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Visual Simulation System Design of Soft-Wing UAV Based on FlightGear

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***Abstract* - Soft-wing UAV is composed of soft ram air parafoil hanging powered vehicle with ropes. Benefit from its special mechanical structure and flight characteristics, soft-wing UAV has some advantages over other kinds of aircraft. However, because of these special characteristics make it possess apparent mass, flexible structure and relative motions between the parafoil and payload vehicle, which are the difficulties in research. Visual simulation based on mathematical model can vividly reappear the relationship between input and output of UAV and realize 3D visually simulation of the aircraft flight status. In this paper, based on the practical physical parameters of the self-designed soft-wing UAV, a 6 DOF mathematical model was built. Then a visual simulation system of soft-wing UAV based on FlightGear was designed. Finally, by using the simulation data from the soft-wing UAV mathematical model, the visual simulation was successfully realized. This visual simulation also testified the validation of this visual simulation system and mathematical model.**

Index Terms - soft-wing UAV; mathematical modeling; FlightGear; visual simulation.

I. INTRODUCTION

Soft-wing UAV (Fig. 1) is a new kind of aircraft, which is composed of a soft ram air parafoil and a powered vehicle hanged with ropes. This type of UAV has its unique advantages like simple structure, low cost and high bearing ratio, so it has the potential of being used in scenarios like transportations in distress area. For landing and take-off, soft-wing UAV only requires small areas and various ways could be used, so it could also has the potential of being used in environmental monitoring, aerial surveillance, power grid construction and disaster relief. So the soft-wing UAV has an incomparable advantage over normal kind of UAVs (fixed-wing UAV or rotary-wing UAV) in those tasks execution, that will also makes it have a wide range of applications either in the military or civilian fields. But because of its surface flexibility in aero dynamics and non-rigid link between parafoil and the vehicle, it has the characteristics of apparent mass, flexibility structure and internal movement. These have become great barriers in its research. In US, soft-wing UAV has been stayed in research for the recent ten years, some progress in numerical simulation and flying test have been made. An autonomous flight experiment has been conducted. The soft-wing UAV research in China is just started. For the soft-wing UAV research, Shenyang Institute of Automation Chinese Academy of Sciences conducted its research systematically in areas like platform construction, control theory modeling, simulation and flying test. Fig. 2 and Fig. 3 shows the soft-wing UAV system used in the research.

Fig 1. Soft-wing UAV

Fig 2. Self-designed soft-wing UAV

Fig 3. Powered vehicle part

Simulation technologies have been widely used in industries since 1960s. Based on computer graphics, the research object with its 3D model and simulation environments can be constructed in detail[1]. In the simulator design for aerial vehicles, visual simulation is widely used. It offers the simulator a sophisticated like-real flying environment, which can be used to train the pilot, solving various problems and help to analyze the performance for the whole system[2]. In 1960s, a visual simulator was used for the operation training for “Mercury” and “Gemini” spacecraft. In 1990s as the advance in computer graphics, visual simulation technologies have made a lot of progresses, like the NASA VR training system, the Canadian STAGE platform and the UK Dimension International desktop visual simulation system. This technology started late in China, but is still making progresses, like the 3D air-force simulator and the class D simulator developed by Wisesoft. After all, all the simulators developed nowadays are concentrated in traditional fixed wing aircraft and rotors, for soft-wing UAV, simulators are still left in blank.

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Fig 4. Fixed-Wing simulator

Fig 5. Helicopter simulator

Visual simulation can let the observer to investigate deeply in its structure and aerodynamic characteristics in a low risk and cost way, so that the control algorithm can be inducted. In this paper, based on real soft-wing UAV, a mathematical model with 6 degrees of freedom was constructed, then a visual simulation model was created in FlightGear simulation environment.

II. THE MATHEMATICAL MODEL FOR SOFT-WING UAV

In this paper, based on a real soft-wing UAV system, while considering the apparent mass, a mathematical model for soft-wing UAV with 6 degrees of freedom was constructed by using Newton Laws and the dynamic equations[3-5]. Fig. 6 shows the structure, coordinates system and system parameters, the related physical parameters are listed in TABLE I.

TABLE I
PHYSICAL PARAMETERS OF SELF-DESIGNED SOFT-WING UAV

No.	Parameters		
	Item	Value	Unit
1	Powered vehicle mass, m_p	20	kg
2	Parafoil mass, m_c	2.4	kg
3	Parafoil area, S	9.83	m^2
4	Parafoil width, b	5.92	m
5	Parafoil thickness, e	0.22	m
6	Parafoil cord length, c	1.66	m
7	Rope length, l	3.84	m
8	With/Cord ratio, AR	3.6	/

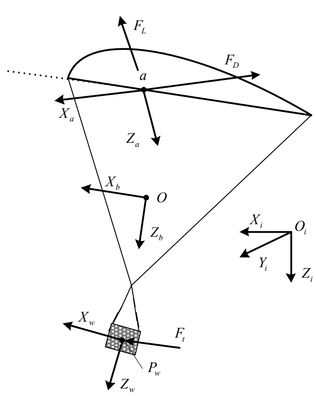

Fig 6. The soft-wing UAV coordinates and its dynamics

In the mathematical model, the following properties are assumed:

1) Center of pressure for the parafoil are the same to the center of mass, and it located at the longitudinal center, 1/4 to the forehead[5].

2) The parafoil is symmetric. After inflated the shape does not change, except the rear edge.

3) The parafoil does not move relatively to the powered vehicle.

4) Gravity is a constant. The Coriolis acceleration and the effects of curvature were neglected.

In this paper earth is considered to be an inertial coordinate system, noted by $\sum_i(X_i, Y_i, Z_i)$, the soft-wing UAV center of mass is O, the body axis system is $\sum_b(X_b, Y_b, Z_b)$, from the center of pressure, the air path axis system is $\sum_a(X_a, Y_a, Z_a)$.

A. *Soft-wing UAV Stress Equation*

Soft-wing UAV has its gravity $\boldsymbol{F_g}$, aero dynamics $\boldsymbol{F_a}$, coupling force $\boldsymbol{F_b}$ and the vehicle force $\boldsymbol{F_t}$, the net force would be:

$$\boldsymbol{F} = \boldsymbol{F_g} + \boldsymbol{F_a} + \boldsymbol{F_b} + \boldsymbol{F_t} \tag{1}$$

There we have,

$$\boldsymbol{F_g} = m\boldsymbol{g}[-\sin\boldsymbol{\theta} \quad \sin\boldsymbol{\phi}\cos\boldsymbol{\theta} \quad \cos\boldsymbol{\phi}\cos\boldsymbol{\theta}]^{\mathrm{T}} \tag{2}$$

$$\boldsymbol{F_a} = -0.5\rho\boldsymbol{V}^2 S\boldsymbol{T_{AB}}[C_D \;\; C_Y \;\; C_L]^{\mathrm{T}} \tag{3}$$

$$\boldsymbol{F_b} = -m\boldsymbol{S_w}[\boldsymbol{u} \;\; \boldsymbol{v} \;\; \boldsymbol{w}]^{\mathrm{T}} - \mathbf{S_w}[m_{app}([\boldsymbol{u} \;\; \boldsymbol{v} \;\; \boldsymbol{w}]^{\mathrm{T}} - \boldsymbol{S_{r_{op}}}[\boldsymbol{p} \;\; \boldsymbol{q} \;\; \boldsymbol{r}]^{\mathrm{T}})] \tag{4}$$

$\boldsymbol{\phi}, \boldsymbol{\theta}, \boldsymbol{\psi}$ are the roll angle, pitch angle and yaw angle respectively. $\boldsymbol{V} = [\boldsymbol{u} \;\; \boldsymbol{v} \;\; \boldsymbol{w}]^{\mathrm{T}}$ is the speed vector; $\boldsymbol{w} = [\boldsymbol{p} \;\; \boldsymbol{q} \;\; \boldsymbol{r}]^{\mathrm{T}}$ is the angular speed vector; S is the area of the parafoil; ρ is the density of air; g is the gravity constant; m is the total mass of the soft-wing UAV; $\mathrm{m_{app}}$ is the apparent mass for the parafoil; $\boldsymbol{T_{AB}}$ is the transfer matrix from the wind coordinate frame to the UAV frame[7-9]; $\boldsymbol{S_w}$ is the cross product matrix for the angular speed[9]; $\boldsymbol{S_{r_{op}}}$ is the center of mass P is the system pitch center O is its vector cross product matrix[10-12]; C_D, C_Y, C_L is the dragging force for the soft-wing UAV; lateral force and the rising force respectively.

$$\boldsymbol{T_{AB}} = \begin{bmatrix} \cos\boldsymbol{\alpha}\cos\boldsymbol{\beta} & -\cos\boldsymbol{\alpha}\sin\boldsymbol{\beta} & -\sin\boldsymbol{\alpha} \\ \sin\boldsymbol{\beta} & \cos\boldsymbol{\beta} & 0 \\ \sin\boldsymbol{\alpha}\cos\boldsymbol{\beta} & -\sin\boldsymbol{\alpha}\sin\boldsymbol{\beta} & \cos\boldsymbol{\alpha} \end{bmatrix} \tag{5}$$

$$\boldsymbol{m_{app}} = \begin{bmatrix} \mathrm{m}_{a.11} & 0 & 0 \\ 0 & \mathrm{m}_{a.22} & 0 \\ 0 & 0 & \mathrm{m}_{a.33} \end{bmatrix} \tag{6}$$

$\mathrm{m}_{a.11} = \rho\pi b^2 t/8$, $\mathrm{m}_{a.22} = 0$, $\mathrm{m}_{a.33} = \rho\pi \mathrm{c}^2 t/8$, b is the parafoil length, c is the cord length, $t = 0.18c$.

B. *Soft-wing UAV Torque Equation*

The soft-wing UAV torque is $\boldsymbol{M_a}$, engine torque is $\boldsymbol{M_t}$, the coupling torque is $\boldsymbol{M_b}$, the total torque is

$$\boldsymbol{M} = \boldsymbol{M_a} + \boldsymbol{M_t} + \boldsymbol{M_b} \tag{7}$$

Within it we have,

$$\boldsymbol{M_a} = \boldsymbol{S_{r_{oa}}}\boldsymbol{F_a} \tag{8}$$

$$\boldsymbol{M_t} = \boldsymbol{S_{r_{oP_w}}}\boldsymbol{F_t} \tag{9}$$

$$\boldsymbol{M_b} = -\boldsymbol{S_w}\boldsymbol{I_w}\begin{bmatrix}\boldsymbol{p}\\\boldsymbol{q}\\\boldsymbol{r}\end{bmatrix} + \boldsymbol{S_v}\boldsymbol{m_{app}}\boldsymbol{S_{r_{op}}}\begin{bmatrix}\boldsymbol{p}\\\boldsymbol{q}\\\boldsymbol{r}\end{bmatrix} + \boldsymbol{S_w}\boldsymbol{S_{r_{op}}}^{\mathrm{T}}\boldsymbol{m_{app}}\begin{bmatrix}\boldsymbol{u}\\\boldsymbol{v}\\\boldsymbol{w}\end{bmatrix} - \boldsymbol{S_w}\boldsymbol{I_{app}}\begin{bmatrix}\boldsymbol{p}\\\boldsymbol{q}\\\boldsymbol{r}\end{bmatrix} \quad (10)$$

In the above equation, $\boldsymbol{S_{r_{oa}}}$ is the center of mass a is the center of pressure O is its cross product matrix; $\boldsymbol{S_{r_{oP_w}}}$ is the system center of mass P_w is the vehicle center of mass O is its cross product matrix; $\boldsymbol{S_v}$ is the speed vector cross product matrix; $\boldsymbol{I_w}$ is the soft-wing UAV rolling inertia; $\boldsymbol{I_{app}}$ is the added rolling inertia.

C. Soft-wing UAV Dynamic Equation

The soft-wing UAV dynamic equation can be inducted by momentum and moment of momentum laws. The momentum and the moment of momentum are constructed by 2 parts, 1st is the real part, 2nd is the apparent mass part[13].

$$\begin{bmatrix}\dot{\boldsymbol{u}}\\\dot{\boldsymbol{v}}\\\dot{\boldsymbol{w}}\\\dot{\boldsymbol{p}}\\\dot{\boldsymbol{q}}\\\dot{\boldsymbol{r}}\end{bmatrix} = \begin{bmatrix}\boldsymbol{B_{11}} & \boldsymbol{B_{12}}\\\boldsymbol{B_{21}} & \boldsymbol{B_{22}}\end{bmatrix}\begin{bmatrix}\boldsymbol{F}\\\boldsymbol{M}\end{bmatrix} \quad (11)$$

$\boldsymbol{B_{11}}$ is the total mass of the soft-wing UAV including the parafoil, $\boldsymbol{B_{22}}$ is the total inertia including the parafoil, $\boldsymbol{B_{12}}$ and $\boldsymbol{B_{21}}$ are the coupling part[14].

$$\boldsymbol{B_{11}} = m\boldsymbol{I_{3\times3}} + \boldsymbol{m_{app}} \quad (12)$$

$$\boldsymbol{B_{22}} = \boldsymbol{I_w} + \boldsymbol{I_{app}} - \boldsymbol{S_{r_{op}}}\boldsymbol{m_{app}}\boldsymbol{S_{r_{op}}} \quad (13)$$

$$\boldsymbol{B_{12}} = -\boldsymbol{B_{21}}^{\mathrm{T}} \quad (14)$$

D. Soft-wing UAV Kinematics Equation

The mathematical model of a soft-wing UAV can be represented by the following equation with 6 degrees of freedom, which includes the 3 attitude angular axis and the 3 inertial movements along their axis.

$$\begin{bmatrix}\dot{\boldsymbol{\phi}}\\\dot{\boldsymbol{\theta}}\\\dot{\boldsymbol{\psi}}\end{bmatrix} = \begin{bmatrix}1 & \sin\boldsymbol{\phi}\tan\boldsymbol{\theta} & \cos\boldsymbol{\phi}\tan\boldsymbol{\theta}\\0 & \cos\boldsymbol{\phi} & -\sin\boldsymbol{\phi}\\0 & \sin\boldsymbol{\phi}/\cos\boldsymbol{\theta} & \cos\boldsymbol{\phi}/\cos\boldsymbol{\theta}\end{bmatrix}\begin{bmatrix}\boldsymbol{p}\\\boldsymbol{q}\\\boldsymbol{r}\end{bmatrix} \quad (15)$$

$$\begin{bmatrix}\dot{\boldsymbol{x}}\\\dot{\boldsymbol{y}}\\\dot{\boldsymbol{z}}\end{bmatrix} = \boldsymbol{T_{IB}}^{\mathrm{T}}\begin{bmatrix}\boldsymbol{u}\\\boldsymbol{v}\\\boldsymbol{w}\end{bmatrix} \quad (16)$$

$\boldsymbol{T_{IB}}$ is the transfer matrix from the earth coordinates to the body axis system.

III. VISUAL SIMULATION SYSTEM OF SOFT-WING UAV

The Visual Simulation System can receive the real time flying data, and from that the system can represent it lively in the system. Also it can replay the historical data in the same way. The system is consisted by data receiving module, visual simulation model library and the simulation module. The data receiving module receives the flying data and feed it to the simulation model, and then the simulation module started to simulate the vehicle and the environment[15].

FlightGear is an open source multiplatform flight simulation software[16]. It has an open software architect and rich input/output interface, developers can use. Buildings, rivers and weathers are also available in the simulation environment. Functions like auto drive, navigation, airport runway. It also has many simulation models in the library.

In this paper FlightGear is used as the simulation platform. A soft-wing UAV simulation system is constructed. Visual simulation could be done in this system. The structure of the system is shown is Fig. 7.

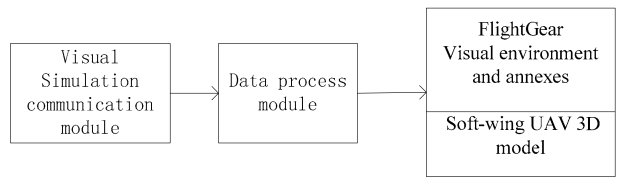

Fig 7. The soft-wing UAV simulation system structure

A 3D Soft-wing UAV Model

The visual simulation system is constructed by 2 parts: the environment simulation system and the 3D flight model. The simulation environment includes the flying scene, airport, airport runway and the sound. FlightGear offers many like real simulation environment around the world; also users can construct their own simulation environment.

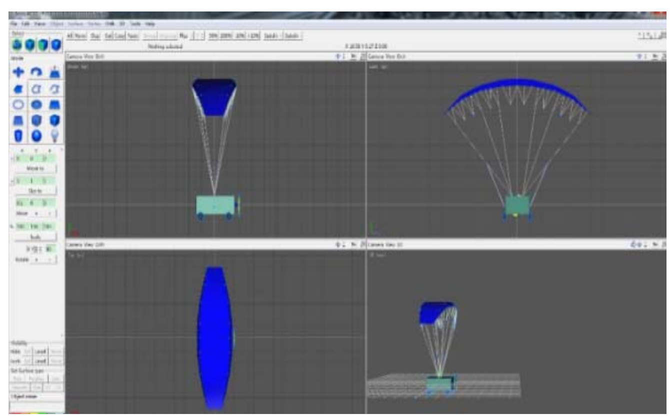

Fig. 8. AC3D modeling Software

For the flying model design, professional 3D design software can be used. FlightGear can read these models after completion. In this paper AC3D is used to complete the 3D model design (Fig. 8).

AC3D is an open source multiplatform 3D commercial model design software. It offers an optimized tool to design models in detail. The design type in AC3D includes apex, curvature, material, object and texture[16]. The most important element in models is "object". The simulation process is to control these "object". Details in materials and textures can make the model look like real.

After the model design with AC3D, the model is imported to FlightGear with an XML file to describe the basic configurations including the actions, positions and the attitude.

After the importation, little offsets could be introduced in the system. Based on these offsets, the XML file should be adjusted accordingly. After the adjustment, in the select flight interface, the new designed flight could be selected (Fig. 9).

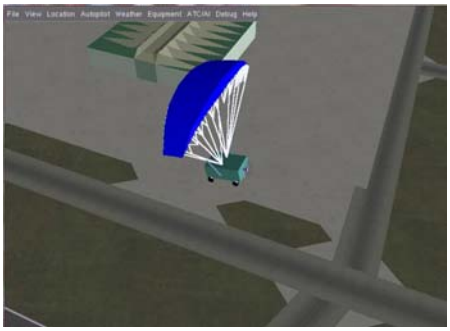

Fig. 9 The soft-wing UAV model in FlightGear

B. Data Exchange in the Simulation Software

To drive the flying model in the simulation environment, a special data transaction module is needed in the soft-wing UAV flying data transaction process.

FlightGear supports 2 communication protocols TCP/IP and UDP[17]. TCP/IP is the protocol that can communication with all the connections. It needs to establish a valid connection. With this type to protocol, the transaction data do not lose easily, but it uses a lot of resources. UDP is a wireless transmission protocol. When transmit, without knowing the status at the other side, it can transmit directly. It do not need much of the resource. The simulation system designed in this paper uses MATLAB dynamic model and FlightGear simulation system on the same computer. These two software talks to each other internally through the internal IP address （127.0.0.1）, which can provide a reliable data transaction. In order to deliver the data in time, in this paper UDP protocol is used to establish the connation.

C Data Process in the Simulation System

The flying status data received by FlightGear consisted by 3-axis position data (latitude, longitude and altitude) and 3-axis attitude data (pitch angle, roll angle and yaw angle). Different flying data may have different reference coordinate system, when exchanging information between subsystems, coordinate frame transformation will be needed.

For soft-wing UAV with 6 degrees of freedom, FlightGear needs to receive 3-axis position data and 3-axis attitude data. The position data solved by soft-wing UAV mathematical model is based on "north east" ground coordinate, which needs to be transferred to the FlightGear "latitude, longitude and altitude coordinate" system. It is very convenient to use the Gaussian projection method to convert forward and backward between the systems. In this paper, backward Gaussian projection method is used to establish a transfer module to transfer between coordinates in the FlightGear simulation system.

IV. TESTING THE VISUAL SIMULATION SYSTEM

MATLAB is used in the mathematical simulation of the soft-wing UAV mathematical model. It can get the attitude and position information of the soft-wing UAV. In this simulation, the soft-wing UAV carried out a trajectory points flying task which is shown in Fig. 10. Fig. 11, Fig. 12 and Fig. 13 showed within the simulation time, the change of the pitch angle (theta), yaw angle (psi) and flight altitude (H).

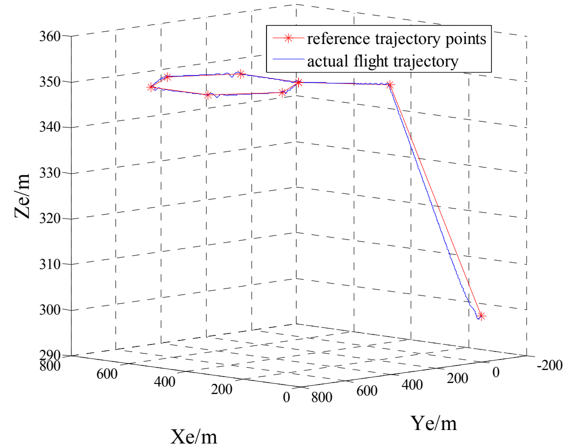

Fig. 10. Soft-wing UAV simulation route

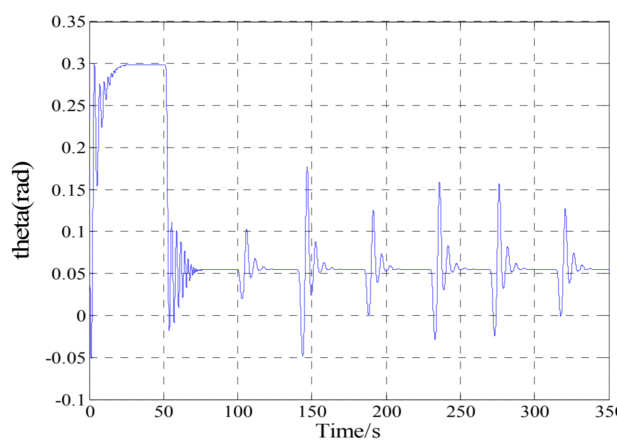

Fig 11. The soft-wing UAV pitch angle

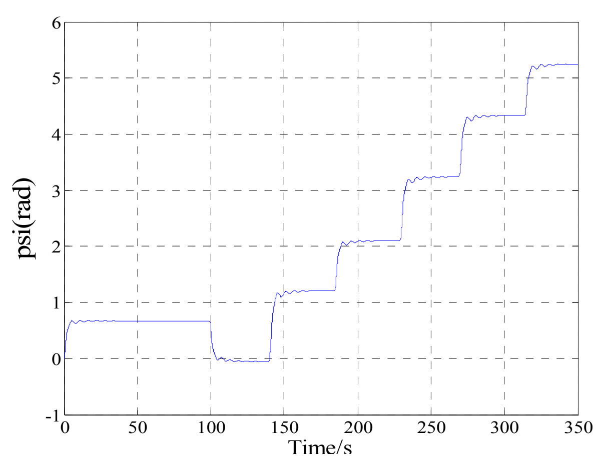

Fig 12. The soft-wing UAV roll angle

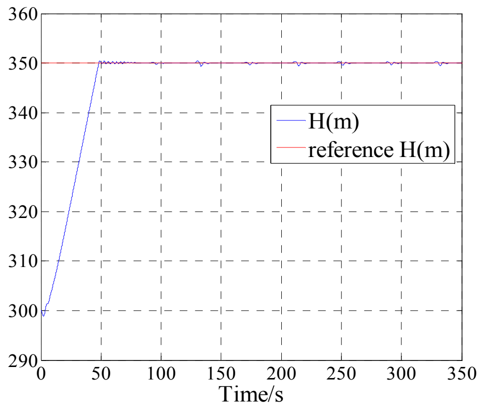

Fig 13 The soft-wing UAV yaw angle

The visual simulation system uses the flying data to process the simulation task. The front view, side view, chase view and chase view without yaw are shown in Fig. 14 and Fig. 15. In this simulation, the 3D model of the soft-wing UAV followed the attitude and position data generated by mathematical model timely. It is more convenient for the user to observe the structure and the flying attribute of the soft-wing UAV.


Fig. 14 The front view and side view of the simulation system

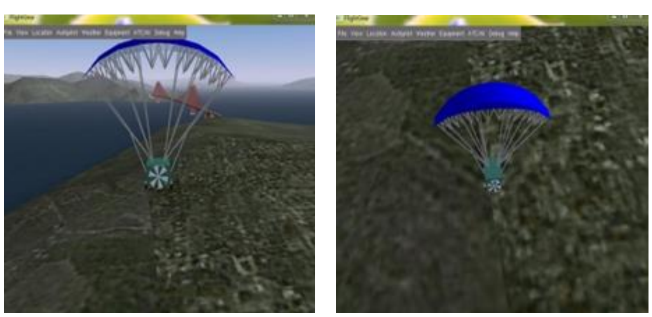
Fig 15. The chase view and chase view without yaw

V. CONCLUSIONS

In this paper, based on a real soft-wing UAV, a mathematical model with 6 degrees of freedom for the soft-wing UAV is firstly introduced. A visual simulation system based on FlightGear is designed. From that, the output of the mathematical model can be viewed in a simulated way. This simulation system offers the user a direct and visualized way to observe the structure and flying attribute of the soft-wing UAV. It could become the basement for designing the hardware-in-the-loop simulation system of the soft-wing UAV in the next step. And may finally become a 3D visual simulation platform that could develop task oriented soft-wing UAV.

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