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A NEW SOLUTION METHOD FOR SIX DEGREE OF FREEDOM FLIGHT DYNAMICS SIMULATION OF A HIGH ASPECT RATIO WING VEHICLE

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Abstract

In this paper, 6 degree of freedom simulations of flight dynamics are constructed and they target an aircraft with high aspect ratio wings, considering its structural flexibility. A new technology is developed by considering the change of the aerodynamic performance due to the structural deformation during flight. This process is performed by using several commercial computing programs including MATLAB/Simulink and MSC/FlightLoads. And then, the results from simulations are compared with those from real flight tests.

1 Introduction

The role of unmanned aerial vehicles has been enhanced in the military area for wide and various purposes. Especially, high altitude and long endurance (HALE) aircrafts have high aspect ratio wings which have high efficiency in aerodynamics and are made of composite materials [1]. High aspect ratio wings experience large deformations during flight by gusts, turbulences, bird strikes, or abrupt maneuvers due to their structural flexibility. The large deformations due to the flexibility may induce the flight instability and even the change of the intended flight paths. Furthermore, structural fatigue and failure can occur [2]. Therefore, it is essential to verify and ensure the flight performances and stability in the developing step of the aircraft with high aspect ratio wings. For that reason, in this paper, a six degree-of-freedom flight simulations are constructed to consider the structural flexibility of the aircraft with high aspect ratio wings. Different from recent research about six degree-of-freedom flight simulations using the equivalent beam model of the aircraft, three dimensional finite element structural model and commercial analysis tools for the airworthiness certification easily are used in this paper [3-4].

2. Problem Statement

2.1 Flight simulation

2.1.1 Simulation algorithm

When performing complete six-degree-of-freedom (6-DOF) simulations of aircraft, using either digital or hybrid computers, the use of wind axes (often called flight path axes) for the solution of the translational equations of motion rather than body axes makes lower demands on computer accuracy and bandwidth [5].

First, assuming the aircraft as a rigid body and earth fixed coordinate system as the inertial coordinate system, the six degree-of-freedom motions in three dimensional space can be expressed as the sum of the translational motion and the rotational motion by applying the Newton's second law. A block diagram of a complete 6-DOF simulation using wind axes, adapted from Ref. [5], is shown in Fig. 1. The equations in each block are explained below [6]. Each number from the very next paragraphs corresponds to the number of each block.

- 1. Computation of aerodynamic force and moment coefficients: C_D, C_Y and C_L are the total drag, side force, and lift coefficients respectively and C_l, C_m and C_n are the components of moment coefficients on stability axis. q is dynamic pressure and M is Mach

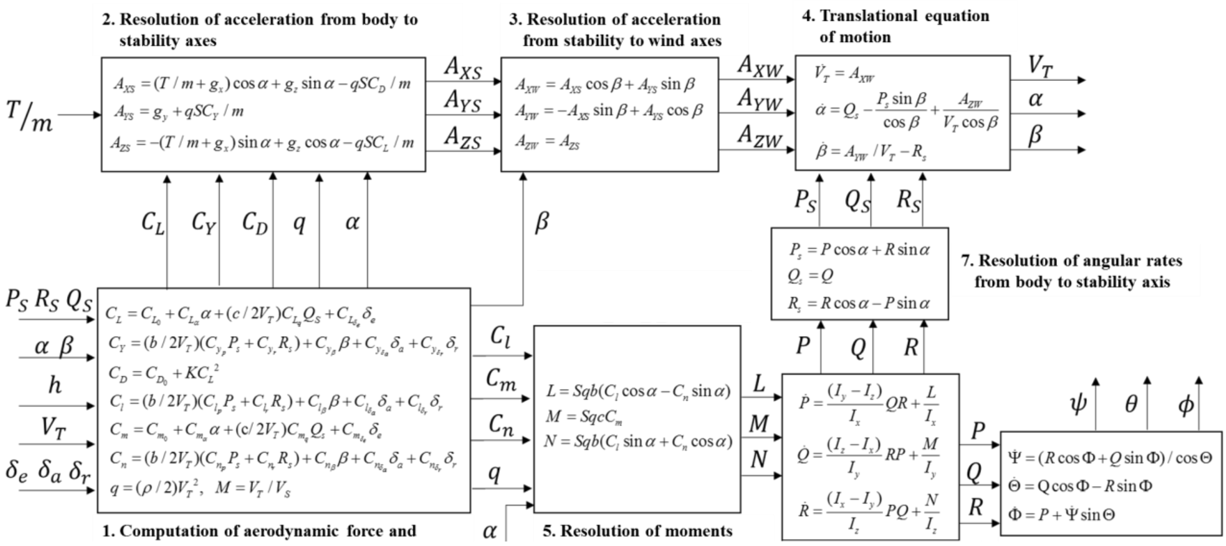


Fig. 1. The block diagram of a complete 6-DOF simulation.

number. Each value must be imported at the initial state of the simulations at least once.

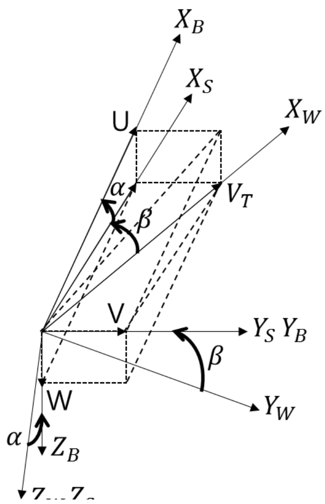


Fig. 2. Decomposition of velocity vector V_T from wind to body axes.

- 2. Decomposition of acceleration from body to stability axes: where A_{XS}, A_{YS} and A_{ZS} are stability axis accelerations resolved from body axis accelerations A_{XB}, A_{YB} and A_{ZB} by decomposition in Fig. 3 (a). The body axis accelerations result from the aerodynamic and gravitational forces acting on the vehicle, and are derived from the body axis translational equations of motion Eq. (1).

$$\sum F = m\frac{d}{dt}(V) = m((\dot{V})_r + \omega \times V) \qquad (1)$$

Expressing the Eq. (1) for the component of each axis of the body fixed coordinate system, Eq. (2) is obtained where u, v, w are the components of the velocity and p, q, r are the components of the angular velocity.

$$\begin{aligned} F_x &= m(\dot{U} + WQ - VR) \\ F_y &= m(\dot{V} + UR - WP) \\ F_z &= m(\dot{W} + VP - UQ) \end{aligned} \qquad (2)$$

Dividing Eq. (3) by the mass m yields the body axis accelerations

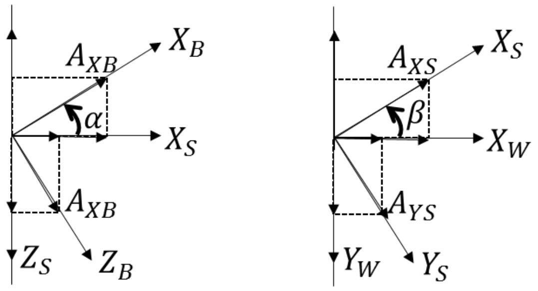
.

$$\begin{aligned} A_{XB} &= \dot{U} + WQ - VR \\ A_{YB} &= \dot{V} + UR - WP \\ A_{ZB} &= \dot{W} + VP - UQ \end{aligned} \qquad (3)$$

From Fig. 2, the body axis components of the total velocity vector can be expressed as Eq. (4).

$$\begin{aligned} U &= V_T \cos\beta \cos\alpha \\ V &= V_T \sin\beta \\ W &= V_T \cos\beta \sin\alpha \end{aligned} \qquad (4)$$

- 3. Resolution of acceleration from stability to wind axes: resolution of Fig. 3 (b) is applied.



(a) (b)

Fig. 3 (a) Decomposition of body axis to stability axis. (b) Decomposition of stability axis to wind axis.

- 4. Translational equation of motion: The total velocity V_T, angle of attack α, angle of sideslip β are integrated from the differentiations of themselves which are yielded by solving Equations of the wind axis accelerations and Equations of the stability angular rates. Also, flight path is integrated from total velocity.
- 5. Decomposition of moments from stability to body axis
- 6. Rotational equations of motion: where the body axis rolling, pitching and yawing moments L, M and N result from the aerodynamic lift and thrust forces acting on the vehicle, and are derived from the body axis rotational equations of motion Eq. (5).

$$\sum M = \frac{d}{dt}(\mathrm{H}) = (\dot{H})_r + \omega \times H \qquad (5)$$

Likewise, expressing the Eq. (5) for the component of each axis of the body fixed coordinate system, Eq. (6) can be obtained.

$$\begin{aligned} L &= \dot{H}_x + QH_z - RH_y \\ M &= \dot{H}_y + RH_x - PH_z \\ N &= \dot{H}_z + PH_y - QH_x \end{aligned} \qquad (6)$$

With the symmetry of the x-z plane and setting the body fixed coordinate system as the principal axes, angular momentums can be expressed as a function of moments of inertia.

$$\begin{aligned} L &= I_x\dot{P} + QR(I_z - I_y) \\ M &= I_y\dot{Q} + RP(I_x - I_z) \\ N &= I_z\dot{R} + PQ(I_y - I_x) \end{aligned} \qquad (7)$$

Body axis angular rates can be obtained by solving the Eq. (7).

- 7. Decomposition of angular rates from body to stability axis: decomposition in Fig. 3 (a) is applied.
- 8. Computation of Euler angle rates: By solving the kinematic equations of the relationship between angular velocity and Euler angles, the rate of change of the Euler angles can be obtained. Integrating the rate of change of the Euler angles, Euler angles can be obtained finally.

2.1.2 Simulation deployment

Algorithm of the simulations is set up by using commercial program, MATLAB/Simulink of Mathworks, Inc. MATLAB/Simulink includes a library composed of block sets about aerospace engineering technology. It is possible to analyze the dynamic responses in real time. Fig. 4 represents the composition of the codes of the simulations made in MATLAB/Simulink [7]. The necessary information for setting the initialization of the simulations is explained in Table. 1. Continuous maneuver inputs can be entered in the simulations and the simulations extract the flight attitudes and the flight paths.

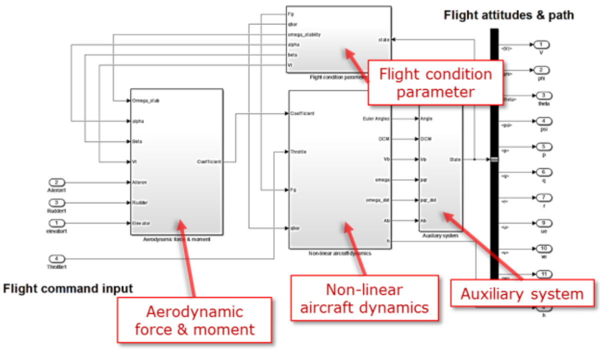
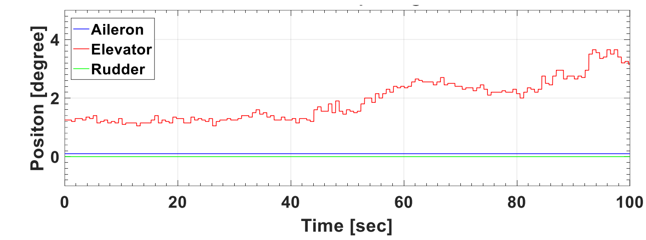


Fig. 4 Non-linear 6-DOF flight simulation with MATLAB/Simulink.

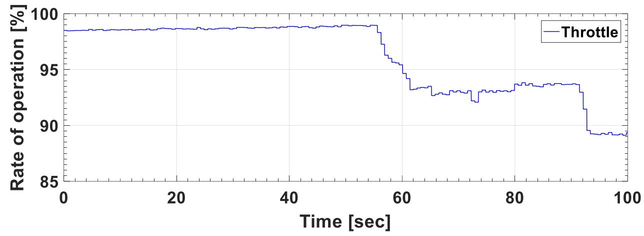
Table. 1 Initial input information.

Category	Description
Configuration	wing area, chord length, span length, center of mass, center of pressure, mass, moment of inertia etc.
Flight condition	altitude, dynamic pressure, angle of attack, angle of sideslip, gravity etc.
Flight attitude	initial location, velocity, acceleration, initial Euler angle, angular rate, angular acceleration etc.
Flight performance	Longitudinal and lateral aerodynamic force and moment coefficient

The main wings in the structural model of the vehicle has high aspect ratio of about 19. The unmanned aerial vehicle (UAV) weighs approximately four-tons. The simulation lasts for one-hundred-seconds and the maneuver input is from the real flight tests of the UAV. First, except for the aileron and the rudder, only elevator input and the engine throttle signals are entered into the simulation to observe the longitudinal motion of the vehicle. The input signals are depicted in Fig. 5 (a), (b)



(a) Command input signal

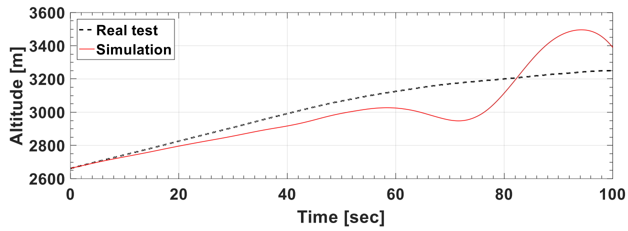


(b) Throttle input signal

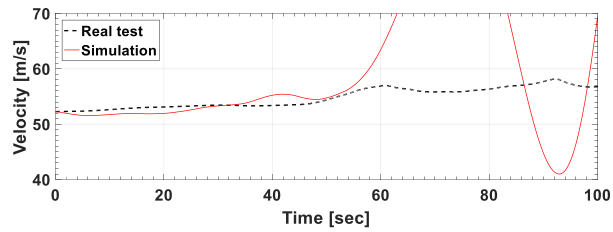
Fig. 5 Input signal data inserted into simulation.

2.1.2 Simulation result

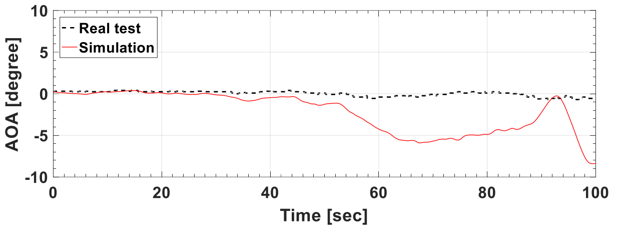
As shown in Fig. 6 (a)-(h), the simulation results are compared with those from the flight tests in parallel under the same maneuver input signals condition. During the initial fifty seconds of the simulation, the results are similar, as showing the smooth climbing states. However, after fifty seconds, the results become depart from each other. There may be many reasons for that phenomenon. One of the most important reasons is that



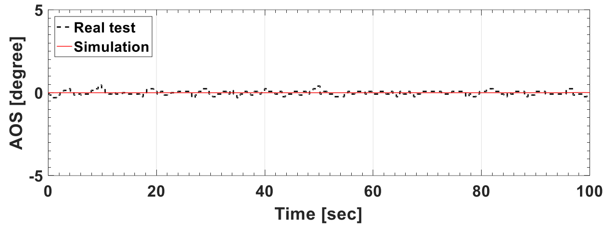
(a) Altitude



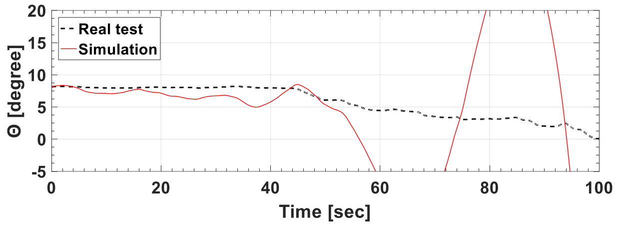
(b) Total velocity



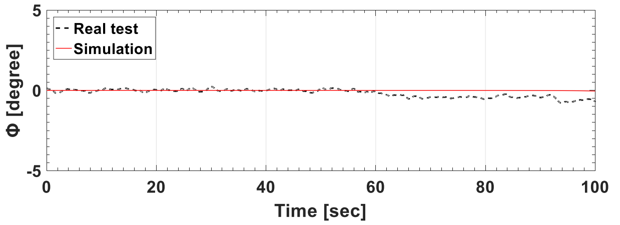
(c) Angle of attack



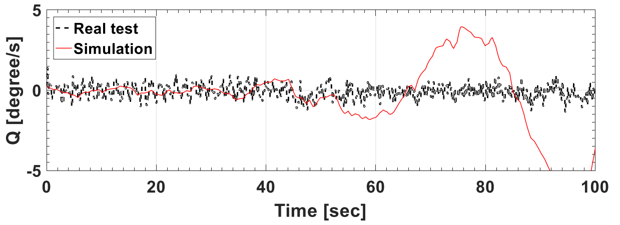
(d) Angle of sideslip



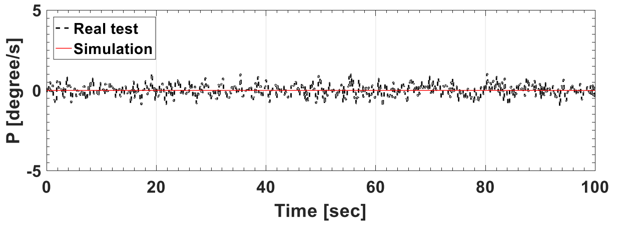
(e) Pitch angle, Θ



(f) Roll angle, Φ



(g) Pitch angular rate, Q



(h) Roll angular rate, P

Fig. 6 The comparison with real flight test and simulation results.

2.2 New solution method

2.1.1 Snap-shot method

The simulation built in this paper, has a limitation, which means that it represents the rigid body motions. A new method is developed to recover the limitation, which can consider the structural flexibility of the aircraft with high aspect ratio wings and the change of the aerodynamic coefficients. The point of the new method is that aerodynamic stability and control derivative coefficients from the trim analysis of the vehicle assuming elastic body, are consistently updated in each time step. For the renewal of the aerodynamic coefficients, the final flight condition of the right prior step is used for the trim analysis, and the new modified aerodynamic coefficients from the trim analysis in MSC.FlightLoads are imported again into the simulation. This process contains the change of the aerodynamic performances due to the structural deformations of the vehicle. Based on the modified aerodynamic coefficients, the simulation is performed in the relevant section during the one step. This process, repeated for the complete simulation time, is called 'snap-shot method' in this paper, and is illustrated in Fig. 7.

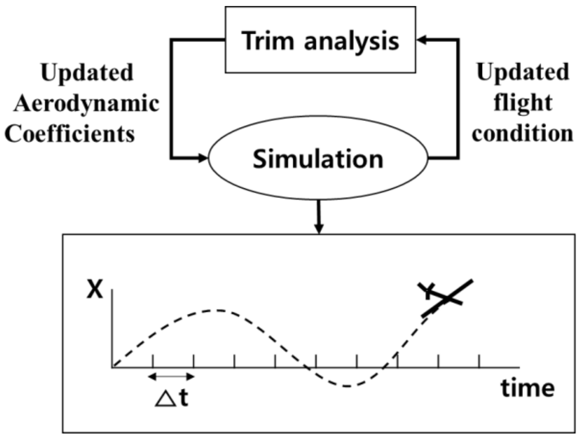


Fig. 7 The process diagram of snap-shot method.

2.1.1 Quasi-static aeroelastic trim analysis

This method is based on quasi-static aeroelastic trim analysis. This trim analysis deal with the interaction of aerodynamic and structural forces on a flexible vehicle that results in a redistribution of the aerodynamic loading as a function of airspeed, and the solution of these problems assumes that the system comes to a state of quasi-static equilibrium. The aerodynamic load redistribution and consequent modifications to aerodynamic stability and control derivatives are the most interest to this method. Therefore, this is a multidisciplinary activity that requires aerodynamic data, structural flexibility, mass distribution, flight control system and maneuver description [8].

Below equation of motion (8) is the governing equation, and each term is explained [9].

$$[K-\bar{q}AIC]\{\mathrm{x}\}+[\mathrm{M}]\{\ddot{\mathrm{x}}\}=[\mathrm{f}_\delta]\{a\} \tag{8}$$

$[K]$ and $\{x\}$ represents the structural stiffness and the displacements, respectively. The product of the two variables represents the maneuver load distributed on the vehicle, and this value is the difference between the aerodynamic load $\{F_a\}$ and the inertial load $\{F_I\}$.

$$[K]\{x\}=\{F_a\}-\{F_I\} \tag{9}$$

Aerodynamic loads can be classified into the rigid aerodynamic forces and the incremental aerodynamic flexible forces due to the structural deformations.

$$\{F_a\}=\{F_R\}+\{F_f\} \tag{10}$$

The rigid aerodynamic forces can be represented by the trim values in Eq. (11), and the incremental flexible aerodynamic forces can be represented by aerodynamic matrices and the structural deflections. The inertial loads can be expressed as Eq. (13).

$$\begin{aligned}\{F_R\}&=F_R(\alpha,\beta,\mathrm{p},\mathrm{q},\mathrm{r},\delta_i\ldots)\\&=\left[\frac{\partial f}{\partial \delta}\right]\{\delta\}=[\mathrm{f}_\delta]\{a\}\end{aligned} \tag{11}$$

$$\{F_f\}=\bar{q}[AIC]\{x\} \tag{12}$$

$$\{F_I\}=[\mathrm{M}]\{\ddot{x}\} \tag{13}$$

The static aeroelastic capability in MSC/Nastran/FlightLoads & Dynamics of MSCsoftware Inc. addresses these needs by the computation of aircraft trim conditions, with subsequent recovery of structural responses, aeroelastic stability derivatives.

Trim analysis in this program need a variety of different information below. 3D finite element structural model of target vehicle, 3D panel method aerodynamic model and trim variables including such as control surfaces position and flight conditions etc., illustrated in Fig. 8. More specific trim variables is explained in Table. 2. After trim analysis, aerodynamic stability derivative coefficients are obtained, provided to simulation for snap-shot method.

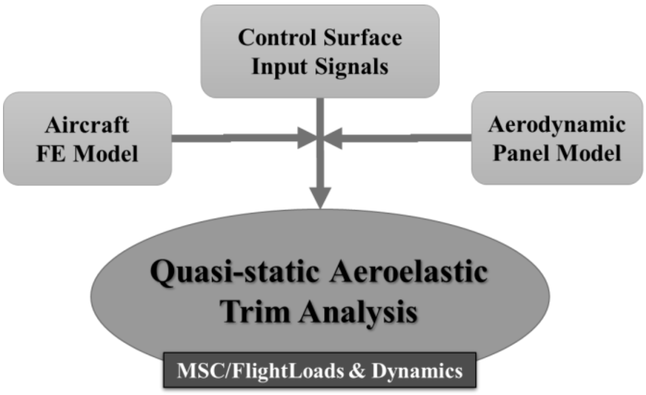


Fig. 8 The process diagram.

Table. 2 Trim Variables.

Category	Variable	Description	
δ	ALPHA	α	AOA
	BETA	β	AOS
	ROLL	$pb/2V$	Roll rate
	PITCH	$qc/2V$	Pitch rate
	YAW	$rb/2V$	Yaw rate
	$\delta_{aileron}$	radian	Aileron
	$\delta_{elevator}$	radian	Elevator

	δ_{rudder}	radian	Rudder
X_2	URDD1	$\ddot{x}/g$	X-acc.
	URDD2	$\ddot{y}/g$	Y-acc.
	URDD3	$\ddot{z}/g$	Z-acc.
	URDD4	$\dot{p}/g$	Roll acc.
	URDD5	$\dot{q}/g$	Pitch acc.
	URDD6	$\dot{r}/g$	Yaw acc.

3. Conclusion

In this paper, flight simulation was built for developing a high aspect ratio wing vehicle with MATLAB/Simulink as a commercial analysis tool. Results of the simulation assumed rigid body, however, was present a much contrast to real flight test results in some cases such as abrupt maneuver.

For recovering this limitation and considering the structural flexibility of the aircraft with high aspect ratio wings and the change of the aerodynamic performance, ‘snap-shot method’ was proposed with MSC/Nastran/FlightLoads & dynamics and applied to simulation. The method adopts a process to update the modified aerodynamic coefficients considering the structural deformations at each time step during simulation case. In the future, for improving predict accuracy of flight simulation, an active feedback control system and gust model will be added to the simulation. This simulation may be useful and robust tool at level stage of vehicle development.

Acknowledgment

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