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AERODYNAMIC MODEL IDENTIFICATION FROM FLIGHT DATA FOR A NOVEL CONCEPT SCALED UAV

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Abstract

In this paper, the Least-Squares (LS) method is used for aerodynamic model identification of a scaled UAV designed for researching the high Mach number aircraft. The LS module is composed of State Matrix, Parameter Measure Vector, Parameter Estimate Vector, and Parameter Estimate Covariance, and so on.

The equation-error method calculates aerodynamic parameter estimates that minimize squared errors between values of the non-dimensional force and moment coefficients determined from measured flight data, and model values computed from the aerodynamic model based wind-tunnel test data.

For conducting the Aerodynamic Model Identification study, the appropriate data are elaborately selected from the whole flight test data based on some rules.

Results presented in the paper show that the identification of lift coefficient derivative about Angle-of-Attack agrees well with the aerodynamic model based on wind-tunnel test data.

1 Introduction

A scaled Unmanned Aerial Vehicle (UAV) was designed and built and is being tested for the development of a low-speed flight test database for a novel aircraft which is fully reusable, designed to take off and land, under its power, from a conventional aircraft runway. The UAV is a full-scale low-speed model of the novel concept of the high Mach number aircraft which may be developed for future cruise vehicles and reusable launch vehicle system. The UAV is a Mach 4 aircraft configuration, for investigation of low-speed performance, handling qualities and approach and landing characteristics as well as validation of flight control laws.

The scaled UAV has completed the initial flight test, recently. The flight test data may provide the foundation of conducting the Aerodynamic Model Identification study.

To extract more valuable information from existing flight test data. The Least-Squares (LS) method is used for estimation of coefficients in an over-determined system of equations by maximizing the compatibility of the flight test data with a set of equations constituting aerodynamic model.

The Equation Error Method (EEM) research based on a set of flight test data obtained from a low-cost instrumentation is described in [1]. Aerodynamic parameters estimation based on flight data from the third flight of the X-43A is presented in [2]. The X-31A's system identification based on specially tailored flight test maneuvers was used to validate the wind tunnel data in [3]. An overview of recent low-speed flight testing of the X-43A-LS UAV was presented in [4]. A real-time, frequency-domain, equation-error parameter identification technique was used to estimate stability and control derivatives from flight data in [5].

The paper is organized as follows: Section 2 explains in detail the configuration and control system of a novel concept Scaled UAV. The method of aerodynamic model identification based on Least-Squares (LS) is presented in Section 3. Section 4 presents the flight test and data evaluation. Section 5 talks about the results and discussion. Section 6 summarizes the conclusions.

2 The Novel Concept Scaled UAV

The UAV is 3.333m long, has a wingspan of 2.445m, weights 103kg (fully fueled) and is powered by two Jetcat-P200 miniature turbojet engine. The UAV's wing has ailerons, trailing-edge chief elevators and secondary elevators control surfaces and both vertical tails incorporate rudder control surfaces. The trailing-edge chief elevators can be deflected from ±25°, while the trailing-edge secondary elevators can only be deflected from ±15° due to the constraint of rudders. Both the ailerons and the rudders can be deflected from ±15°. Conventional pitch control is provided by symmetric deflection of the trailing-edge chief elevators and the secondary elevators according to allocation scale of 1 to 0.5. Roll control uses aileron, while directional control is provided by rudder deflection.

The UAV is constructed of advanced carbon composite skin and internal structure. All structures are designed for a normal load factor of ±2g and an ultimate structural limit of ±3g. The tricycle-type, retractable landing gear were incorporated to facilitate runway takeoff and landing. The wheels and the tires were designed for a taxi-speed of 55m/s. The two main wheels have pneumatically operated drum brakes, while the nose gear is steerable for high-speed and low-speed ground operations.

To meet the requirement of running the complicated fully autonomous flight control laws software, the UAV is specially equipped with a high performance flight control computer which has already been applied to some famous UAVs. A set of air data, inertial, uplink/receiver and GPS/DGPS instrumentation are integrated into the flight control computer. All parameters used in the Aerodynamic Model Identification study are obtained by the above instrumentations and transmitted to the ground control station (GCS).

3 Aerodynamic Model Identification Method

The flight-determined aerodynamic parameters can be used to update the aerodynamic database for improved simulation and dynamic analysis.

3.1 Identification Procedure

These parameters include indicated airspeed V_i, pressure altitude H_p, lateral acceleration a_x, lateral acceleration a_y, vertical acceleration a_z, roll rate p, pitch rate q, yaw rate r, trailing-edge chief/secondary elevators deflection (δ_{ec}, δ_{es}), aileron deflection δ_a, rudder deflection δ_r, and engine RPM.

It is regretful that the UAV has not instrumentation for measuring angle-of-attack α and side-slip angle β, because it is extremely difficult for a lower cost scaled UAV to obtain indicated angles of attack and sideslip from the nose-boom by correcting for boom offset angles, nose-boom bending, angular rates, up-wash and side-wash.

In this paper, the scheme of the SysId-model used for the identification of the aerodynamic parameters is illustrated in Fig.1.

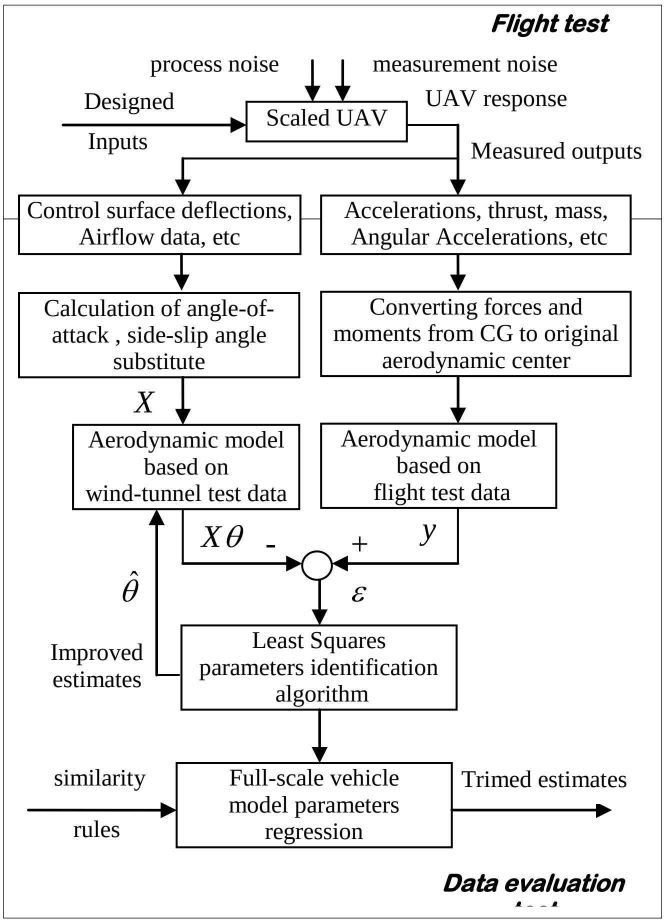

Fig.1 Aerodynamic Parameters Identification Procedure

In Fig.1, the coefficients for drag, lift and side forces as well as for pitching, rolling, and yawing moments are the observation variables to be replicated by the output of the SysId-model. For that, the cg-related forces recalculated from the measured accelerations considering the position of Acceleration Sensor Assembly, and the moments are recalculated from the angular accelerations which are derived from the measured Rate Sensor Assembly signals by means of numerical differentiation. Then, calculated thrust is subtracted, the remaining aerodynamic forces and moments are normalized, and the resulting coefficients are converted from the body-fixed coordinate system to the experimental coordinate system with its origin in the aerodynamic center. All calculations use measured signals with actual UAV mass, inertia, and cg-location depending on calculated fuel quantity.

3.2 The Aerodynamic Equations

In all case, a linear aerodynamic model was adequate to characterize the measured data. For the scaled UAV, the aerodynamic model based on wind-tunnel test data is adopted following equations:

$$C_L = C_{L_0} + C_{L_\alpha}\bar{\alpha} + C_{L_{\delta_a}}\delta_a + C_{L_{\delta_{ce}}}\delta_{ce} + C_{L_{\delta_{se}}}\delta_{se} \quad (1)$$

$$C_D = C_{D_0} + C_{D_\alpha}\bar{\alpha} + C_{D_{\delta_a}}\delta_a + C_{D_{\delta_{ce}}}\delta_{ce} + C_{D_{\delta_{se}}}\delta_{se} \quad (2)$$

$$C_Y = C_{Y_0} + C_{Y_\beta}\bar{\beta} + C_{Y_{\delta_r}}\delta_r \quad (3)$$

$$C_m = C_{m_0} + C_{m_\alpha}\bar{\alpha} + C_{m_q}\frac{q\bar{c}}{2V} + C_{m_{\delta_a}}\delta_a + C_{m_{\delta_{ce}}}\delta_{ce} + C_{m_{\delta_{se}}}\delta_{se} \quad (4)$$

$$C_l = C_{l_0} + C_{l_\beta}\bar{\beta} + C_{l_{\delta_a}}\delta_a + C_{l_{\delta_r}}\delta_r \quad (5)$$

$$C_n = C_{n_0} + C_{n_\beta}\bar{\beta} + C_{n_{\delta_a}}\delta_a + C_{n_{\delta_r}}\delta_r \quad (6)$$

Where all state and control variables are perturbations from a reference condition, define at the beginning of each maneuver. Lift and drag coefficients were used instead of the body-axis x and z components of aerodynamic force, so that the flight results could be compared directly to the values from the pre-flight aerodynamic database, which was based on wind tunnel data with CFD augmentation.

The aerodynamic moment coefficients were modeled at the aerodynamic reference point used for the aerodynamic database, again to facilitate comparisons.

The equation-error method calculates aerodynamic parameter estimates that minimize squared errors between values of the non-dimensional force and moment coefficients determined from measured flight data, and model values computed from equations (1)-(6). For the scaled UAV, the aerodynamic model based on flight test data is expressed as follows:

$$C_X = \frac{ma_x}{q_c S} \quad (7)$$

$$C_Y = \frac{ma_y}{q_c S} \quad (8)$$

$$C_Z = \frac{ma_z}{q_c S} \quad (9)$$

$$C_L = -C_Z\cos\bar{\alpha} + C_X\sin\bar{\alpha} \quad (10)$$

$$C_D = -C_X\cos\bar{\alpha} - C_Z\sin\bar{\alpha} \quad (11)$$

$$C_m = \frac{I_y}{q_c S\bar{c}}\left[\dot{q} + \frac{(I_x - I_z)}{I_y}pr + \frac{I_{xz}}{I_y}(p^2 - r^2)\right] \quad (12)$$

$$C_l = \frac{I_x}{q_c Sb}\left[\dot{p} - \frac{I_{xz}}{I_x}(pq + \dot{r}) + \frac{(I_z - I_y)}{I_x}qr\right] \quad (13)$$

$$C_n = \frac{I_z}{q_c Sb}\left[\dot{r} - \frac{I_{xz}}{I_z}(\dot{p} - qr) + \frac{(I_y - I_x)}{I_z}pq\right] \quad (14)$$

Substituting measured data into the right sides of equations (9)-(14) results in N values of the non-dimensional force and moment coefficients, where N is the number of data points for the maneuver. Using these values and measured states and controls in equations (1)-(6) results in an over-determined set of equations for the unknown aerodynamic parameters, which can be solved with a standard least-squares method.

For the scaled UAV, where $\bar{\alpha}$ is the substitute of the angle-of-attack α and has been obtained by the special converting Calculation from V to α, according to a calibrated relationship curve.

3.3 Least Squares Estimation

In this paper, the Least-Squares (LS) method is used for estimation of coefficients in an over-determined system of equations by maximizing the compatibility of the flight test data with a set of equations constituting aerodynamic model.

If the number of samples for the considered maneuver is N, the LS parameters identification algorithm for lift coefficient can be written in vector notation:

$$y = X\theta + \varepsilon$$

where

$y = \left[C_L(1), C_L(2), \cdots, C_L(N)\right]^T$ is $N \times 1$ vector of values computed from equations (7), (9), and (10)

$\theta = \left[C_{L_0}, C_{L_\alpha}, C_{L_{\delta_a}}, C_{L_{\delta_{ce}}}, C_{L_{\delta_{se}}}\right]^T$ is 5×1 vector of unknown parameters

$X = \left[1, \bar{\alpha}, \delta_a, \delta_{ce}, \delta_{se}\right]$ is $N \times 5$ matrix of vectors of ones and explanatory variables

$\varepsilon = \left[\varepsilon(1), \varepsilon(2), \cdots, \varepsilon(N)\right]^T$ is $N \times 1$ vector of equations errors

The best estimator of θ in a least-squares sense comes from minimizing the sum of squared differences between the measurements and the model,

$$J(\theta) = 0.5(y - X\theta)^T (y - X\theta)$$

The least-squares solution for the unknown parameter vector θ is

$$\hat{\theta} = \left(X^T X\right)^{-1} X^T y$$

The estimated parameter covariance matrix is computed from

$$Cov\left(\hat{\theta}\right) = E\left[\left(\hat{\theta} - \theta\right)\left(\hat{\theta} - \theta\right)^T\right] = \hat{\sigma}^2 \left(X^T X\right)^{-1}$$

$$\hat{\sigma}^2 = \frac{(y - \hat{y})^T (y - \hat{y})}{\left(N - n_p\right)} \qquad \hat{y} = X\hat{\theta}$$

Where the number of unknown parameters n_p is 5 for this example.

4 Parameter Identification Experiments

The scaled UAV has completed the initial flight test, recently. The flight test data may provide the foundation of conducting the Aerodynamic Model Identification study.

4.1 Flight Test and Data Evaluation

To refining performance, stability and control models for controls simulations, and verifying take-off and landing characteristics, Shenyang Aircraft Design and Research Institute (SADRI) has recently completed the initial flight test of a novel aircraft.

Takeoff weight was 103kg with 18kg fuel. The UAV accelerated smoothly upon throttle-up and tracked straight down the runway. The takeoff roll was approximately 500m. Rotation was begun at 52m/s (indicated airspeed), and the UAV continued to accelerate through the climb-out to approximately 64m/s. The initial turn was flown between 64-66m/s, and the UAV was trimmed for level flight between 66-69m/s on the approximately 220m pressure altitude. The entire flight was flown in the gear-down configuration.

The flight was a complete success, demonstrating acceptable flying qualities, verifying systems functionality and procedures.

Total flight time was 7.8 minutes (throttle up to touchdown). There are 1863 lines data recorded during the entire flight time. The following data channels were collected during the flight test.

- Pressure Altitude H_p
- Indicated Airspeed V_i, True Airspeed V_t
- Dynamic Pressure q_c
- Poll, Pitch, Yaw Euler Angles
- Poll, Pitch, Yaw Rates
- Body axis accelerations - a_x, a_y, a_z
- GPS – Lat, Long, Time
- Control Surface Deflections, Aileron δ_a, chief elevator δ_{ce}, secondary elevator δ_{se}, and rudder δ_r
- Engine Parameters – RPM, %Throttle k

But it is forced to accept for us that the UAV has not instrumentation for measuring Angle-of-Attack α and Side-slip-Angle β.

For conducting the Aerodynamic Model Identification study, the 331 lines appropriate data are elaborately selected from the whole 1863 lines data based on some rules which include " $H_p \ge 0m$ ", " $0 \le \alpha \le 4^{\circ}$ " , and "$a_x \ge 2m/s^2$ $a_z \ge 2m/s^2$".

Fig.2 shows the time histories for the Pressure Altitude H_p and the True Airspeed V_t. In Figs. 3-4, the time histories for the Lateral Acceleration a_x and Vertical Acceleration a_z as well as for the Dynamic Pressure q_c and the Engine Parameters – %Throttle k are shown.

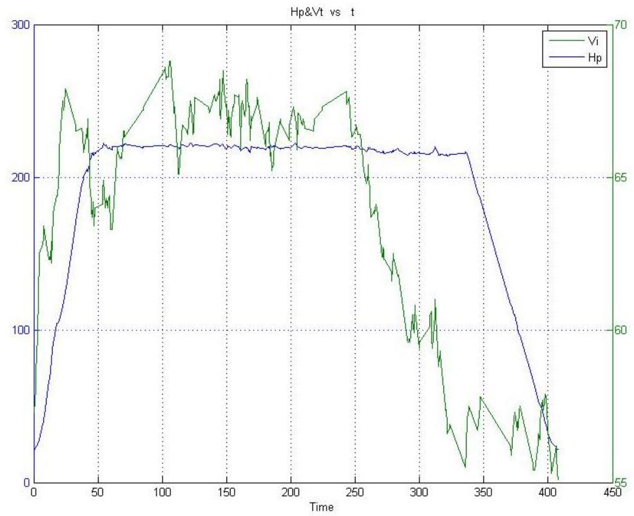

Fig.2 Time History of Pressure Altitude and True Airspeed

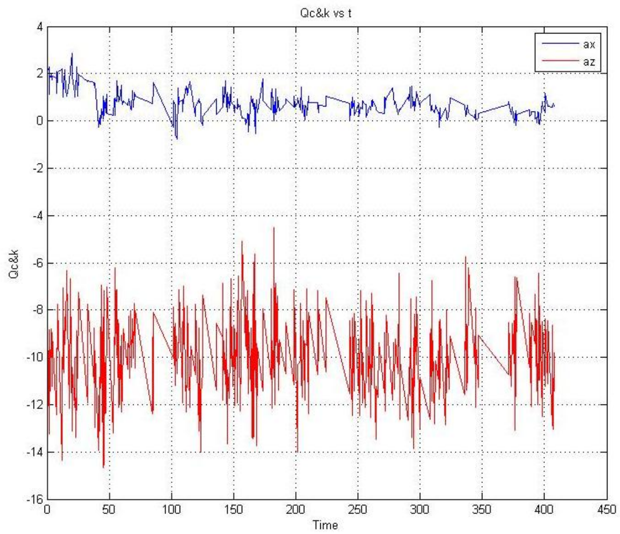

Fig.3 Time History of Lateral Acceleration and Vertical Acceleration

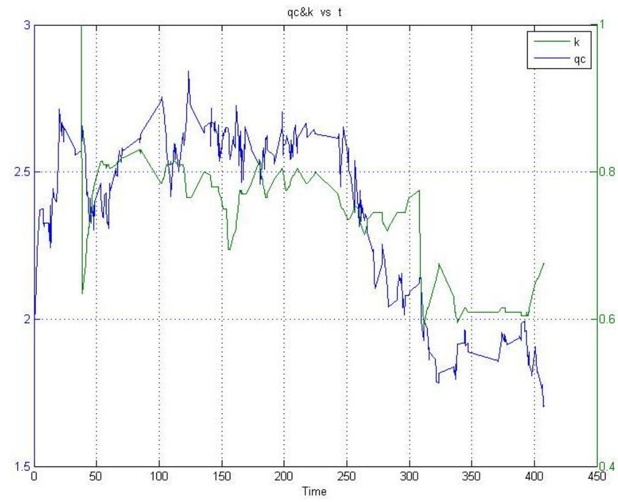

Fig.4 Time History of Dynamic Pressure and %Throttle

4.2 Aerodynamic Parameter Estimation

In this paper, the Aerodynamic Model Identification study is shown based on the Least-Squares (LS) method, the lift coefficient, for example. There are two reasons for selecting the lift coefficient. On the one hand, the lift is so important that it must be firstly estimated for any one aircraft's design. On the other hand, the flight measure parameters asked for lift coefficient identification is relatively less than other parameters such as pitching moment coefficient, and more suitable for a lower cost scaled UAV which is usually limited to equip with those high performance instrumentations.

- *The State Matrix* X

The elements of the state matrix for lift coefficient identification include that angle-of-attack (AoA) α, aileron deflection δ_a, trailing-edge chief elevator deflection δ_{ce}, and trailing-edge secondary elevators deflection δ_{se}.

The control surface deflections of δ_a, δ_{ce}, and δ_{se} can be extracted from the 331 lines flight test data.

However, because the scaled UAV has not the angle-of-attack sensor onboard, a troublesome problem must be solved that the angle-of-attack α can't be obtained from the flight test data.

In this paper, a way has been used to solve the problem of the angle-of-attack measure absenting from the flight test data. The way is that the expression about True Airspeed V_t and Angle-of-Attack (AoA) α, shown in Fig.5, can is got by multinomial fit. The fitting polynomial is obtained by the Least-Squares (LS) method and presented as follows:

$$AoA = -0.0036V_t^3 - 0.2193V_t^2 - 7.2207V_t + 105.63$$

Based on the fitting polynomial obtained above, the element α of the state matrix for lift coefficient identification may be calculated by V_t which can be measured onboard.

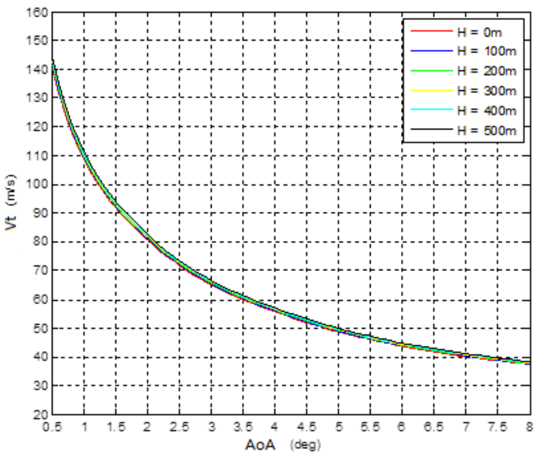

Fig.5 Angle-of-Attack vs. True Airspeed Graph

In this paper, the state matrix X for lift coefficient identification is a 311×5 matrix. Three sections of X are expressed as follows:

$X =$

	1	α	δ_α	δ_{ce}	δ_{se}
1	1	3.9310	1.0300	−7.000	−3.5000
2	1	3.8973	2.6500	−6.9600	−3.4800
3	1	3.7982	1.8700	−7.0400	−3.5200
4	1	3.7338	0.4000	−7.1200	−3.5600
5	1	3.6916	2.3900	−6.2100	−3.1000
⋮	⋮	⋮	⋮	⋮	⋮
211	1	2.9732	0.9700	−6.2300	−3.1100
212	1	3.0076	0.2500	-6.5100	-3.2500
213	1	2.9818	1.3600	-6.3100	-3.1500
214	1	2.9732	1.8500	-6.3100	-3.1500
215	1	2.9818	0.6000	-6.4700	-3.2300
⋮	⋮	⋮	⋮	⋮	⋮
327	1	4.1176	0.8400	-7.2600	-3.6300
328	1	4.0112	1.8300	-6.9100	-3.4500
329	1	4.0463	0.6200	-6.8600	-3.4300
330	1	4.1176	0.5400	-7.3300	-3.6600
331	1	4.1418	0.3400	-7.3900	-3.6900

- *The Parameter Measure Vector* y

In this paper, the lift coefficient based on flight test data is expressed as follows:

$$C_X = \frac{ma_x}{q_c S} \qquad C_Z = \frac{ma_z}{q_c S}$$
$$C_L = -C_Z \cos\bar{\alpha} + C_X \sin\bar{\alpha}$$

For the scaled UAV, the parameters of lateral acceleration a_x, vertical acceleration a_z, and dynamic pressure q_c can be extracted from the 331 lines flight test data. The wing reference area S is $2.205m^2$. The parameter $\bar{\alpha}$ is substituted by the angle-of-attack α obtained above.

The mass of the scaled UAV m have to take into account the fuel consuming amount of turbojet engine, and be updated in real time. The m update method is formulated as follows:

$$m = m_0 - \dot{m}_f \times (t - t_0) \times k \times n_T$$

Where m_0 is the initial mass; $\dot{m}_f$ and k is defined as the fuel consuming rate and the engine throttle percentage k, respectively; t and t_0 is defined as the current time and the initial time, respectively; n_T is the engine number.

In this paper, the Parameter Measure Vector y for lift coefficient identification is a 311×1 vector. Three sections of y are expressed as follows:

$y =$

$$\begin{matrix} 1 & 2 & 3 & 4 & 5 \\ [0.2374 & 0.1864 & 0.2891 & 0.1907 & 0.2546 \end{matrix}$$

$$\begin{matrix} & 211 & 212 & 213 & 214 & 215 \\ \cdots & 0.1945 & 0.1347 & 0.1973 & 0.1598 & 0.2121 \end{matrix}$$

$$\begin{matrix} & 327 & 328 & 329 & 330 & 331 \\ \cdots & 0.2008 & 0.3158 & 0.2096 & 0.3300 & 0.2477]^T \end{matrix}$$

- *The Parameter Estimate Vector* $\hat{\theta}$

In this paper, the least-squares cost function for lift coefficient identification is formulated as follows:

$$J(\theta) = 0.5(y - X\theta)^T (y - X\theta)$$

The parameter vector estimate that minimizes the cost function is formulated as follows:

$$\hat{\theta} = \left(X^T X\right)^{-1} X^T y$$

The parameter estimate vector $\hat{\theta}$ can be calculated by utilizing the State Matrix X and the Parameter Measure Vector y which have been obtained above.

$$\hat{\theta} =$$
$$[-0.0408 \quad 0.0521 \quad 0.0026 \quad -0.4641 \quad 0.9105]^T$$

- *The Parameter Estimate Covariance*

The estimated parameter covariance matrix is formulated as follows:

$$Cov\left(\hat{\theta}\right) = E\left[\left(\hat{\theta} - \theta\right)\left(\hat{\theta} - \theta\right)^T\right] = \hat{\sigma}^2 \left(X^T X\right)^{-1}$$

$$\hat{\sigma}^2 = \frac{(y - \hat{y})^T (y - \hat{y})}{\left(N - n_p\right)} \qquad \hat{y} = X\hat{\theta}$$

Where N in this case is the number of elements in the vector y and n_p is the number of elements in the vector $\hat{\theta}$. The parameter standard errors $\hat{\sigma}$ are calculated by taking the square root of the diagonal of the covariance matrix.

$$\hat{\sigma}^2 = 0.0015$$
$$Cov\left(\hat{\theta}\right) =$$

$$\begin{bmatrix} 0.0009 & 0 & 0 & 0.0025 & -0.0048 \\ 0 & 0.0001 & 0 & 0.0001 & -0.0001 \\ 0 & 0 & 0 & 0 & 0 \\ 0.0025 & 0.0001 & 0 & 0.1817 & -0.3628 \\ -0.0048 & -0.0001 & 0 & -0.3628 & 0.7246 \end{bmatrix}$$

Finally, it is need that converting the estimation of aerodynamic coefficients from the scaled UAV to the full-scale vehicle according to the pro-designed scaling similarity rules.

5 Results and Discussion

The results of compare the lift coefficients extracted from flight test data with that based on wind-tunnel test data are shown in Table.1.

Table 1 Comparing Result of lift coefficients

	wind-tunnel test data	flight test data identification	deviation percentage
C_{L_0}	0	-0.0408	——
C_{L_α}	0.0575	0.0521	-9.33 %
$C_{L_{\delta_a}}$	0.0080	0.0026	-67.54 %
$C_{L_{\delta_{ce}}}$	0.0076	-0.4641	-6205.93 %
$C_{L_{\delta_{se}}}$	0.0074	0.9105	12204.46 %

Table1 shows that the identification deviation of the derivative C_{L_α} is less than 10 % and agrees well with the aerodynamic model based on wind-tunnel test data. It is lucky for us to get a good identification of C_{L_α} because C_{L_α} is more important than four other derivatives (C_{L_0} , $C_{L_{\delta_a}}$, $C_{L_{\delta_{ce}}}$, and $C_{L_{\delta_{se}}}$). The identification deviation of the derivative $C_{L_{\delta_a}}$ is less than 70 % and can still be tolerated for designing the conceptual aircraft.

However, the identification deviation of two derivatives ($C_{L_{\delta_{ce}}}$ and $C_{L_{\delta_{se}}}$) is too large to accept for checking the aerodynamic model based on wind-tunnel test data. The reason for the large identification deviation above, may involve several facts:

- The angle-of-attack α is obtained by calculation rather than measure. The error is inevitable and is difficult to compensate;
- Control surface deflections (aileron δ_a, chief elevator δ_{ce}, and secondary elevator δ_{se}) is obtained by estimate rather than measure. The error may be large due to several disadvantageous factors about control surface driving mechanism such as transfer motion gap, flexible deformation, and actuating motor zero deviation, and so on ;
- There are not specially tailored maneuvers in entire flight test so that body axis accelerations (a_x, a_z) are not large enough to achieve aerodynamic model identification.
- For a lower cost, the scaled UAV have to be usually equipped with low-grade instrumentation such as inertia measure units and pressure sensors, so that it is not practical to ensure high precision accuracy of the flight test data.

In an actual flight test, the history of the elevator deflection is presented in Fig.6.

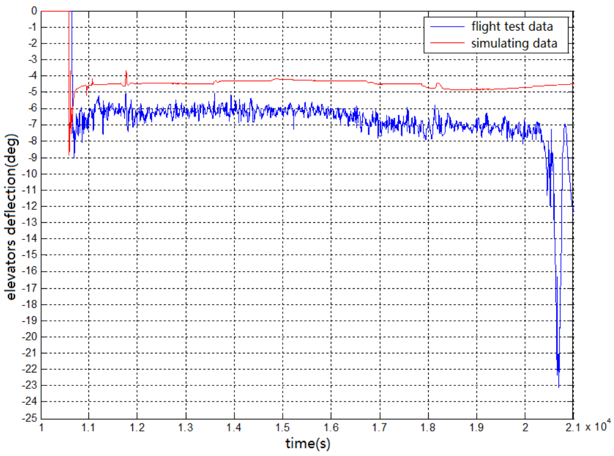

Fig.6 Time history of the elevators deflection

The flight control simulating data based on wind-tunnel model has been compared to the relative parameter measured from flight test data.

Figure 6 show an encouraging evidence: the identification result that the estimated parameter C_{L_α} is less than the coefficients based on wind-tunnel data coincides with the flight test fact that the actual elevator deflection is larger than the pro-designed simulating input.

6 Conclusions

In this paper, the UAV is a full-scale low-speed model of the novel concept of the high Mach number aircraft. The flight test of the scaled UAV is conducted for investigation of low-speed performance rather than identification of aerodynamic model. Therefore, there are not specially tailored maneuvers in entire flight test so that body axis accelerations (a_x, a_z) are not large enough to achieve aerodynamic model identification. In other words, the flight test data is inappropriate to needs of aerodynamic model identification, in fact. The study of the lift coefficients identification is only an attempt to extract more valuable information from existing flight test data. However, to us, it is lucky that the identification of derivative C_{L_α} agrees well with the aerodynamic model based on wind-tunnel test data.

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