DOI: 10.13009/EUCASS2025-375
11TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

Aerodynamic Parameter Estimation and Validation of a JET-Powered UAV From Real Flight Test Data

Büşra Özvarinli, Buğra Umay*, Dilber Büşra Yıldırım*, Haluk Altay*, Mert Işıldar†*
** Turkish Aerospace Industries, Inc.*
Teknopark Istanbul, 34912, Istanbul, Turkiye Tel.: + 0850 755 70 00
†Advanced Control and Systems Engineering, University of Sheffield, United Kingdom
busra.ozvarinli1@tai.com.tr, bugra.umay@tai.com.tr, dilberbusra.yildirim@tai.com.tr,
haluk.altay@tai.com.tr, misildar1@sheffield.ac.uk

Abstract

Aircraft system identification involves determining mathematical model that describe the system's dynamics using the relationship between inputs to control surfaces and outputs of flight measurements. This process provides aircraft's validated aerodynamics model. The methodology used in this research is based on Ravindra V. Jategaonkar's Quad-M stages. It includes designing optimum inputs for control surfaces to excite dynamic modes of the aircraft, executing flight tests with these inputs, establishing aerodynamics parameters' structure and iteratively estimating the aerodynamic coefficients from flight data using the least squares method and output error method algorithm to ensure consistency with flight data.

1. Introduction

System identification is the process of determining the mathematical model that describes a system in which inputs and outputs are available. In the aircraft-specific system identification study, inputs designed to find the coefficients of the aerodynamic model are given to the control surfaces to stimulate the dynamic motion of the aircraft. Aerodynamic coefficients are found by system identification algorithms by checking the kinematic consistency of measured and calculated flight data. This process is used in aircraft development processes, in the study of aircraft performance and characteristics, generation of highly accurate aerodynamic data sets, verification of predictions made by numerical and analytical methods, and development of flight control algorithms [1].

System identification provides mathematical modeling of experimental data. The process involves the following basic assumptions [1]:

1. The dynamic system is deterministic. The results do not involve randomness. The deterministic model will always give the same result for the same initial values.
2. The physical laws that make up a dynamic system can be modeled. The system can be described mathematically.
3. Specific experiments can be performed. Appropriate maneuver design can be done to reveal the different modes of dynamic motion.
4. Measurement or calculation of the inputs and outputs of the system is available.

This research is based on the DEHA unmanned aerial vehicle given in Fig. 1. Detailed experimental verification of simulation model and specification of the vehicle is given in Reference [2].

Fig. 1. DEHA Unmanned Aerial Vehicle

DOI: 10.13009/EUCASS2025-375

2. Methodology

The methodology used in this system identification study is based on the book "Flight Vehicle System Identification: A Time-Domain Methodology" by Ravindra V. Jategaonkar[1]. The parameter estimation algorithm used in this research includes the code mentioned in this book.

There are four important stages in a system identification study, referred to as Quad-M [1].

- Maneuvers: should be performed with input designs that stimulate the dynamics of the aircraft.
- Measurements: The selection of test equipment and filters is important for high accuracy data measurement.
- Methods: The most appropriate time domain or frequency domain system identification method should be selected.
- Model: The structure of the mathematical model should be determined according to the type of aircraft to be identified.

With the system identification study, it is aimed to determine the aerodynamic coefficients of the aircraft from the flight data using the input-output relationship. In order to stimulate the oscillatory motion of the aircraft in the desired direction, the optimal input design for the control surfaces is made by looking at the energy (power) spectrum of the input signal. Angle of attack and sideslip angle must be swept as a range by designed inputs to identify the aircraft. Information that is not in the flight data cannot be identified [1]. Maneuvers are performed with the inputs determined for the flight envelope in which the aircraft will be identified. The correct transfer of the desired maneuver input to the aircraft is ensured by performing the maneuver autonomously.

Data acquisition from maneuvers is important for the accuracy of the result, as the system identification process depends on the flight data which includes input and output for the study [4]. The resolution of the data should be increased by using high accuracy measuring instruments. The data obtained should be used considering the sensor locations and where it is calculated relative to. For example, for the coefficients to be calculated from the aerodynamic center, the flight data processed according to the center of gravity should be converted to be from the aerodynamic center. For maneuvers with data loss, those maneuvers should not be used to define the system since the behavior of the aircraft is not reflected in the data. The data should be organized considering that the input signals given to the aircraft are not the same as the input experienced by the aircraft in the air. For data that cannot be measured in flight but derived from physical phenomenon, the quality of the data depends on the model used.

The aerodynamic coefficients are determined iteratively using the least squares method. The number of aerodynamic coefficients should not be more than necessary to describe the aircraft. By adding and subtracting aerodynamic coefficients from the mathematical formula of base force and moment coefficients, one can see how the model's response is affected by the statistical results of the newly found parameters. In dutch roll and bank to bank maneuvers, for the coefficients affected by the other maneuver, a different maneuver is fed, keeping the coefficients constant. Thus, the values of the affected parameters are found. In the coefficient comparison with the computational fluid dynamic analyses, aerodynamic terminology is considered so that comparison is consistent. For example, for moment coefficients, the position where the moment is calculated, for force coefficients, the positive direction, and for control surfaces, the signs of their deflections should be checked.

The conformity of all coefficient values found from the least squares algorithm, to the equations of motion of the aircraft is checked using the output error method algorithm. Iteratively, considering the effect of the coefficient on the motion of the airplane, the coefficients are re-found by the algorithm and the mathematical model is brought closer to the flight data.

Finally, the aerodynamic coefficients found by system identification are integrated into the existing Simulink mathematical model, the flight and model data are compared and, if necessary, the parameters are tuned to fit the model.

3. Input Design

During the aerodynamic model validation and system identification flight tests of DEHA UAV, 18 maneuvers were performed. Maneuver inputs are designed for excitation of the aircraft's dynamic mode to gather information about aircraft's aerodynamic characteristic. For dutch roll maneuvers: 1-2-1 rudder, for bank-to-bank maneuvers: 1-2-1 aileron, for short period maneuvers: 3-2-1-1 elevator deflection input are used for stimulating directional, lateral and longitudinal direction respectively. Since the frequency band triggered by these inputs is wider than the target frequency range and the energy density of the target frequency range is lower, in addition to standard input signals, modified 3-2-1-1 and multisine input are designed. Multisine input and it's energy spectrum is given in Fig. 2. These inputs are applied to control surfaces autonomously by sending inputs to UAV from ground control station.

DOI: 10.13009/EUCASS2025-375

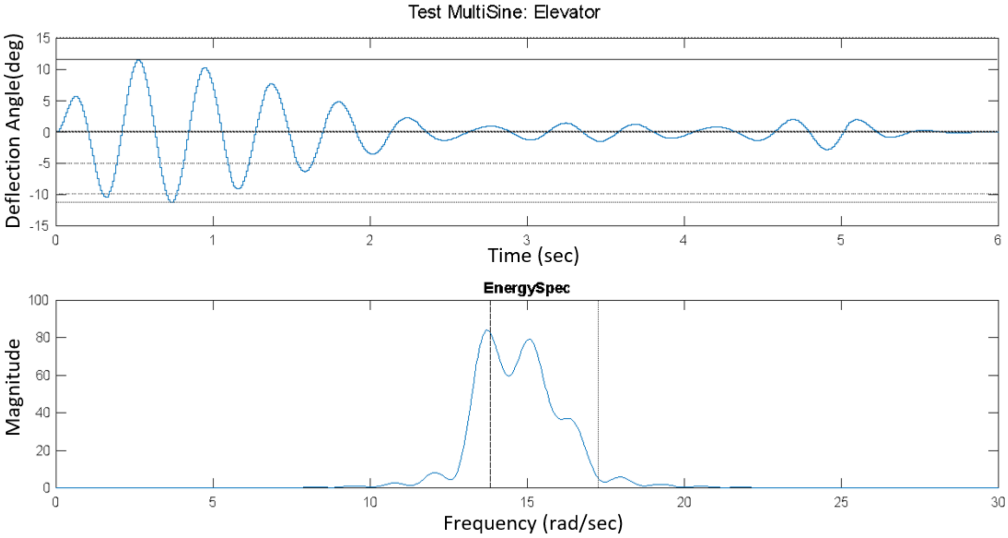

Fig. 2. Multisine maneuver energy spectrum

4. Flight Tests and Data Gathering

Body axis system is used with the origin at the center of gravity of the aircraft. The x axis is taken as positive towards the nose, the y axis towards the right wing and the z axis towards the ground. The right-hand rule applies to the sign of the control surface deflections and angular rates. Aileron is positive when right wing trailing edge down, left wing trailing edge up position, which creates negative yawing moment. Elevator is positive when trailing edge down, which causes negative pitching moment by lift force from horizontal tail. Rudder is positive when the leading edge deflected to the left of the plane, causing a negative yawing moment. Angle of attack and sideslip angle are defined between the centerline of the aircraft and the wind direction.

The PX4 software running on the flight control computer records the sensor outputs with different sampling rates. Since the algorithms are suitable for a single time interval, all data is sampled at 40 Hz with linear interpolation.

Angle of attack and angle of sideslip are derived from flight data using the 2-state extended Kalman filter method (EKF) using Reference [3], since DEHA aircraft does not have an angle of attack sensor. EKF consists of two stages. In the first 'prediction' stage, states are calculated using the dynamic model. In the second 'correction' stage the first predicted values are corrected with the 'observation' model. Estimation phase formulas are as follows [3]:

$$\dot{\alpha} = q + \frac{1}{V.\cos\beta}(g.\cos\varphi.\cos\theta.\cos\alpha + g.\sin\theta.\sin\alpha - a_x.\sin\alpha + a_z.\cos\alpha) - (p.\cos\alpha + r.\sin\alpha).\tan\beta \tag{1}$$

$$\dot{\beta} = \frac{1}{V}\left[-a_x.\cos\alpha.\sin\beta + a_y.\cos\beta - a_z.\sin\alpha.\sin\beta + g(\sin\theta.\cos\alpha.\sin\beta + \cos\theta.\sin\varphi.\cos\beta - \cos\theta.\cos\varphi.\sin\alpha.\sin\beta)\right] + p.\sin\alpha - r.\cos\alpha \tag{2}$$

The correction part of the EKF uses lift and lateral force equations.

$$L = C_L\, q\, S \tag{3}$$

$$C_{L_0} + C_{L_\alpha}.\alpha + C_{L_{\delta elevator}}.\delta elevator + C_{L_{\delta flap}}.\delta flap + C_{L_{\delta rudder}}.\delta rudder + C_{L_{\delta aileron}}.\delta aileron + \frac{C_{L_q}.q.c}{2V} = \frac{m(a_x\ .\sin\alpha - a_z\ .\cos\alpha) - T.\sin\alpha}{q.S} \tag{4}$$

$$Y\ = m.a_y \tag{5}$$

$$Y = C_Y\,.q.S \tag{6}$$

$$m.a_y = (C_{Y_0} + C_{Y_\beta}.\beta + C_{Y_{\delta elevator}}.\delta elevator + C_{Y_{\delta flap}}.\delta flap + C_{Y_{\delta aileron}}.\delta aileron + C_{Y_{\delta rudder}}.\delta rudder + \frac{C_{Y_p}.p.b}{2V} + \frac{C_{Y_r}.r.b}{2V}).q.S \tag{7}$$

DOI: 10.13009/EUCASS2025-375

Engine thrust and aircraft mass cannot be obtained from the flight sensors. For these values, the engine model was isolated from the open loop model of DEHA. Flight throttle and altitude is used to get throttle output. For aircraft mass during maneuver, all flight data is fed into the fuel consumption model to find the consumed and remaining fuel weight of the airplane throughout the flight. By subtracting the fuel consumed from the take-off weight of the aircraft, the weight of the aircraft during the maneuver is obtained.

5. Least Squares Method

The least squares method fundamentally aims to reduce the overall discrepancy between measured data and model predictions by minimizing the squared errors accumulated across all data points. The performance of the method depends on the quality of the data used [1]. Estimated parameters are applicable to flight region which it is found from. Equations of least squares method is given in reference [1] elaborately.

θ represents unknown parameters, for aerodynamic system identification sense it is moment and force coefficients of aircraft. These stability and control derivatives cannot be measured directly and instead can be found by estimation. Y value is total force and moment coefficient. X values are independent variables which stability and control derivatives are created with respect to them such as angle of attack, roll, pitch, yaw rates and deflections. ε is the error due to inadequacy in modeling and noise in the measurement. The aim is to find the unknown aerodynamic coefficients that will minimize the sum of the squares of these errors between the flight data and mathematical formulation. The objective function (cost function) to be minimized is shown below [6].

$$J(\theta) = \frac{1}{2}\sum_{k=1}^{N} \varepsilon^{2}(k) = \frac{1}{2}\varepsilon^{T}\varepsilon \tag{8}$$
$$\varepsilon = Y - X\theta$$

Aerodynamic force and moment coefficients, which cannot be obtained directly from flight data, are calculated using linear acceleration and angular velocity measurement values. When the aircraft is considered as a point mass, the resulting aerodynamic forces and moments act from the center of gravity. The aerodynamic forces on the body axis can be calculated by,

$$\begin{aligned} C_X &= \frac{ma_x^{CG} - F_{eng}\cos\sigma_{eng}}{\bar{q}S} \\ C_Y &= \frac{ma_x^{CG}}{\bar{q}S} \\ C_Z &= \frac{ma_x^{CG} + F_{eng}\sin\sigma_{eng}}{\bar{q}S} \end{aligned} \tag{9}$$

In the formula, m is the mass of the aircraft, F_{eng} is the total thrust, σ_{eng} is the angle of the engines relative to the fuselage axis, $\underline{q}$ is the dynamic pressure, S is the reference wing surface area.

In the calculation of the three moment coefficients, the angular accelerations are not measured directly but are obtained by numerical derivation of the angular velocities. The moment coefficients in the body axis are found as follows.

$$\begin{aligned} C_l^{CG} &= [I_X\dot{p} - I_{XZ}\dot{r} - I_{XZ}pq - (I_Y - I_Z)qr - \Delta F_{eng}\sin\sigma_{eng}y_{ENCG}]\,/(\bar{q}Sb) \\ C_m^{CG} &= \left[I_Y\dot{q} + I_{XZ}(p^2 - r^2) - (I_Z - I_X)pr - F_{eng}\cos\sigma_{eng}Z_{ENCG} - F_{eng}\sin\sigma_{eng}X_{ENCG}\right]/(\bar{q}Sl) \\ C_n^{CG} &= \left[I_Z\dot{r} - I_{XZ}\dot{p} + I_{XZ}qr - (I_X - I_Y)pg - \Delta F_{eng}\cos\sigma_{eng}Y_{ENCG}\right]/(\bar{q}Sb) \end{aligned} \tag{10}$$

Where $I_X,\ I_Y,\ I_Z,\ I_{XZ}$ is the moments of inertia, $\Delta\ Feng$ is the thrust difference between the two engines (left-right), $xENCG$, $yENCG$, $zENCG$ is the position of the engine relative to the center of mass and l and b are the reference lengths.

DOI: 10.13009/EUCASS2025-375

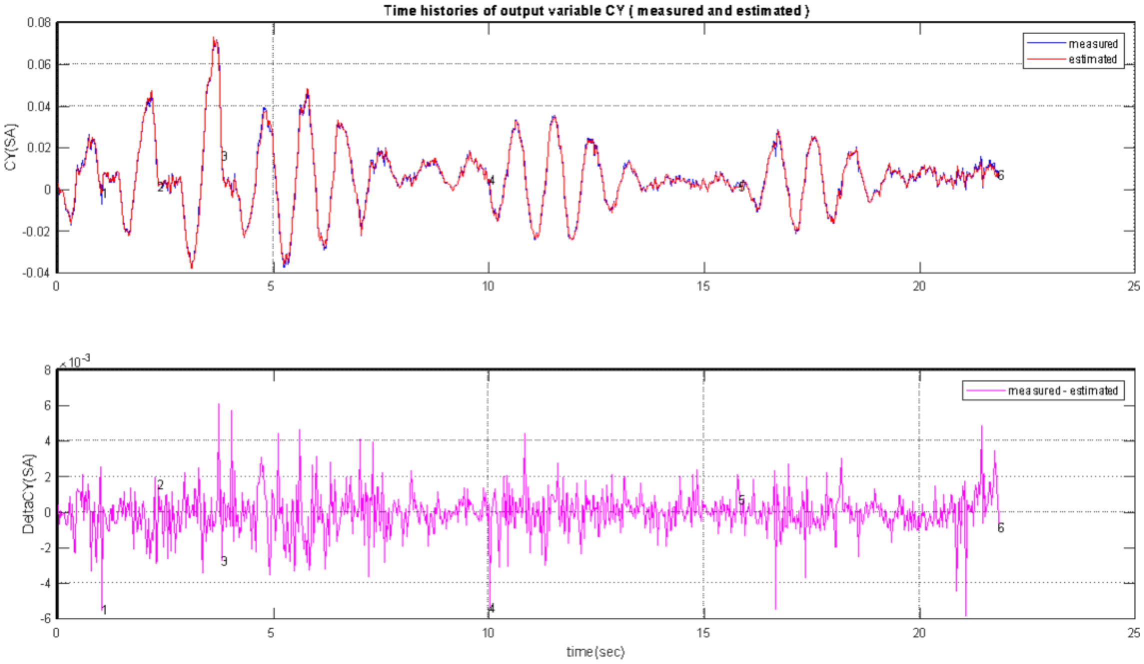

Fig. 3. Time Histories of Measured and Estimated Side Force Coefficient

The main aerodynamic moment and force coefficients are formulated with coefficient values in accordance with the parameters affecting them. These coefficent values come from the dynamics of the aircraft and are defined differently depending on the characteristics of the aircraft. When estimating the parameters affecting the maneuver, equations are derived by trying different coefficients. The aerodynamic moment and force mathematical model of the DEHA aircraft are calculated as follows.

$$\begin{gathered}
C_X = C_{X_0} + C_{X_\alpha}\alpha + C_{X_{\alpha^2}}\alpha^2 + C_{X\delta_e}\delta_e + C_{X_q}q_n + C_{X_{q^2}}{q_n}^2 \\
C_Z = C_{Z_0} + C_{Z_\alpha}\alpha + C_{Z\delta_e}\delta_e + C_{Z_q}q_n \\
C_m = C_{m_0} + C_{m_\alpha}\alpha + C_{m_{\delta_e}}\delta_e + C_{m_q}q_n \\
C_Y = C_{Y_0} + C_{Y_\beta}\beta + C_{Y_{\delta_r}}\delta_r + C_{Y_p}p_n + C_{Y_r}r_n \\
C_r = C_{r_0} + C_{r_\beta}\beta + C_{r_{\delta_r}}\delta_r + C_{r_{\delta_a}}\delta_a + C_r p_n + C_{r_r}r_n \\
C_n = C_{n_0} + C_{n_\beta}\beta + C_{n_{\delta_r}}\delta_r + C_{n_{\delta_a}}\delta_a + C_{n_p}p_n + C_{n_r}r_n
\end{gathered} \tag{11}$$

The coefficent values on the right hand side of the equation are the parameters to be found. The angular velocity values in the formula are normalized by the reference length and the actual airspeed to ensure dimensionless.

$$p_n = \frac{pb}{2V};\ q_n = \frac{ql}{2V};\ r_n = \frac{rb}{2V} \tag{12}$$

Fig. 3. compares the time history of flight measured(blue) versus system identification estimated(red) lateral force coefficient during six dutch roll maneuver including three 1-2-1 and three multisine input applied to rudder control surface. Below graph shows the difference between measured and estimated values. Figure show high level of overlap.

6. Output Error Method

The output error method, a type of response curve fitting method, uses physics formulation describing the dynamic system for predicting model. For application in aircraft system, natural formulation of physics includes equations of motion of aircraft to be modelled in OEM method [5]. In this method, aerodynamic coefficients creating the model are iteratively modified to minimize the error between measured flight data and the model prediction. OEM is the most widely used time-domain method for aircraft parameter estimation [1]. In this method, six-degree-of-freedom aircraft

DOI: 10.13009/EUCASS2025-375

equations of motion are used with maximum likelihood estimation to find aerodynamic parameters in a way that minimizes the error between the output equation and the measured values.

Coefficient values for the three moment and three force values previously found by least squares method are loaded into the code used, and the OEM model output and flight data for longitudinal and lateral maneuvers are compared separately. The graphs are analysed and the coefficient values that cause the phase, amplitude, trend difference and shift values in the data are found by the algorithm by keeping the other parameters constant. The found parameter values are optimized according to the equations of motion of the aircraft. Along with the system parameters, time delays and deviations in the control surfaces are also found with the algorithm, and initial values can also be assigned. Different parameters are found iteratively through maneuvers to ensure that the aerodynamic coefficients are in accordance with the equations of motion. The comparison of the dutch roll and bank to bank maneuvers with the flight is given in the Fig. 4.

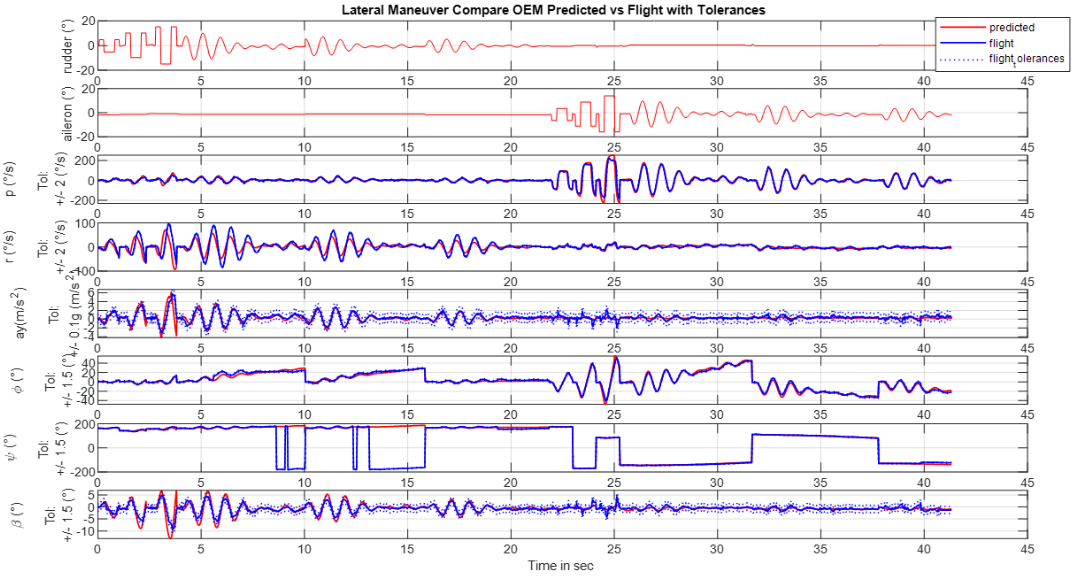

Fig. 4. Dutch roll and bank to bank maneuver OEM predicted vs flight compare

The coefficients found with the output error method are given in the table one and table two below. Calculations are made in radians.

7. Validation with CFD Database

The coefficient values found as a result of the system identification study are compared with the CFD database within DEHA open loop model.

Fig. 5. compares flight measured data, DEHA open loop model with CFD database and model with system identification coefficients by showing values of euler angles, angular rates, angle of attack, angle of sideslip, true airspeed, above ground level altitude and density. Tolerances have been added to assess the model's proximity to flight. Angle of attack, sideslip and euler angles are selected to have a tolerance of 1.5 degrees, pitch 1.5 degrees/s, yaw and roll rate 2 degrees/s.

DOI: 10.13009/EUCASS2025-375

Table 1. Longitudinal coefficients

Postulate	Parameter
C_{X_0}	-0.04527
C_{X_α}	0.058195
$C_{X_{\alpha^2}}$	3.320548
$C_{X\delta_e}$	0.021564
C_{X_q}	-0.01146
$C_{X_{q^2}}$	-534.909
C_{Z_0}	0.090478
C_{Z_α}	-4.34711
$C_{Z\delta_e}$	-0.03035
C_{Z_q}	-10.694
C_{m_0}	-0.01725
C_{m_α}	-0.30884
$C_{m_{\delta_e}}$	-0.43756
C_{m_q}	-3.99295

Table 2. Lateral and directional coefficients

Postulate	Parameter
C_{Y_0}	0.000163
C_{Y_β}	-0.43911
$C_{Y_{\delta_r}}$	0.042618
C_{Y_p}	-0.03659
C_{Y_r}	0.094119
C_{r_0}	0.001531
C_{r_β}	-0.03489
$C_{r_{\delta_r}}$	0.013466
$C_{r_{\delta_a}}$	-0.07284
C_{r_p}	-0.16997
C_{r_r}	0.0383
C_{n_0}	0.002118
C_{n_β}	0.085654
$C_{n_{\delta_r}}$	-0.04288
$C_{n_{\delta_a}}$	-0.02131
C_{n_p}	-0.03437
C_{n_r}	-0.42103

Tolerances have been added to assess the model's proximity to flight. Angle of attack, sideslip and euler angles are selected to have a tolerance of 1.5 degrees, pitch 1.5 degrees/s, yaw and roll rate 2 degrees/s.

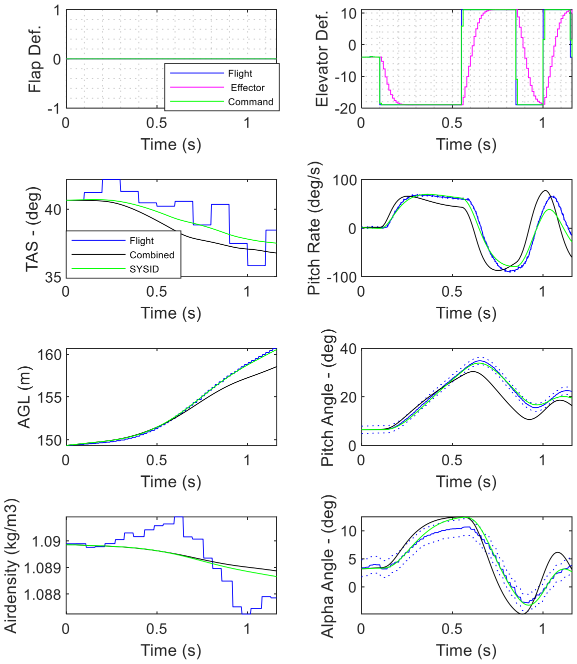

Fig. 5. Validation of short period 3-2-1-1 maneuver

8. Conclusion

This study describes the aerodynamic coefficient determination process of the DEHA aircraft using the system identification flights performed in March 2024. First of all, it is mentioned how the system identification study will be

DOI: 10.13009/EUCASS2025-375

performed and what processes it includes. In order to identify the aircraft in the desired flight condition, the control inputs are designed to excite the dynamic modes of the aircraft. Short period maneuver was performed to obtain longitudinal coefficients, dutch roll and bank to bank maneuver were performed to obtain lateral coefficients. Multisine, 3-2-1-1, modified 3-2-1-1 and 1-2-1 control surface inputs were used in the maneuvers. The data obtained as a result of the maneuvers were taken according to the maneuver times and the data set was created by resampling to be used in the algorithm. An estimation algorithm based on the Kalman filter was used for the angle of attack and sideslip angle, and an engine model isolated from the DEHA open loop model was used for estimating thrust and aircraft weight values.

In the next step, the Least squares method was utilized to estimate the aircraft's aerodynamic coefficients by using the relationship between control surface inputs to their corresponding flight outputs. To estimate the aerodynamic coefficients within the mathematical equation describing the aircraft's aerodynamic behaviour, the graphs of the aerodynamic force and moment coefficients calculated using the linear acceleration and angular velocity values were analyzed and coefficients were determined. It is seen that the coefficients of aerodynamic forces (CX, CZ) and moment (CM) effective on the longitudinal axis depend on the variables α, q, δe; the coefficients of aerodynamic forces (CY) and moment (CN, CR) effective on the lateral axis depend on the variables β, p, r, δa, δr. The compatibility of the aerodynamic coefficients obtained by the least squares method with the equations of motion of the airplane was examined using the output error method. Considering the effect of the coefficients on the mathematical model of aircraft's aerodynamic characteristic, parameter estimation is done with algorithm and the model response is ensured to approximate the flight data.

In the final stage, the aerodynamic coefficients were compared with the flight data and the existing aerodynamic model within the DEHA open loop model. It is seen that the longitudinal parameters coincide with the flight data, while the lateral parameters have an amplitude difference with the flight data. It can be concluded that in the rudder and elevator maneuvers, the coefficients in the system identification follow the trend and give better results than the CFD database, while in the aileron maneuver, the CFD database gives better results. Consequently, by using estimated aircraft aerodynamic coefficients based on this method, high fidelity aerodynamic model was obtained and validated from real flight data.

Acknowledgements

The authors extend their sincere gratitude to their esteemed colleagues from the Flight Mechanics and Control team for their invaluable support throughout this study. Special thanks are also directed to Turkish Aerospace Industries for their instrumental role in enabling this research.

References

[1] Jategaonkar, R. V. 2015. *Flight Vehicle System Identification: A Time-Domain Methodology*. Reston, Virginia: AIAA.

[2] Altay, H., and F. Caliskan. 2022. Experimental verification of a simulation model for jet UAV with model-based design. In: *8th International Conference on Control, Decision and Information Technologies*, Istanbul, Türkiye, May 2022. 419–424.

[3] Tian, P., and H. Chao. 2018. Model aided estimation of angle of attack, sideslip angle, and 3D wind without flow angle measurements. In: *AIAA Guidance, Navigation, and Control Conference*, Kissimmee, Florida, 8–12 January 2018.

[4] Millidere, M. 2021. Optimal input design and system identification for an agile aircraft. Ph.D. Thesis, Middle East Technical University.

[5] Klein, V., and Morelli, E. A. 2006b. Aircraft system identification: Theory and practice. In American Institute of Aeronautics and Astronautics eBooks. https://doi.org/10.2514/4.861505

[6] Hamel, P. G., and Jategaonkar, R. V. 1996. Evolution of flight vehicle system identification. Journal of Aircraft, 33(1), 9–28. https://doi.org/10.2514/3.46898