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Quasi Steady Stall Modelling of Aircraft Using Least-Square Method

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Abstract

Quasi steady stall is a phenomenon to characterize the aerodynamic behavior of aircraft at high angle of attack region. Generally, it is exercised from a steady state level flight to stall and its recovery to the initial flight in a calm weather. For a theoretical study, such maneuver is demonstrated in the form of aerodynamic model which consists of aircraft's stability and control derivatives. The current research paper is focused on the appropriate selection of aerodynamic model for the maneuver and estimation of the unknown model coefficients using least-square method. The statistical accuracy of the estimated parameters is presented in terms of standard deviations. Finally, the validation has been presented by comparing the measured data to the simulated data from different models.

Key Words: Quasi-Steady Stall, Aerodynamic Modeling, Parameter Estimation, Least-Square Method.

Nomenclature

V, W	Linear velocity (m/s) and angular velocity of aircraft (rad/s), respectively.
$\alpha, \mathrm{p}, \mathrm{q}, \mathrm{r}, \delta_{\mathrm{e}}$	Angle of attack (rad), roll rate (rad/s), pitch rate (rad/s), yaw rate (rad/s) and Control surface elevator deflection (rad) of aircraft, respectively.
M, I	Mass (kg), and moment of inertia of aircraft (kg-m^2), respectively.
C_D, C_L, C_m	Coefficients of drag, lift and pitching moment, respectively.
$C_{D_0}, C_{D_a}, C_{D_{d_e}}, C_{D_{a^2}}, C_{D_{d_e^2}}$	Non-dimensional coefficients of drag.
$C_{D_q}, C_{D_{q^2}}$	Dimensional coefficients of drag.
$C_{L_0}, C_{L_a}, C_{L_{d_e}}, C_{L_{a^2}}, C_{L_{d_e^2}}$	Non-dimensional coefficients of lift.
$C_{L_q}, C_{L_{q^2}}$	Dimensional coefficients of lift.
$C_{m_0}, C_{m_a}, C_{m_{d_e}}, C_{m_{a^2}}, C_{m_{d_e^2}}$	Non-dimensional coefficients of pitching moment.
$C_{m_q}, C_{m_{q^2}}$	Dimensional coefficients of pitching moment.
$\overline{c}, S, \overline{q}$	Mean aerodynamic chord (m), reference area (m^2), dynamic pressure (N/m^2), respectively.
$I_{xx}, I_{yy}, I_{zz}, I_{xz}$	Moment of inertia of aircraft along x-x, y-y, z-z axes, and x-z plane, respectively.
F_T, Z_{enCG}	Total thrust of engine (N), vertical distance of engine to the centre of gravity (CG) location of aircraft (m), respectively.

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1. Introduction

Aerodynamic forces and moments play a vital role in the operation of aircraft. They are variables in nature which depend on the current motion and control variables of aircraft such as angle of attack, side slip angle, true air speed, attitude angles, angular rates, control surface deflections, altitude, ambient pressure etc[1]. They are usually expressed as an aerodynamic model which is defined for each of the operating conditions of the flight envelope represented as a graph between altitude and flight speed. The operating point of the flight envelope demonstrates the operational flight phases of aircraft such as take-off, climb, cruise, descend and approach. These flight phases are a combination of such maneuvers which are used for flight testing and validation of the aircraft. Usually, the flight testing is conducted for the certification of aircraft where longitudinal and lateral-directional modes are excited in their linear or non-linear operational regions by using suitable control surface deflections and/or engine throttle settings[2,3]. These regions are also categorized as small and large amplitude maneuvers. One of such large amplitude maneuver is an aerodynamic stall and its recovery which take place at a higher angle of attack region. The stall corresponds to an aerodynamic phenomenon where the flow gets separated from the body due to the unsteady flow. From past few decades, researchers are extensively investigating the unsteady aerodynamic flow at high angles of attack using analytical, computational fluid dynamics (CFD) software, wind-tunnel testing, and real flight testing based methods[4-10].

In our research study, we have used a real flight data of such a maneuver which carries the steady and unsteady flows. The unsteady flow is a cause of vortex breakdown in high angle of attack regime which was presented as a relationship between them in the form of an ordinary differential equation to incorporate the time dependency. Using the relationship, a state space model was proposed with an assumed aerodynamic model[4]. Such model was investigated with conventional airfoil, delta wing, and a prototype aircraft. An approximate solution of the differential equation was used to compute the flow separation point with an assumption of the quasi steady flow. Simplifying the above state-space model, a non-linear aerodynamic model using Kirchhoff's theory of flow separation was established for longitudinal operation where the flow separation point based aerodynamic derivatives were introduced along with the conventional stability and control derivatives[5,6]. Some of researchers have used it to develop the aerodynamic model by assuming effective stability and control derivatives of aerospace vehicles[7-10]. A proper establishment of such concepts require wind tunnel testing which is only possible for wings and low scale aircraft models. In case of large aircrafts, conventional approaches of modeling are preferred such as linear for small amplitude maneuver and non-linear for large amplitude maneuver. As the number of motion and control variables are limited for longitudinal motion so, many pseudo inputs are generated for non-linear model development[11]. The role of these coefficients is vital in-flight simulations which find further applications in the field of designing control law, flight simulators for on ground pilot training etc. Generally, maximum likelihood estimators are used in estimating these stability and control derivatives of the model from a gathered real flight data while performing the flight testing[12]. These estimators are based on an optimization method to minimize the residual error between the measured and estimated responses. They are categorized into three methods namely: output error method (OEM), filter error method (FEM), equation error method (EEM). The first two methods require the equations of the aircraft's dynamics in the state space form and the initial guess values of the aerodynamic coefficients. The initial guess values are supplied either from wind tunnel (WT) testing or computational fluid dynamics (CFD) software results which may or may not be true in some cases. Due to their inaccuracy, these methods suffer from intermediate numerical divergence or result improper estimates of parameters[13]. The dependency on such issues is overcome by using EEM method which employs least-square principle to estimate the unknown parameters. In its simplest form, it estimates the aerodynamic parameters by minimizing the sum of squared differences between the values of the aerodynamic force and moment coefficients determined from the measured motion and control variables of the real flight data and the corresponding postulated aerodynamic model. The procedure of EEM is relatively simple and provides a non-iterative solution based on linear algebra without any requirements of the integration process and the initial guess values unlike OEM, and FEM methods. Therefore, such approach is widely accepted to handle dataset of wind-tunnel tests or multiple flight maneuvers as a standard approach of estimating parameters of the investigating models[11, 14].

The objective of the research paper is to establish an aerodynamic model for the quasi steady stall of aircraft which undergoes a real flight maneuver. A set of aerodynamic models have been investigated in our study and their coefficients have been estimated using EEM method. The statistical values of the estimates are computed in terms of standard deviations. Finally, comparison between the measured and generated responses has been presented for validation of the estimates.

2. Research Objective

The motion of aircraft is expressed by Newton's second law of motion with the consideration of a rigid body. It states two statements in the inertial frame of reference: one for force and the other for moment[1].

$$\sum F = \frac{d}{dt}(MV) \tag{1}$$

Where $\sum F = F_{Aero} + F_{Thrust} + F_{Gravity}$ – External forces due to aerodynamics, engine thrust and weight of the body.

$$\sum M = \frac{d}{dt}(IW) \tag{2}$$

Where $\sum M = M_{Aero} + M_{Thrust}$ – Moments due to external forces due to aerodynamics and engine thrust.

The equations state that the rates of change of linear and angular momentums of the body in three-dimensional space are equal to the external forces and moments, respectively. F_{Aero} , M_{Aero} are the external forces and moments due to the aerodynamics, respectively and they are functions of aircraft's present motion and control variables. Our research objective is focused to the longitudinal dynamics of the aircraft. Hence, F_{Aero} and M_{Aero} can be defined with a functional relationship to be determined using real flight data of a maneuver as follows:

$$\begin{aligned} F_{Aero} &= f(\alpha, q, \delta_e) \\ M_{Aero} &= g(\alpha, q, \delta_e) \end{aligned} \tag{3}$$

3. Aerodynamic Modeling

Aerodynamic models are essential tool to demonstrate the behavior of aircraft in an operating condition[1, 2]. Usually, they are expressed as a functional relationship using motion and control parameters. Now-a-days, such relationship is made using machine learning techniques like neural-networks, support vector machine etc[15, 16]. They use a black-box concept in identifying the relationship without the physical knowledge of the system. However, the conventional approach in finding the relationship is to consider the variables whose steady and perturbed effects are present in the data. Initially, theoretical studies are conducted on WT results where forces and moments are modeled in their coefficient forms using angle of attack and its variants. In the real scenario, the forces and moments generated using the control surfaces play a key role in their modeling and hence, they are obtained alternatively to characterize the stability and controllability of the aircraft from the measured motion and control variables as follows:

$$\begin{aligned} C_D &= -C_X \cos a - C_Z \sin a \\ C_L &= C_X \sin a - C_Z \cos a \\ C_m &= [I_y \dot{q} - F_T Z_{enCG}] / (\bar{q} S \bar{c}) \end{aligned} \tag{4}$$

The body force coefficients C_X and C_Z are obtained from the measured linear accelerations as $ma_x / \bar{q}S$, and $ma_z / \bar{q}S$, respectively. The rate of change of q is not directly measured. Hence differentiation of q is performed for the computation of the pitching moment coefficient.

In the current study, an aerodynamic model is suggested based on two independent variables namely α, and δ_e as follows:

<u>Aerodynamic Model 1 (AM1):</u>

$$\begin{aligned} C_D &= C_{D_0} + C_{D_\alpha}\alpha + C_{D_{\delta_e}}\delta_e \\ C_L &= C_{L_0} + C_{L_\alpha}\alpha + C_{L_{\delta_e}}\delta_e \\ C_m &= C_{m_0} + C_{m_\alpha}\alpha + C_{m_{\delta_e}}\delta_e \end{aligned} \tag{5}$$

The inherent damping of aircraft is seen through the q term. Hence, three independent variables namely α, q, and δ_e are chosen for our second case of study as follows:

Aerodynamic Model 2 (AM2):

$$\begin{aligned} C_D &= C_{D_0} + C_{D_\alpha}\alpha + C_{D_q}q + C_{D_{\delta_e}}\delta_e \\ C_L &= C_{L_0} + C_{L_\alpha}\alpha + C_{L_q}q + C_{L_{\delta_e}}\delta_e \\ C_m &= C_{m_0} + C_{m_\alpha}\alpha + C_{m_q}q + C_{m_{\delta_e}}\delta_e \end{aligned} \tag{6}$$

As the quasi steady stall is a large amplitude maneuver which produces non-linear response, hence, a non-linear aerodynamic model is suggested by incorporating a number of pseudo inputs in AM2. The pseudo inputs are generated using the primary independent variables as α^2, q^2, and δ_e^2 . The final aerodynamic model is expressed as follows:

Aerodynamic Model 3 (AM3):

$$\begin{aligned} C_D &= C_{D_0} + C_{D_\alpha}\alpha + C_{D_q}q + C_{D_{\delta_e}}\delta_e + C_{D_{\alpha^2}}\alpha^2 + C_{D_{q^2}}q^2 \\ &\quad + C_{D_{\delta_e^2}}\delta_e^2 \\ C_L &= C_{L_0} + C_{L_\alpha}\alpha + C_{L_q}q + C_{L_{\delta_e}}\delta_e + C_{L_{\alpha^2}}\alpha^2 + C_{L_{q^2}}q^2 \\ &\quad + C_{L_{\delta_e^2}}\delta_e^2 \\ C_m &= C_{m_0} + C_{m_\alpha}\alpha + C_{m_q}q + C_{m_{\delta_e}}\delta_e + C_{m_{\alpha^2}}\alpha^2 + C_{m_{q^2}}q^2 \\ &\quad + C_{m_{\delta_e^2}}\delta_e^2 \end{aligned} \tag{7}$$

4. Equation Error Method

The least square estimation method is one of the oldest estimation procedures and is widely used in numerous engineering applications, including aerospace field[11, 14]. Its estimation procedure is as follows:

Let's assume that the dependent variable Y is a linear combination of m number of independent variables, $x_1, x_2, \ldots, x_m$ as given below:

$$\mathrm{Y} = \theta_1\mathrm{x}_1 + \theta_2\mathrm{x}_2 + \theta_3\mathrm{x}_3 + \ldots + \theta_\mathrm{m}\mathrm{x}_\mathrm{m} + \varepsilon \tag{8}$$

Where $\mathrm{Y} = [\mathrm{y}_1\,\mathrm{y}_2 \ldots \mathrm{y}_\mathrm{N}]^\mathrm{T}$ is a vector of response variable and each x_i is a vector of the independent variable with N sample data.

In a matrix notation, $X = [x_1\, x_2 \ldots x_m]$ and let $\theta = [\theta_1\ \theta_2\ \theta_3 \ldots \theta_\mathrm{m}]^\mathrm{T}$ is a vector of unknown parameters to be determined and $\varepsilon = [\varepsilon_1\,\varepsilon_2 \ldots \varepsilon_\mathrm{N}]^\mathrm{T}$ is a modeling error vector of the assumed relationship. The equation (8) can be written as a standard least squares problem as follows:

$$\mathrm{Y} = \mathrm{X}\theta + \varepsilon \tag{9}$$

According to the least squares principle, the modeling error vector ε is minimized by the following cost function:

$$\mathrm{J} = \frac{1}{2}\varepsilon^\mathrm{T}\varepsilon \tag{10}$$

Using equation (9), $\varepsilon = Y - X\theta$. Hence,

$$\mathrm{J} = \frac{1}{2}(\mathrm{Y} - \mathrm{X}\theta)^\mathrm{T}(\mathrm{Y} - \mathrm{X}\theta) \tag{11}$$

The above cost function is minimized by differentiating it with respect to θ and equated to zero as $\partial\mathrm{J}/\partial\theta = 0$.

The optimum value of the unknown parameter is given by

$$\hat{\theta} = (\mathrm{X^TX})^{-1}\mathrm{X^TY} \tag{12}$$

Where, X^TX is the information matrix of the data to be analyzed.

The confidence of the estimated parameters is defined as a square root of diagonal elements of the covariance matrix, P which is defined as follows:

$$\mathrm{P} = \mathrm{E}((\hat{\theta} - \theta)(\theta - \theta)^\mathrm{T}) = \sigma^2(\mathrm{X^TX})^{-1} \tag{13}$$

Where σ^2 is the fit error variance determined from the residual errors as follows:

$$\hat{\sigma}^2 = \frac{\mathrm{v^Tv}}{\mathrm{N} - \mathrm{m}} \tag{14}$$

Where, v is the residual error between the measured and estimated responses as follows:

$$\mathrm{v} = \mathrm{Y} - \mathrm{X}\hat{\theta} \tag{15}$$

The independent variables with their corresponding unknown parameters for the modeling of the dependent variable are chosen to minimize the mean-square-error (MSE) as follows:

$$\mathrm{MSE} = \frac{(\mathrm{Y} - \mathrm{X}\hat{\theta})^\mathrm{T}(\mathrm{Y} - \mathrm{X}\theta)}{\mathrm{N}} \tag{16}$$

4. Results and Discussion

The real flight data of quasi steady stall maneuver has been considered from the advanced testing technology aircraft system (ATTAS) with geometrical data presented in Table 1. It was gathered at an altitude of 16,000 ft with a velocity of 92.5 m/s. The maneuver was excited in two steps: one by an elevator command to occur quasi steady stall and the other to bring the aircraft from stall using reversal of elevator command and increasing the thrust to control the loss of velocity[2]. The raw data of the maneuver has to undergo through the data compatibility check to improve its quality in terms of scale factor, biases etc. and the final corrected data of the longitudinal maneuver is presented in Fig. 1. The coefficients of aerodynamic forces and moment as defined in equation (4) is computed using the measured motion and control variables, and the geometrical data of the example aircraft[2].

Table 1 Geometrical data of ATTAS aircraft

Wing span, b	21.50 m
Mean Aerodynamic chord, $\bar{c}$	3.16 m
Wing area, S	64 m^2
Aspect ratio, AR	7.22
Mass of aircraft, M	17631 kg
Velocity, V	700 km/h (max.)
Moment of Inertia, I_{xx}	1.33x105 kg-m^2
Moment of Inertia, I_{yy}	2.53x105 kg-m^2
Moment of Inertia, I_{zz}	3.59x105 kg-m^2
Moment of Inertia, I_{xz}	1.14x104 kg-m^2
Engine Thrust, F_T	64 kN (max.)
Range (approx.)	1800 km

Three basic aerodynamic models have been presented to show their capability in capturing the quasi steady stall maneuver. AM1 is the basic one excluding pitch rate effects whereas AM2 includes it. Both the models are linear in nature due to the presence of first order aircraft's states whereas AM3 includes pseudo inputs of order two which are derived from the measured states. The unknown aerodynamic parameters of these models have been estimated using EEM method which employs the least-square principle in finding the optimal solution. MSE is computed as per equation (16) for each of the model coefficients as shown in Table 2. It is found that the inclusion of more inputs in the aerodynamic model can decrease MSE as seen with AM3 model which depicts a better regression with the data. Hence, the corresponding parameters have been estimated and shown in Table 3.

As the reference values of the estimates are not found in the literature, so standard deviations of each estimate are computed using equation (13). To verify the modeling results, the estimated parameters are used to simulate the responses of forces and moment coefficients as shown in Fig. 2.

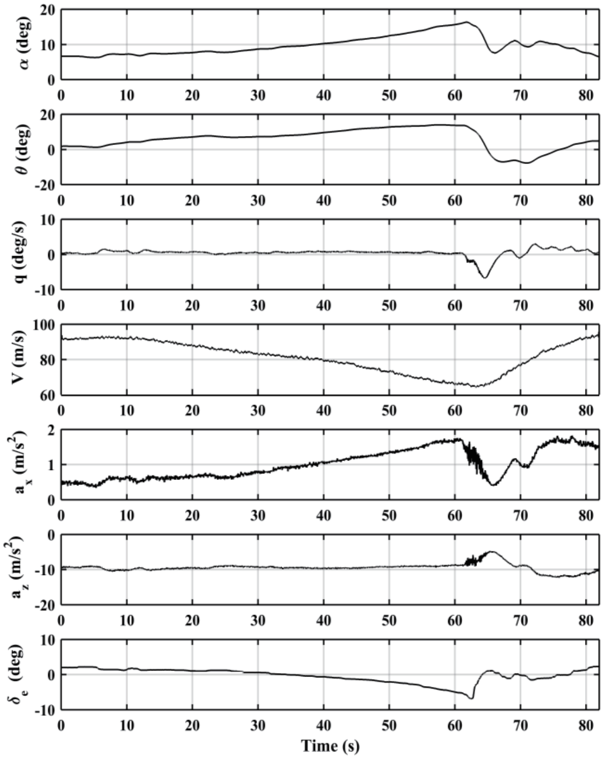


Fig. 1 Measured flight data

Table 2 Comparison of MSEs from different aerodynamic models

Aero. Coeff.	AM1	AM2	AM3
C_D	3.828E-05	3.447E-05	2.073E-05
C_L	1.972E-03	2.491E-04	1.937E-04
C_m	1.132E-04	1.107E-04	9.643E-05

It is seen that AM1 is insufficient to model the coefficients of C_D and C_L whereas AM2 and AM3 match satisfactorily. In the case of C_m modeling, all models are approximating the response up to the stall region where a high frequency oscillation takes place. After that, low frequency oscillations are seen in the post stall region which is due to the inherent damping of the aircraft. AM3 model has shown a better performance in this region where other models are just producing approximation. Finally, it can be concluded that AM1 could be used for steady motion whereas AM2 and AM3 for steady as well as perturbed motions.

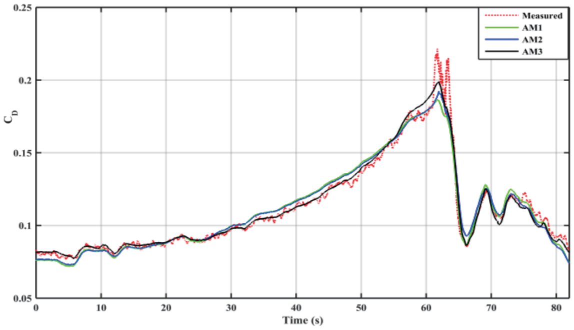
Table 3 Parameter estimates of AM3

$\hat{\Theta}$	EEM	$\hat{\Theta}$	EEM	$\hat{\Theta}$	EEM
C_{D_0}	0.0292 (0.0045)	C_{L_0}	0.1315 (0.0138)	C_{m_0}	0.0706 (0.0098)
C_{D_α}	0.2420 (0.0446)	C_{L_α}	5.8167 (0.1362)	C_{m_α}	-0.1093 (0.0961)
C_{D_q}	-0.0014 (0.0082)	C_{L_q}	1.9620 (0.0251)	C_{m_q}	-0.0899 (0.0177)
$C_{D_{\delta e}}$	0.1637 (0.0196)	$C_{L_{\delta e}}$	1.3285 (0.0600)	$C_{m_{\delta e}}$	-0.8267 (0.0423)
$C_{D_{\alpha^2}}$	1.3063 (0.1079)	$C_{L_{\alpha^2}}$	-0.8931 (0.3296)	$C_{m_{\alpha^2}}$	-1.1840 (0.2326)
$C_{D_{q^2}}$	0.5480 (0.1021)	$C_{L_{q^2}}$	-1.7489 (0.3119)	$C_{m_{q^2}}$	1.1498 (0.2201)
$C_{D_{\delta e^2}}$	0.9916 (0.1692)	$C_{L_{\delta e^2}}$	-4.7384 (0.5171)	$C_{m_{\delta e^2}}$	-0.7100 (0.3649)

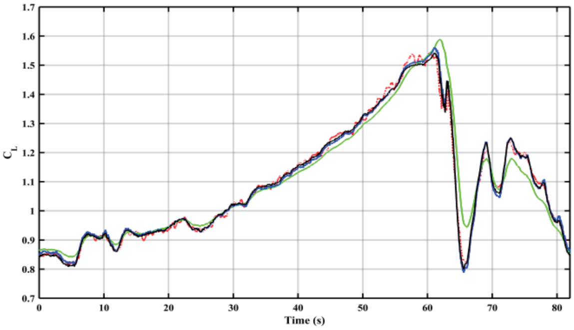
Note: Values in parentheses indicate standard deviations

4. Conclusions

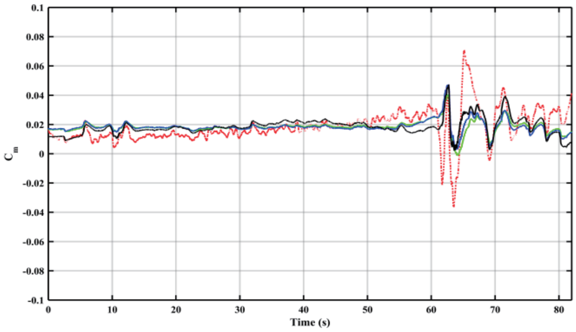
In the present study, the aerodynamic modeling of quasi steady stall maneuver has been investigated using EEM which employs the model matching technique rather than the matching of the states or observations as in OEM or FEM. The real flight data presents a physical insight of aircraft's behavior which contains essential information about the stability and controllability of aircraft. Linear and non-linear aerodynamic models have been investigated to capture the quasi steady stall maneuver. The aerodynamic model without the damping effect term is not suitable for the current investigation whereas the other models have shown relatively better performances. More number of pseudo inputs in the aerodynamic model could produce a better regression which may also lead to more complexity in the aerodynamic modeling. It is seen that the coefficients of drag and lift are modeled well in linear, stall and post stall regions whereas the coefficient of pitching moment is approximated by each of the aerodynamic models due to the non-inclusion of the cross-coupling parameters while a lower value of MSE is found with AM3 model. It has also been observed that EEM could be a better parameter estimation method to be applied in the investigation of the aerodynamic modeling at higher angle of attack regions where the aircraft's equations of motion can't be defined effectively without the knowledge of external forces and moments based on the motion and control variables.



(a) Coefficient of drag force, C_D



(b) Coefficient of lift force, C_L



(c) Coefficient of pitching moment, C_m

Fig. 2. Comparison of measured and generated aerodynamic force and moment coefficients

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