the needs of calculation, the whole wing is divided into discrete sections along the span wise direction. The UAV is calculated as $n$ discrete sections, each section includes the motion model and the force model, and also includes the calculation of the strain force caused by deformation. It has an overall structure as follows:

![Figure 1. Structure of distributed simulation model.](image-url)
In the simulation results, due to the interaction of structural deformation and flight dynamics, the structural deformation of solar-powered UAV is coupled with the flight mode of the aircraft itself. In the longitudinal direction, due to the large aspect ratio of the UAV, the bending stiffness of the wing is small, the structure bending mode may be coupled with the long-period mode, and it shows some different flight modes from other airplanes. So, compared with the traditional flight mechanics analysis method, the distributed simulation model can better reflect the flight characteristics of the flexible UAV and predict the hidden risks in actual flight. For this solar-powered UAV project, the following characteristics are reflected in the simulation:

1. Due to the coupling of long-period mode and wing bending mode, the long-period movement not only affects the trajectory stability of UAV, when the wing stiffness is reduced and the concentrated load mass is increased, the long-period stability reduction may bring structural divergence, this factor needs to be taken into account in the design of distributed loads.

2. Due to the limitation of energy, the speed of solar-powered UAV is very low, and as the decrease of flight altitude, the flight speed also slows down significantly, this will affect the performance of long-period mode, and makes the UAV is easy to be disturbed by turbulence in flight.

3. Due to the distributed propulsion system adopted by the solar-powered UAV, the course damping of the UAV is changed, which affects the motion characteristics of the lateral direction. With the distributed dynamic model, the lateral characteristics of the UAV can be improved by arranging the propellers and reasonably selecting the parameters of the motor controller.

This model not only be used to analyze the flight dynamic characteristics, but also can be used to design the layout of the solar-powered UAV and choose the important parameters. The design of solar-powered UAV is a complex process with many phases. The establishment of a simulation model with certain accuracy has contributed to forecast the force and motion characteristics of UAV in the flight process. This is conducive to the reasonable design of solar-powered UAV. The whole system has the following structure:

![Diagram](image)

**Figure 2.** Design flow of solar-powered UAV based on simulation.

Compared with the traditional flight dynamics analysis method, the distributed dynamics simulation model can more accurately reflect the flight characteristics of the flexible UAV with large deformation and provide a new simulation method to assistant the aircraft design. It can find out the incorrect design scheme in time to prevent the possible risks in the flight test phase, which can effectively assist the UAV design and reduce the cost. Based on the distributed flight dynamic functions, a simulation aided design method for solar-powered UAV is established.
5. Conclusion
As a new type of aircraft, solar-powered UAV has many advantages that traditional aircraft can't compare with, but also has great difficulty in design, especially the uncertainty in prediction of traditional flight dynamics model. It is an effective technology to establish a flight dynamics simulation model which can reflect the large deformation of solar-powered UAV, and to use reasonable computing resources to verify the design idea with the simulation results, these efforts speeding up the research and development progress. It is helpful to reduce the research funds and shorten the development cycle. The dynamic simulation model can assist the design of distributed propulsion system and load optimization. Moreover, the model can integrate the knowledge of other disciplines, establish a simulation system that can reflect more factors, and further improve the design efficiency of solar-powered UAV.

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