Advanced Materials Research Vols. 915-916 (2014) pp 7-11 Online: 2014-04-09
© (2014) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/AMR.915-916.7

# Analysis and Simulation of UAV Aircraft Flight Dynamics

Tariq O. Mohammed[1, a], Naser M. Elkhmri[1, b], Hamza AboBakr. O[1, c]

[1]School of aeronautical Science and Mechanical Engineering, Beihang University, Beijing 100191, China

[a] tariq_aburass@yahoo.com, [b] naserkhemri@yahoo.com, [c] almuonu2008@yahoo.com

**Keywords**: linear equations, Longitudinal Dynamics, Lateral Dynamics, simulation and analysis.

**Abstract.** The objective of the present work is to evaluate the static and dynamic stability of the Flying Wing Unmanned Aircraft Vehicle (UAV) model using the Tornado software. The longitudinal and the lateral-directional aerodynamics were studied using the model with incompressible flow, asymmetric, conditions. The stability coefficients were calculated and give proof that the aircraft is statically stable. Using the stability coefficients, the longitudinal and lateral-directional equations of motion were written to evaluate the dynamic stability of the vehicle. Good flying qualities were obtained, rating in Level 1 for the Cooper and Harper scale.

## Introduction

The aircraft stability and flying qualities of the UAV model have been evaluated and analyzed using mainly the vortex lattice method to compute the aerodynamic and stability coefficients[1]. T135_export which based in the vortex lattice method, were used in different flight cases for these purposes. The vortex lattice method has limitations that the aircraft must be in low subsonic speeds, below the stall limit, small angles of attack[2]. Moreover, this method simulates only steady and quasi-steady flow, and the stability coefficients with respect to rate of change of angle of attack must be obtained using analytical-empirical methods[3], such as Digital Datcom.

The objective of the present work is to evaluate the static and dynamic stability of the UAV research model by an inviscid panel method. The aerodynamic coefficients were calculated using the low order panel code Tornado. These coefficients were used to write the dynamic equations of motion, from which the eigenvalues to analyze the dynamic stability of the aircraft were obtained.

The UAV is research model aircraft, driven by micro jet engine of 230 N. The aircraft has a maximum take-off mass of 88 kg, and swept wing of 4.2 m of span, and 3.96 $m^2$ of surface area, for an aspect ratio of 4.452. The center of gravity is located at 0.25*c*. It is expected that the UAV will have a cruise speed of 60 m/s at sea level for a wing Reynolds number of 5.0706e+006. Center of gravity (CG) positions *CG x*=1.7447m, *CG y* =0, *CG z* =0.0324m, and inertia properties as *Ix*=70.01, *Iy*=109.27, *Iz*=113.66, *Ixy*= *Iyz=0, Ixz*=1.57 kg.$m^2$. The simulations were performed at 60 m/s for cruise speed, with an air density 1.225 kg/$m^3$.

The inviscid fluid flow field around the UAV was analyzed using Tornado T135_export version. This is a low order panel method code which solves inviscid, irrotational and incompressible flow by the Laplace equation, and it is capable of analyzing the entire fluid flow field around a three-dimensional arbitrary configuration. A vortex-lattice method code called Tornado, version T135,was used to calculate the forces and moments of the airplane[4]. Tornado is a three-dimensional vortex-lattice open-source program written in MATLAB.

## Longitudinal Stability Analysis

Steady flow was simulated around the UAV to obtain the stability coefficients with respect to the variation of angle of attack and elevator deflection. At M=0.1763 (v=60 m/s) cruise speed the non dimensional longitudinal stability were calculated[5], UAV model is longitudinal statically stable since $Cm_{\alpha} = -0.8301 < 0$ (negative value). Rewriting the equations in the state space form using dimensional stability derivatives yields:

$$\begin{bmatrix}\dot u\\ \dot w\\ \dot q\\ \dot\theta\end{bmatrix}=\begin{bmatrix}X_u & X_w & 0 & -g\\ Z_u & Z_w & u_0 & 0\\ M_u+M_{\dot w}Z_u & M_w+M_{\dot w}Z_w & M_q+M_{\dot w}u_0 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}u\\ w\\ q\\ \theta\end{bmatrix}+\begin{bmatrix}X_\delta & X_{\delta_T}\\ Z_\delta & Z_{\delta_T}\\ M_\delta+M_{\dot w}Z_\delta & M_{\delta_T}+M_{\dot w}Z_{\delta_T}\\ 0 & 0\end{bmatrix}\begin{bmatrix}\delta\\ \delta_T\end{bmatrix} \quad (1)$$

$$\begin{bmatrix}\dot u\\ \dot w\\ \dot q\\ \dot\theta\end{bmatrix}=\begin{bmatrix}-0.0367 & -0.0002 & 0 & -9.8106\\ -0.0087 & -9.0657 & 60.0035 & 0\\ 0 & -2.2455 & -3.1512 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}u\\ w\\ q\\ \theta\end{bmatrix}+\begin{bmatrix}0\\ 0\\ -9.4422\\ 0\end{bmatrix}\eta \quad (2)$$

The incidence $\alpha$ and flight path angle $\gamma$ are useful variables in the evaluation of flying qualities; the output equation is augmented, to contains the variables of $[u\ w\ q\ \theta\ \alpha\ \gamma]^T$ [6], in order to obtain their response transfer functions in the solution of the equations of motion. The response of the aircraft to a unit step (1°) elevator input is shown in Fig. 1. All of the variables in the solution of the equations of motion are shown. The responses being characterized by transfer functions equations obtained.

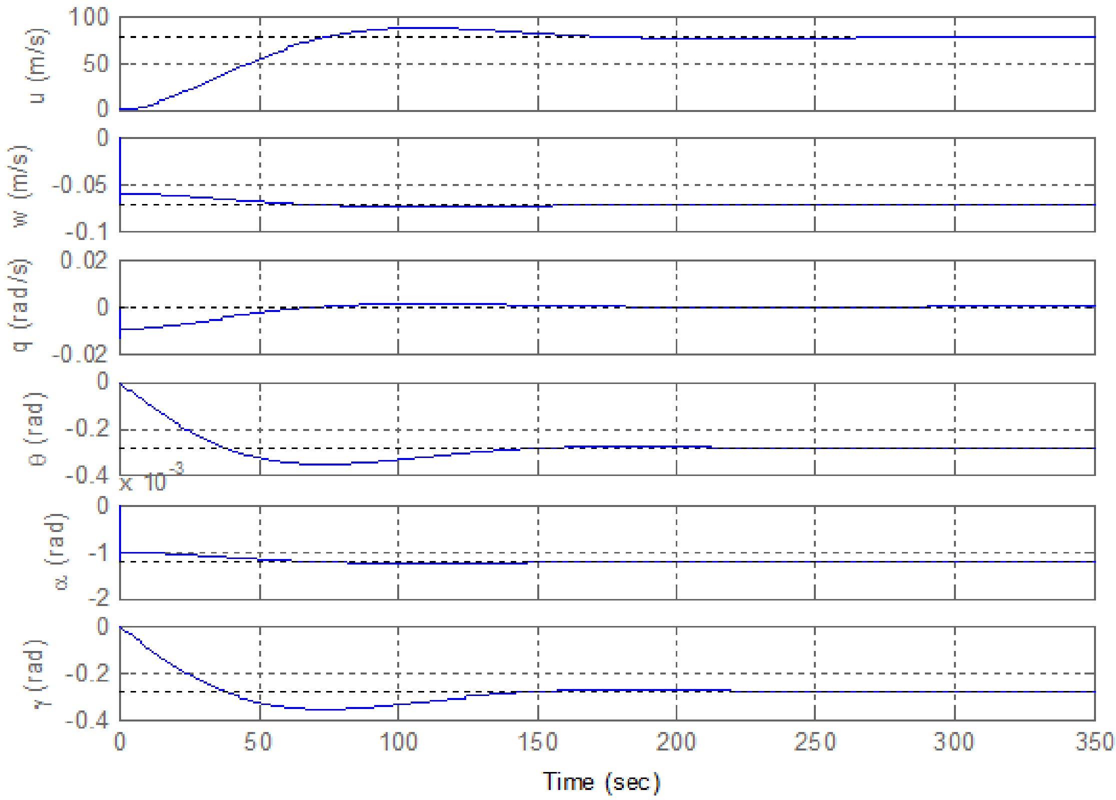


Fig. 1 Aircraft response to 1° elevator step input

## Lateral-Directional Stability Analysis

At flight condition corresponds to level cruising flight at sea level conditions with Mach= 0.1763 (v=60 m/s) cruise speed the dimensional lateral-directional stability were calculated [5], UAV model is lateral and directional statically stable since $Cl_\beta = -0.002077 < 0$ and $Cn_\beta = 0.040579 > 0$. For lateral equation the matrix A is given by:

$$A=\begin{bmatrix} Y_v & Y_p/V_0 & -(1-\frac{Y_r}{V_0}) & \frac{g}{V_0} \\ L_\beta & L_p & L_r & 0 \\ N_\beta & N_p & N_r & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}=\begin{bmatrix} -0.4987 & -0.0012 & -1.0062 & 0.1635 \\ -1.0889 & -5.6043 & 0.0581 & 0 \\ 13.1008 & -0.0160 & -0.2762 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad (3)$$

The equations of motion, referred to a body axis system using dimensional derivatives, in state space:

$$\begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{r} \\ \dot{\phi} \end{bmatrix}==\begin{bmatrix} -0.4987 & -0.0012 & -1.0062 & 0.1635 \\ -1.0889 & -5.6043 & 0.0581 & 0 \\ 13.1008 & -0.0160 & -0.2762 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}\begin{bmatrix} v \\ p \\ r \\ \phi \end{bmatrix}+\begin{bmatrix} 0 & -0.0817 \\ -0 & 1.3825 \\ 0 & -2.6059 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} \delta a \\ \delta r \end{bmatrix} \quad (4)$$

It is useful to have the transfer function describing sideslip angle β as well as side slip velocity v, the output equation is augmented to contain the variables $[v\,p\;r\;\phi\;\beta]^T$. Solution of the equations of motion gives two sets of transfer function. The first set describes response to aileron: and the second, the transfer functions describing responses to rudder input. The response of the aircraft to a unit aileron pulse 1° (deg) in 2 sec is shown in Fig. 2. The response of the aircraft to a unit (1°) rudder step input is shown in Fig.3. All variables obtained in the solution of the equations are shown, the individual responses being characterized by the transfer functions for lateral-directional variables.

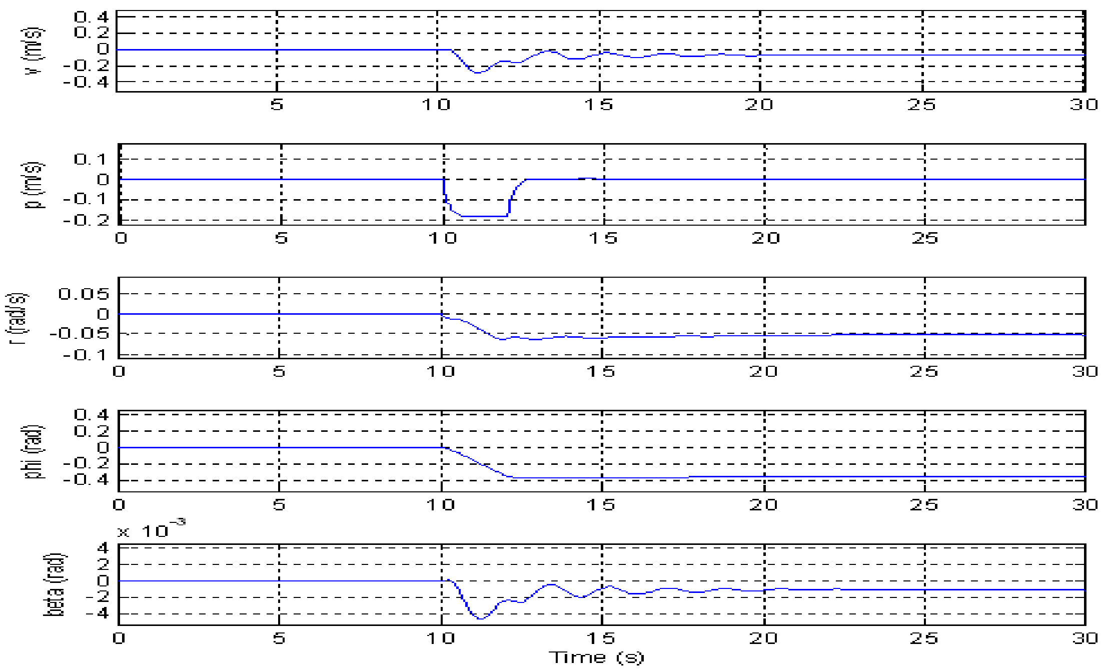


Fig. 2 UAV Elevon differential pulse input for roll response (aileron pulse 1 deg in 2 sec)

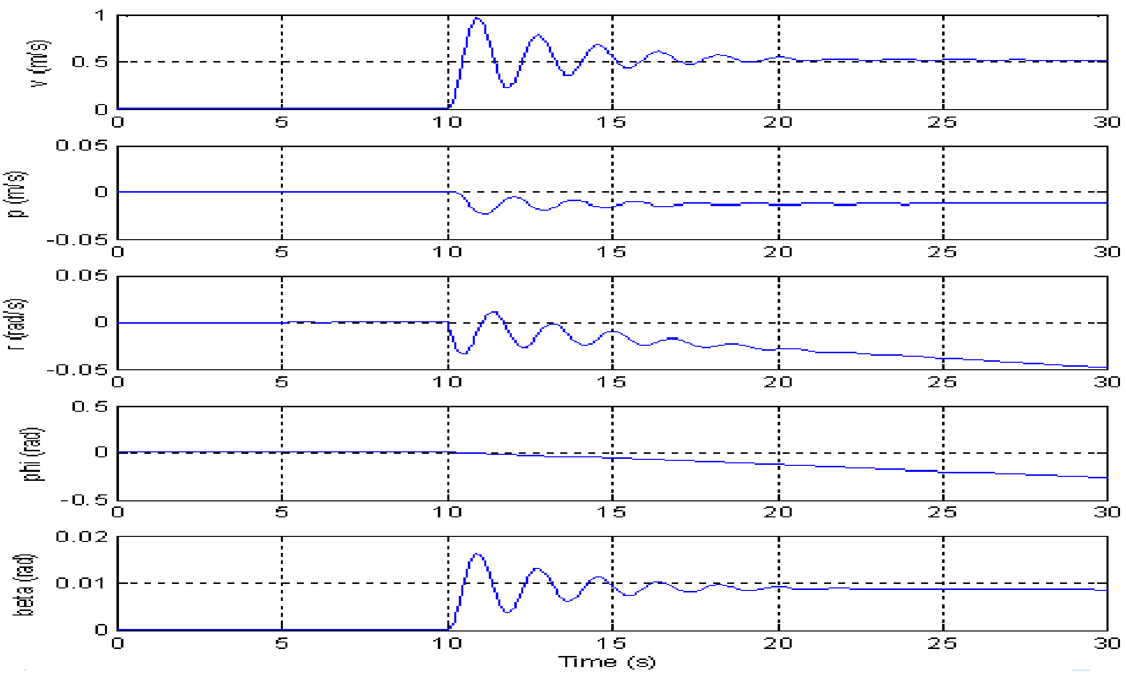


Fig. 3 UAV rudder step input response

**Results and Discussion**

The values of non-dimensional derivatives obtained from Tornado results were used to calculate the dimensional stability derivatives, which were utilized to write the longitudinal and lateral-directional equations of motion.

Four eigenvalues are obtained from matrix *A*, and they describe; the two responses of longitudinal modes of motion: the short-period, $\lambda_{1,2}$= -6.1085 ±11.2247i ; and the phugoid, $\lambda_{3,4}$= -0.0183 ± 0.0289i. The eigenvalues of both modes indicate that the aircraft is longitudinally dynamically stable, because these are complex and have negative real parts. The phugoid has an undamped natural frequency of 0.0342 rad/s and for the short-period mode this is equal to 12.77 rad/s. The damping ratios are 0.535 for the phugoid mode and 0.478 for the short-period modes. The time to half-amplitude at the short-period is equal to 0.113 s, and at the phugoid is 37.705 s. From Fig. 1 the Phugoid mode is dominant in *u*, the short period is dominant in w, also short period is dominant in q, and the short period and Phugoid modes content in $\theta$ are of a similar order.

The eigenvalues estimated from matrix *A* are associated with linearized lateral-directional motion: The spiral mode, $\lambda_1$ =0.0010, the roll mode $\lambda_2$ = -5.6096, and Dutch roll $\lambda_{3,4}$ = -0.3853 ±3.6327i The Dutch roll mode, which is described by a pair of complex roots with negative real part, has a damped oscillation motion with 1.7296 s of period, requiring 1.7908 s to half-amplitude. The root for the roll mode is real and negative and spiral mode is too small value, indicating a stable and heavily damped roll and spiral motions has too small effect for stability. These take 0.1783 s and 1000 s to double-amplitude, respectively. From Fig. 2 and Fig. 3, the roll mode is dominant in roll rate p, and the spiral mode is dominant in roll attitude response.

The dynamic stability characteristics were used to evaluate the flying qualities of the aircraft in the Cooper and Harper rating scale to evaluate the flying qualities of remote piloted vehicles [7,8]. The UAV model is classified according to size and maneuverability as class I, in flight phases B. Using the dynamic characteristics obtained, the aircraft rates for all the modes of motion in Level 1[9].

**Summary**

Standard vortex lattice theory software Tornado, T135, was used to compute the forces and moments on the UAV model aircraft. These values were utilized to calculate the stability coefficients and stability derivatives at a given flight condition. The negative values of $C_{M\alpha}$ and $C_{\ell\beta}$ and a positive $C_{n\beta}$, demonstrate that the airplane is statically stable. It is possible to conclude that the aircraft is dynamically stable. For the two modes of longitudinal motion of response, the short-period and the phugoid, the reaction is an oscillatory mode describing sinusoidal motion with amplitude that decreases exponentially with time. The Dutch roll mode is damped and convergent, and the roll and the spiral modes of motion are convergent. The flying qualities for all the modes of motion are excellent, rating in Level 1 for the Cooper and Harper scale.

**References**

[1] T. Melin, "User's guide and reference manual for Tornado. Royal Institute of Technology (KTH), Department of aeronautics," 2001.

[2] T. Melin, "A Vortex Lattice MATLAB Implementation for Linear Aerodynamic Wing Applications," Master's Thesis, Department of Aeronautics, Royal Institute of Technology (KTH), Stockholm, Sweden, 2000.

[3] E. M. C. and A. A. Pedro J, Boschetti, "Stability of an Unmanned Airplane using a Low-Order Panel Method," *AIAA 2010-8121*, no. August, pp. 1–13, 2010.

[4] P. J. G. R., "Evaluation of the Flying Qualities of a Half-Scale Unmanned Airplane via Flight Simulation," 2010, no. January, pp. 1–7.

[5] D. R. C. Nelson, *Flight Stability and Automatic Control*. McGraw-Hill Book Company, 1989.

[6] M. V Cook, *Flight Dynamics Principles.* Butterworth-Heinemann, 2007.

[7] G. E. Cooper and R. P. Harper Jr, "The use of pilot rating in the evaluation of aircraft handling qualities," 1969.

[8] E. M. Cárdenas, P. J. Boschetti, A. Amerio, U. S. Bolívar, and S. Litoral, "Stability and Flying Qualities of an Unmanned Airplane using Vortex Lattice Method," in *AIAA 2009-306*, 2009, no. January, pp. 1–9.

[9] J. C. Bingaman, "Unmanned Aircraft and the Applicability of Military Flying Qualities Standards," in *AIAA Atmospheric Flight Mechanics Conference 13-16 August*, 2012, no. August, pp. 1–24.

**Advanced Engineering Research**
10.4028/www.scientific.net/AMR.915-916

**Analysis and Simulation of UAV Aircraft Flight Dynamics**
10.4028/www.scientific.net/AMR.915-916.7