ANALYTIC METHOD FOR FLIGHT MOTION OF AIRCRAFT WITH A SINGLE VIDEO CAMERA AND ITS APPLICATION TO A FREE FLIGHT GLIDER

Hiromitsu Kawazoe*, Takeshi Sawa*, Takaaki Miura*, Goji Yamada*, Takashi Matsuno* and Makoto Ueno**
***Department of Mechanical and Aerospace Engineering, Tottori University, Tottori,**
**** Wind Tunnel Technology Center, JAXA, Chofu, Tokyo, JAPAN**
kawazoe@mech.tottori-u.ac.jp; tsawa44@gmail.com; sawatashi510@yahoo.co.jp; yamada@mech.tottori-u.ac.jp; matsuno@mech.tottori-u.ac.jp; ueno.makoto@jaxa.jp

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Abstract

Non-intrusive method to analyze the motion of a flight vehicle is proposed by using a single video camera. The new technique is suggested to measure aerodynamic force and moment as well as temporal vehicle's behavior. It can utilize an arbitrarily shaped aircraft and can make measurement with higher accuracy than the previous study. The reason is that the size of a gauge to decide the motion of a flight vehicle can be enlarged.

This method was applied to a free-flight glider. The aerodynamic force and moment acting on the glider can be explained concerning to the translational and the rotational velocities and the posture of the glider. As the result of the application, this method was confirmed to be useful and widely applicable besides an aircraft.

1 Introduction

A widely used technique to measure aero-dynamic force and moment has been conducted with a force balance in a wind tunnel, mainly in steady state condition. Although a force balance is popular and useful, the rod supporting an aircraft model has some effects on the surrounding airflow. Another technique to know aerodynamic force and moment is the way to use an accelerometer with a signal-transmittance wire which sometimes disturbs airflow and interferes with the natural motion of the flight model. The research by Smith[1], Breuhaus et al.[2] and Muzzy et al.[3] have been reported for an unsteady motion of a flight vehicle.

It is desired to analyze aerodynamic force and moment acting on an aircraft, especially in the unsteady flight condition. Provided it becomes successful to evaluate them by a series of pictures taken by a single video camera, it will be a powerful, useful, convenient and easily applicable method.

The first objective of the research is to propose a new method to analyze the motion of a free flight aircraft with a single video camera, which does not need such an particular gauge as our previous study[4]. It means the behavior of an aircraft will not be affected by such an obstacle as the gauge attached additionally in the previous research. The second object is to develop the manner of measuring aerodynamic force and moment with higher accuracy than the previous study. The third one is to apply this method to free flight of a glider and to certain usefulness of the method.

2 Analytical Procedures with a Single Video Camera

2.1 Decision of instantaneous location and posture of a free flight aircraft

Two coordinates systems were adopted for the analysis of an aircraft motion as shown in Fig.1. The one is a fixed coordinate system on the ground (x, y, z), and the other is a body coordinate (X_i, Y_i, Z_i) at instantaneous time, i, the origin of which was set on the center of gravity of the aircraft as shown in Fig.1. The location and the posture of an aircraft at the time, i, can be derived by using the equation(1)[4], which means a marker painted or pasted on an aircraft at the initial location, (x_0, y_0, z_0) moves to the position (x_i, y_i, z_i) in the fixed coordinate.

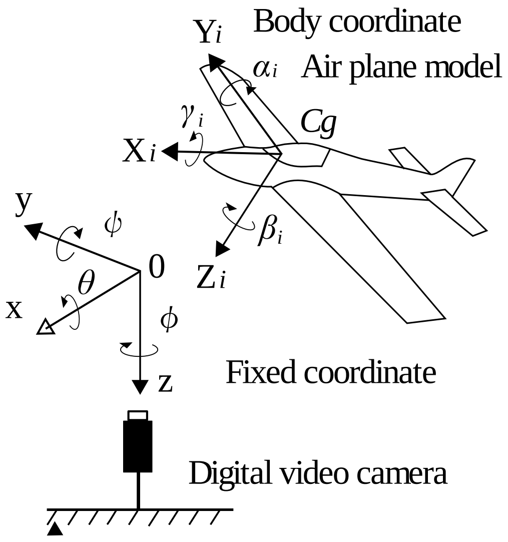


Fig.1 Definition of the two coordinates.

In other words, the marker was rotated θ_i, ψ_i, ϕ_i about the x, y and z axes and translated by the displacement, (x_{gi}, y_{gi}, z_{gi}), which is the position of the center of the gravity of the aircraft from the initial location, (x_{g0}, y_{g0}, z_{g0}) , that is (0, 0, 0) in this case.

On the other hand, aerodynamic force and moment from the view of the body coordinate is often desired. In the case for the lapse of time from i to i+1, the body coordinate at the time i+1, (X_{i+1}, Y_{i+1}, Z_{i+1}), is considered to be rotated γ_i, α_i, β_i about the X_i, Y_i and Z_i axes and translated by the displacement, (d_{xi}, d_{yi}, d_{zi}) at the time i, which is the displacement as in the equation (2)[4].

2.2 Markers on an aircraft for accurate measurement

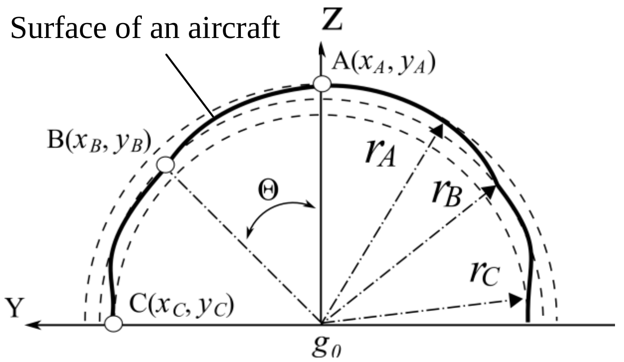
Markers can be distributed on an aircraft directly and arbitrarily as shown in Fig.2(a), which are just like painted dots or pasted stickers. Therefore, these markers will not be an obstacle to affect the motion of an aircraft. As one of the example for this research with a glider, Figure 2(b) shows the two groups of circles having markers, which form the two

$$\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & x_{gi} \\ 0 & 1 & 0 & y_{gi} \\ 0 & 0 & 1 & z_{gi} \end{bmatrix} \begin{bmatrix} \cos\phi_i & -\sin\phi_i & 0 \\ \sin\phi_i & \cos\phi_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\phi_i & 0 & \sin\phi_i \\ 0 & 1 & 0 \\ -\sin\phi_i & 0 & \cos\phi_i \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_i & -\sin\theta_i \\ 0 & \sin\theta_i & \cos\theta_i \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix}$$

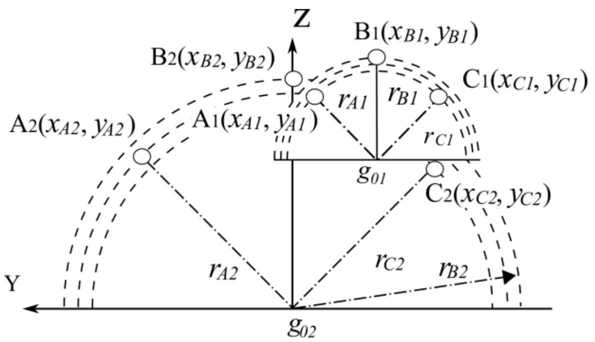
$$= \begin{bmatrix} e_{xxi} & e_{xyi} & e_{xzi} & x_{gi} \\ e_{yxi} & e_{yyi} & e_{yzi} & y_{gi} \\ e_{zxi} & e_{zyi} & e_{zzi} & z_{gi} \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} \qquad \cdots(1)$$

$$\begin{bmatrix} d_{xi} \\ d_{yi} \\ d_{zi} \end{bmatrix} = \begin{bmatrix} e_{xxi} & e_{xyi} & e_{xzi} \\ e_{yxi} & e_{yyi} & e_{yzi} \\ e_{zxi} & e_{zyi} & e_{zzi} \end{bmatrix} \begin{bmatrix} D_{Xi} \\ D_{Yi} \\ D_{Zi} \end{bmatrix} \qquad \cdots(2)$$

$$\begin{cases} e_{xxi} = \cos\phi_i \cos\phi_i \\ e_{yxi} = \cos\phi_i \sin\phi_i \\ e_{zxi} = -\sin\phi_i \\ e_{xyi} = \sin\phi_i \cos\phi_i \sin\theta_i - \sin\phi_i \cos\theta_i \\ e_{yyi} = \sin\phi_i \sin\phi_i \sin\theta_i + \cos\phi_i \cos\theta_i \\ e_{zyi} = \cos\phi_i \sin\theta_i \\ e_{xzi} = \sin\phi_i \cos\phi_i \cos\theta_i + \sin\phi_i \sin\theta_i \\ e_{yzi} = \sin\phi_i \sin\phi_i \cos\theta_i - \cos\phi_i \sin\theta_i \\ e_{zzi} = \cos\phi_i \cos\theta_i \\ d_{xi} = x_{gi+1} - x_{gi} \\ d_{yi} = y_{gi+1} - y_{gi} \\ d_{zi} = z_{gi+1} - z_{gi} \end{cases}$$



(a) Markers on arbitrary configuration surface



(b) Two circle gauges with markers

Fig.2 Example of reference makers set.

gauges to measure the location and the posture of the glider.

On the other hand, these markers distributed widely on an aircraft should be favorable to measure its position and posture with higher accuracy than the previous research[4] owing to their constructing a large gauge. The location vector of the center of each circle-gauge from the center of the gravity of the aircraft is known because of setting them by ourselves. The location and posture of an aircraft at instantaneous time was decided from these circle gauges recorded by a video camera.

3 Experiment of a Free Flight Glider

3.1 Glider and the procedure for its flight

Figures 3 and 4 show the photograph of the glider (Cassiopeia, mini-ASK21) and the experimental setup for the measurement of the free flight. The glider has the wing span of 1305*mm*, and the other specifications are listed

Fig.3 Glider model.

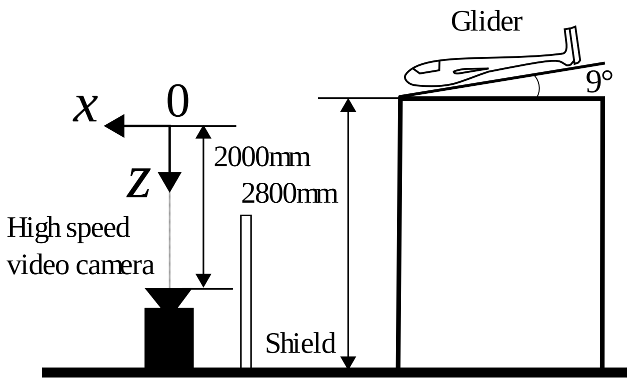


Fig.4 Set of the experimental apparatus.

Table 1 Specifications of the glider

Fuselage length	670 *mm*
Wing span	1305 *mm*
Wing area	1370 cm^2
Overall mass	0.473 *kg*

Table 2 Inertial characteristics

I_{xx}	0.01788 kgm^2
I_{yy}	0.01151 kgm^2
I_{zz}	0.02485 kgm^2
$I_{xy}=I_{yx}$	0 kgm^2
$I_{yz}=I_{zy}$	0 kgm^2
$I_{zx}=I_{xz}$	0.00209 kgm^2

in Tables 1 and 2. Table 2 indicates the tensor of the inertia of the glider to get aerodynamic force and moment, which was measured by the free oscillation method with two suspension wires. The symmetry of the glider was utilized and therefore, I_{xy} and I_{yz} become zero. The flight behavior was recorded by the high-speed video camera (AMETEK, Phantom v710) at the recording speed of 7500fps.

The glider was launched by rubber drive from the stage at 2.8m height with the ejection angle of 9 degrees as shown in Fig.4. The shield was set to prevent the glider from crashing into the camera. The aerodynamic force and moment acting on the glider from the point of the body coordinate are calculated by the equations (3) and (4), respectively. V_X, V_Y, V_Z, V_γ, V_α and V_β are velocities in the direction of the X, Y and Z axes and angular velocities about the X, Y and Z axes, respectively.

$$
\begin{aligned}
F_X &= m\left(\dot{V}_X + V_\alpha V_Z - V_\beta V_Y + g\sin\phi\right)\\
F_Y &= m\left(\dot{V}_Y + V_\beta V_X - V_\gamma V_Z - g\cos\phi\sin\theta\right)\\
F_Z &= m\left(\dot{V}_Z + V_\gamma V_Y - V_\alpha V_X - g\cos\phi\cos\theta\right)
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
M_\gamma &= I_{xx}\dot{V}_\gamma - I_{yz}\left(V_\alpha^2 - V_\beta^2\right) - I_{zx}\left(\dot{V}_\beta + V_\gamma V_\alpha\right)\\
&\quad - I_{xy}\left(\dot{V}_\alpha - V_\beta V_\gamma\right) - V_\alpha V_\beta\left(I_{yy} - I_{zz}\right)\\
M_\alpha &= I_{yy}\dot{V}_\alpha - I_{zx}\left(V_\beta^2 - V_\gamma^2\right) - I_{xy}\left(\dot{V}_\gamma + V_\alpha V_\beta\right)\\
&\quad - I_{yz}\left(\dot{V}_\beta - V_\gamma V_\alpha\right) - V_\beta V_\gamma\left(I_{zz} - I_{xx}\right)\\
M_\beta &= I_{zz}\dot{V}_\beta - I_{xy}\left(V_\gamma^2 - V_\alpha^2\right) - I_{yz}\left(\dot{V}_\alpha + V_\beta V_\gamma\right)\\
&\quad - I_{zx}\left(\dot{V}_\gamma - V_\alpha V_\beta\right) - V_\gamma V_\alpha\left(I_{xx} - I_{yy}\right)
\end{aligned} \tag{4}
$$

3.2 Examination for the decision of location z of the glider in the optical direction

Location of the glider in the direction of the camera optical line, namely in the z-direction of Fig.4, was decided on the basis of the measured gauge size, which becomes small by the glider's leaving from the camera and vise versa. Therefore, the examination for the relation between glider location in the z-axis direction and measured representative circle-gauge radius was carried out, which was calculated from such the plural gauges defined by markers plotted on the glider as in the Fig.2(b). The results is shown in Fig.5, where the gauge size is expressed by the contraction/extension ratio to the reference radius, $r_t=r/r_0$. Here r_0 is the reference radius of the gauge which was positioned at the original point, (0, 0, 0).

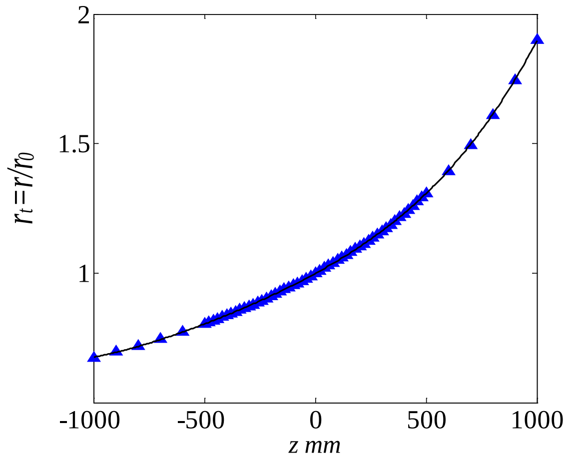


Fig.5 Relation between the circle radius and the location z.

4 Results

4.1 Measurement Accuracy

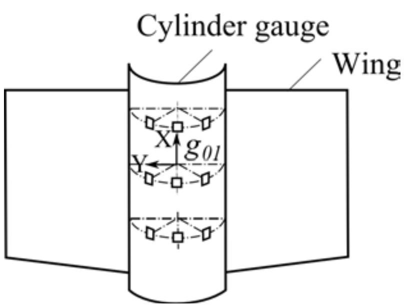
Calibration tests of the measurement accuracy were carried out for translational and rotational motions. The glider with the markers constructing the gauges was translated every 20mm from -200mm to +200mm at the location of 2000mm from the camera in the three directions individually. Rotational motions were also undertaken every 5 degrees from -30 to +30 degrees at the same position as the translation test. The results are shown in Tables 3 and 4 for the translational and rotational motions, respectively. The words of Single and Plural in these tables are corresponding to the previous and this time analysis methods as shown in Fig.6. Higher accuracy could be obtained by the proposed method owing to the plural and large gauges in this research.

Table 3 Measurement error for translational motion, standard deviation, σ

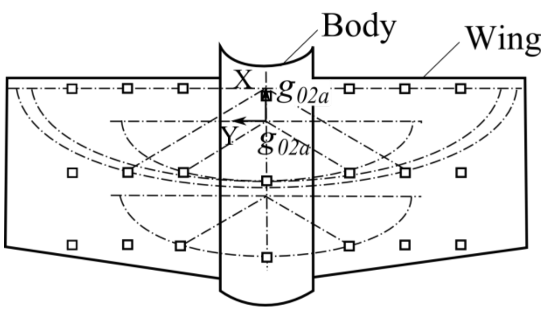
translation	σ (mm) by Single gauge	σ (mm) by Plural gauges
x	1.116	0.627
y	0.556	0.557
z	3.508	0.939

Table 4 Measurement error for rotational motion, standard deviation, σ

rotation	σ (degree) by Single gauge	σ (degree) by Plural gauges
Roll θ	2.982	1.239
Pitch ψ	2.020	0.481
Yaw ϕ	0.152	0.203



(a) Single gauge in the previous research[4]



(b) Plural gauges in this research

Fig.6 The image of the gauges on the aircraft in the previous and the present methods.

4.2 Flying Glider

Sequential image of the flight of the glider by piling on one layer is shown in Fig.7, which indicates the motion of the under-side wing with the markers at every 0.04 seconds. By using such the sequential series of images as Fig.7, the translational and rotational behavior of the glider was calculated based on the above mentioned manner. The translational behavior is indicated in Fig.8, where the blue dots are the spatial variation of the center of the gravity of the glider in the fixed coordinate.

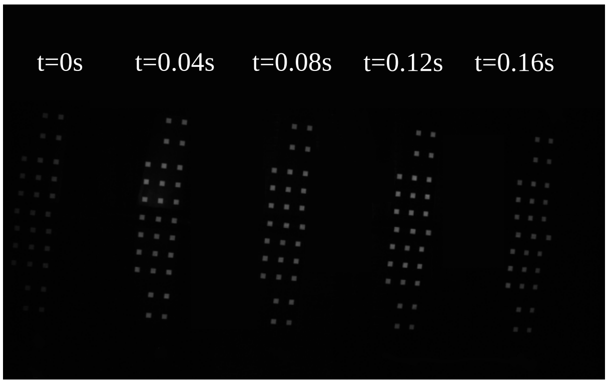


Fig.7 Sequential images of the flight of the glider at every 0.04 sec.

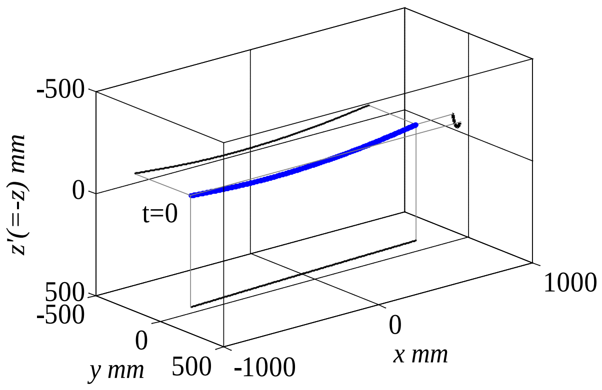
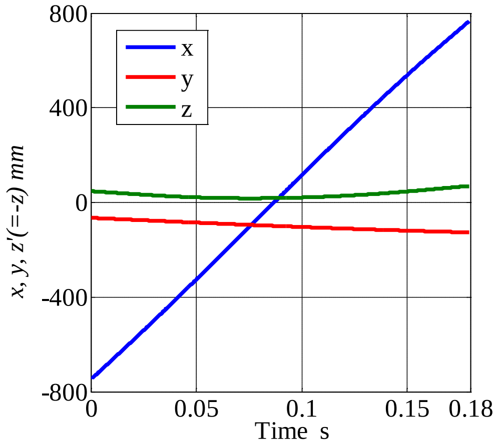
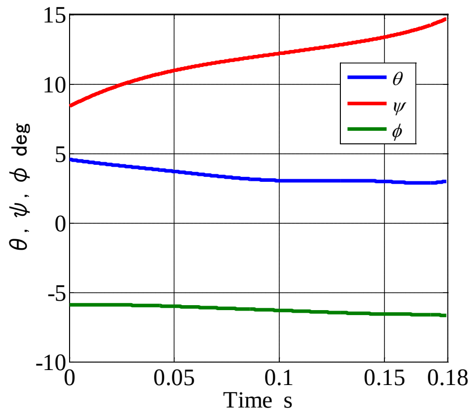


Fig.8 Trajectory of the center of the gravity of the glider.

The position of the glider moves about 100mm to the negative direction of the y axis, and in the vertical direction the glider first flies down according to its launch manner and then goes up owing to the increase of the flight speed and thus the lift. The detail variations of the position and the rotation angle in the fixed coordinate are indicated in Fig.9. Their first and second time-derivatives lead velocities and accelerations, and the resultant aerodynamic force and moment can be obtained by multiplying the mass and the inertial moment of the glider according to the equations (3) and (4). The results will be shown later in the body coordinate.



(a) Location, x, y, z



(b) Posture, θ, ψ, ϕ

Fig.9 Temporal variations of the glider location and the posture in the fixed coordinate.

The glider turned to go up after 0.07s as shown in Fig.9(a). The time of 0s is not the instant of the glider launch but the beginning of the glider motion analysis. The yaw angle ϕ was almost constant and the flight trajectory of the glider is nearly straight on the x-y plane as shown in Fig.8. It suggests the yaw moment was almost not acted on the glider during the flight.

ψ in the fixed coordinate increases from 8 to 15 degrees as shown in Fig.9(b) , the glider, although, turned the motion from down to up. Therefore, the effective angle of the attack from the view of a pilot on the glider was moreover analyzed, and the result is shown in Fig.10. The effective angle of attack was monotonously decreased with the reduction rate decreasing during the period. It was mainly from the longitudinal motion of the glider.

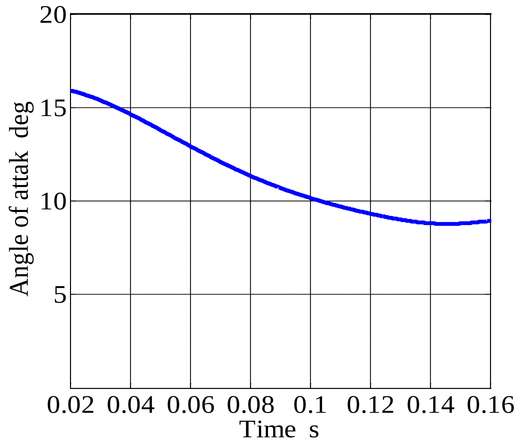


Fig.10 The effective angle of the attack.

The velocity in the body coordinate and the speed, that is $V = \sqrt{V_x^2 + V_y^2 + V_z^2}$, are shown in Figs.11 and 12, respectively. At first the velocity in the X direction, V_x, increase and then decreases from 0.07s. The similar sign to this can be seen in the speed variation of Fig.12. It is as if the decrease of the potential energy of the glider might compensate by the increase of the momentum energy, which corresponds to

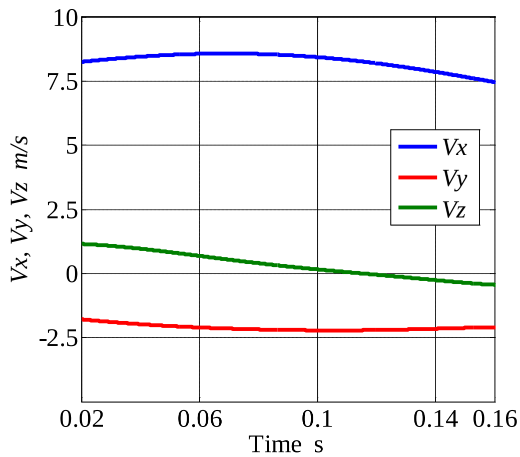


Fig.11 Temporal variations of the glider velocity in the body coordinate systems.

the temporal variation of the glider's altitude in Fig.9(a). The speed drastically decreases after 0.07s and the sudden fall of 1m/s in speed occurred during 0.09s. In the direction of Y axis of the body coordinate, the glider flies to the left hand side and is in the condition of little side slip with the constant yaw angle.

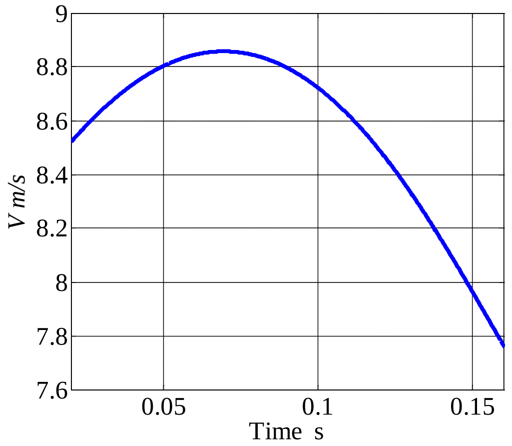
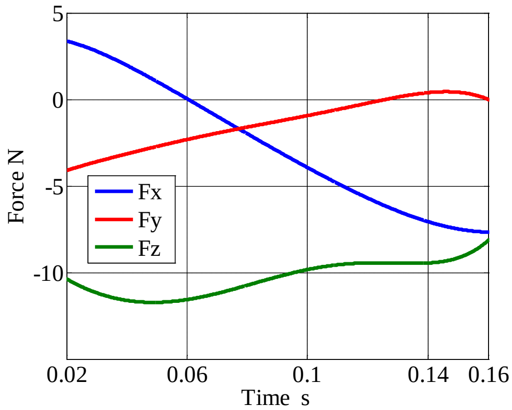


Fig. 12 Speed of the glider.

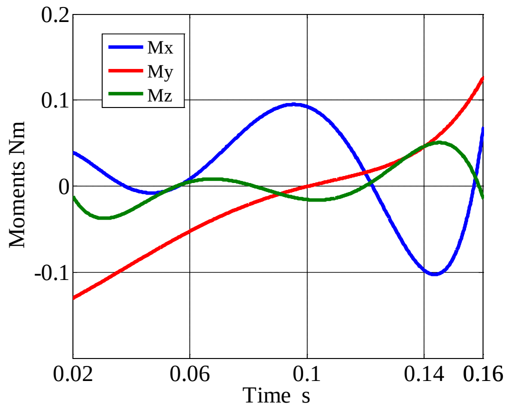
The aerodynamic force and moment are shown in Fig.13 in the body coordinate, where the effect of gravity was omitted. It means these forces express a real aerodynamic force because the glider does not have such a propulsion device as a propeller. The aerodynamic force in the X direction, F_x, acted as acceleration force till 0.06s and then it acted as drag with its negative value and monotonous decrease. At the end of the period, 0.16s, the drag of -7N was loaded on the glider. On the other hand, the side force in the direction of the Y axis, F_y, changed from -5N to 0N, and the side slip motion of the glider as shown in Figs.8 and 11 was brought out by the negative value of the side force.

With regard to F_z , upward force, namely negative value, was slightly increased by 0.05s and then decreased with its oscillation. By the way, the notable point is that the upward force of about 10N was acted on the glider, which is equal to just twice of the glider weight. The reason should be considered that the speed of the glider was rather faster than that of its steady gliding flight. It could be estimated to be about 6m/s. Therefore, the glider would have fallen into its gliding afterward.

The pitching moment about the Y axis, M_y, changes minus to plus values, namely from pitch down to pitch up, at 0.1s as shown in Fig.13(b). Here, taking the longitudinal motion of the glider into consideration, the angle of attack becomes large while the glider goes down. Hence, the glider should have the moment to make pitch down motion on the wing characteristics. Shortly after that, the pitch up motion might occur with the decrease of the effective attack angle, as the glider flies upward. The yawing moment oscillates around 0Nm but the value is small and does not affect the posture of the glider largely. It corresponds to the results of Fig.9(b).



(a) Forces



(b) Moments

Fig.13 The force and the moment acting on the glider in the body coordinate.

Finally, the change of the lift coefficient with an effective angle of the attack during the glider flying, that is C_L-α, is shown in Fig.14.

The C_L decreases from 1.6 to 1.2 between 0.04s and 0.11s with decreasing the attack angle from 14 to 9 degrees, and then the C_L turns to increase up to 1.3 at 0.16s. It is the contrary to the former period, whereas the decrease of the angle of attack continues during the latter period. Decrease of attack angle generally brings low lift at constant speed, namely low C_L, which can be easily understood by tracing the behavior on the C_L-α map for the former period. The reason for the behavior for the latter period could be considered as follows. In the latter period from 0.11s to 0.16s, the glider got the lift which gradually diminished as shown in Fig.13(a). However, the rapid reduction of the speed, the loss of 1m/s during 0.05s as shown in Fig.12, was observed and it should bring the C_L increasing.

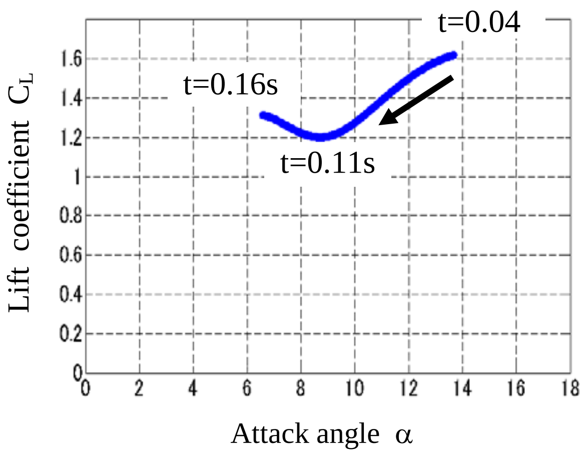


Fig.14 Time history of C_L with angles of attack during the glider flying.

5 Conclusions

New non-intrusive method for aerodynamic force and moment acting on a free flight aircraft was suggested. It is based on a series of video pictures taken by a single video camera. The characteristics of the method are

(1) to be applicable to an arbitrarily shaped aircraft,

(2) not to need a particular gauge for measurement location and posture of an aircraft,

(3) to measure with higher accuracy than the previous study[4] because of making markers widely distributed, which forms large and plural gauges,

(4) to apply such a complicated aircraft motion as a turn.

The method was applied to the free flight glider and the aerodynamic force and moment acting on it could be explained in relation to the translational and the rotational velocities and the posture of the glider. As the result of this application, the proposed method was confirmed to be useful.

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