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Stability and Control Analysis in Twin-Boom Vertical Stabilizer Unmanned Aerial Vehicle (UAV)

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Abstract- Flying and handling qualities are substantially dependent on, and this paper is described it, in terms of the stability and control characteristics of UAV. It is essential to be able to describe and quantify the stability and control parameters completely.

It is absolutely essential to understand the relationship between the aerodynamics of the airframe and its stability characteristics to prolong the flight endurance and effective deployment. And this paper is described the stability analysis based on the dynamic model of the twin boom double vertical stabilizer UAV.

Key words – Stability and control, UAV, Dynamic stability, dynamic model

I. INTRODUCTION

The purpose of Stability and Control Analysis is to evaluate the dynamic stability and time response of the UAV for such a perturbation in open loop behavior and Static stability analysis enables the *control displacement* and the *control force* characteristics to be determined for both steady and manoeuvring flight conditions.

A well designing UAV has to be fulfilled the stability for the appropriate condition. In this analysis will test and analyze the outputs parameters of UAV (i.e– displacements, velocities and accelerations) on various flight conditions.

In this paper will further discuss, how to replace the conventional , time consuming process of model making and testing in wind tunnel by using sophisticated XFLR5 numerical simulation software[4] which can generate and manipulate data significantly on computational aerodynamic.

II. METHODOLOGY

The methodology of this analysis is based on stability and control theories and the purpose of it is to improve the dynamic model through the stability analysis. The dynamic model was simulated on XFLR5 open source simulation software[4] for the given input control commands and the generated flight data (fig.1) through this method were used for the stability analysis[10].

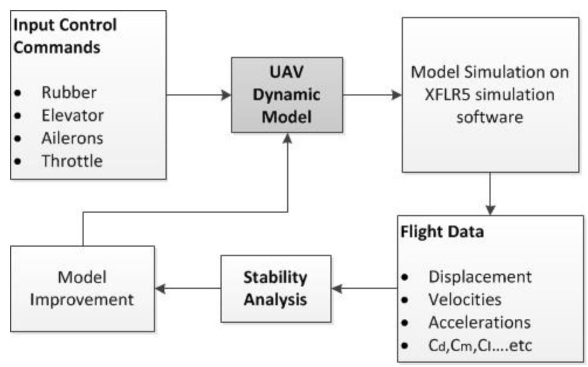

Fig.1 Structure of methodology

And also the results were compared with the stability norms and the theories in aerodynamic. When it was confusing with the stability and control standard the airframe structure and input commands have also been changed and adjusted to fulfill the stability requirements. This exercise was repeated till the results were optimal and stable to the best flying qualities.

A. Aerodynamic model

The aerodynamic equations of this UAV are very important to discuss the stability and control behavior in different flying condition. Because of the aerodynamic complexity of the conditions applying to the airframe in a compressible flow field it is difficult to derive other than the very simplest mathematical models to describe those conditions. Thus for analytical application, as required in aerodynamic derivative estimation, mathematical modeling is usually limited to an approximate description of the effects of compressibility on the lifting surfaces of it only. In particular, the ease with which the aerodynamic properties of a wing in compressible flow can be estimated is dependent, to a large extent, on the leading edge flow conditions.

The dynamic model has been built by using Lagrange –Euler formalism based on potential and kinematic energy concept[6]. Main purpose of this analysis is to improve the model though stability analysis.

$$\Gamma_i = \frac{d}{dt}\left(\frac{\delta L}{\delta \dot{q}_i}\right) - \frac{\delta L}{\delta q_i} \quad (1)$$

$$L_{(q,\dot{q})} = E_{c_{Trans}} + E_{c_{Rot}} - E_p \quad (2)$$

Where,
q_i : generalized coordinates
Γ_i : generalized force given by non-conservatives forces
$E_{c_{Trans}}$: Total translational kinetic energy
$E_{c_{Rot}}$: Total rotational energy
E_p: Total potential energy

The kinetic energy due to the translation is :

$$E_{c_{Trans}} = \tfrac{1}{2}m\dot{x}^2 + \tfrac{1}{2}m\dot{y}^2 + \tfrac{1}{2}m\dot{z}^2 \quad (3)$$

Then the kinetic energy due to the rotation is[6] ;

$$E_{c_{Rot}} = \tfrac{1}{2}I_{xx}\omega_x^2 + \tfrac{1}{2}I_{yy}\omega_y^2 + \tfrac{1}{2}I_{zz}\omega_z^2 \quad (4)$$

Then the total kinetic energy:

$$E_T = \tfrac{1}{2}\begin{pmatrix} m\dot{x}^2 + m\dot{y}^2 + m\dot{z}^2 \\ +I_{xx}\omega_x^2 + I_{yy}\omega_{y+}^2 I_{zz}\omega_z^2 \end{pmatrix} \quad (5)$$

The potential energy can be expressed by:

$$V = -m.g.Z = -mg\begin{pmatrix} -sin\theta.x + sin\emptyset cos\theta.y \\ + cos\emptyset cos\theta.z \end{pmatrix} \quad (6)$$

Where $\omega_x, \omega_y, \omega_z$ are the rotational speed that can be expressed as a function of the roll, pitch and yaw rate $(\vec{\dot{\emptyset}}, \vec{\dot{\theta}}, \vec{\dot{\Psi}})$[4]:

$$\omega_x = \dot{\emptyset} - \dot{\Psi} sin\theta \quad (7)$$
$$\omega_y = \dot{\theta} cos\emptyset + \dot{\psi} cos\theta sin\emptyset \quad (8)$$
$$\omega_z = -\dot{\theta} sin\emptyset + \dot{\Psi} cos\theta cos\emptyset \quad (9)$$

The force equation for the linear momentum can be derived from the Lagrangian formation as follows :

$$\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{x}}\right) - \frac{\delta L}{\delta x} = F_x \quad (10)$$

$$\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{y}}\right) - \frac{\delta L}{\delta y} = F_y \quad (11)$$

$$\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{z}}\right) - \frac{\delta L}{\delta z} = F_z \quad (12)$$

Then the motion equation for the angular [5] momentum can be derived as follows;

$$\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{\psi}}\right) - \frac{\delta L}{\delta \psi} = \tau_\psi \quad (13)$$

$$\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{\emptyset}}\right) - \frac{\delta L}{\delta \emptyset} = \tau_\emptyset \quad (14)$$

$$\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{\theta}}\right) - \frac{\delta L}{\delta \dot{\theta}} = \tau_\theta \quad (15)$$

The non-conservative forces and moments come from the aerodynamics as per Lagrange-Euler approach. On this UAV, five parts are considered to calculate the aerodynamics. They are mainly on left and right wings, elevator, and two vertical stabilizers(fig.2).
The airframe is considered as a rigid body associated with the aerodynamic forces generated by the propeller and the wing. This model is obtained under the assumptions that the center of mass and the body fixed frame origin are coincided; The structure is supposed to be rigid and symmetric (diagonal inertia matrix); The wind speed in the Earth frame is set to zero so that the relative wind on the body frame is only due to the UAV speed.

Total forces and moments on the UAV are[2],

$$f_t\| = f_{propler} + \textstyle\sum_{i=1}^{5}(f_{i_{lift}} + f_{i_{drag}}) \quad (16)$$
$$M_t\| = \sum_{i=1}^{5} M_i + f_{i_{lift}} \times r_i + f_{i_{drag}} \times r_i \quad (17)$$
$$f_{propler} = f(\dot{x}, U_i) \quad (18)$$
$$f_{i_{lift}} = C_{i_{lift}} \tfrac{\rho}{2} S_i v^2 \quad (19)$$
$$f_{i_{drag}} = C_{i_{drag}} \tfrac{\rho}{2} S_i v^2 \quad (20)$$
$$M_i = C_{i_{mom:}} \tfrac{\rho}{2} S_i v^2 .chord_i \quad (21)$$

Where - U_i is control input

Isolating the acceleration and applying the small angle approximation as it shows linearity for very short time, where the rotational speed in the solid basis are equal to Euler's angles rates. Then,

$$\ddot{x} = \frac{F_{tot,x}}{m} - gsin\theta \quad (22)$$
$$\ddot{y} = \frac{F_{tot,y}}{m} + gsin\emptyset cos\theta \quad (23)$$
$$\ddot{z} = \frac{F_{tot,z}}{m} + gcos\emptyset cos\theta \quad (24)$$

$$\ddot{\emptyset} = \frac{I_{yy} - I_{zz}}{I_{xx}}\dot{\psi}\dot{\theta} + \frac{M_{tot,x}}{I_{xx}} \quad (25)$$
$$\ddot{\theta} = \frac{I_{zz} - I_{xx}}{I_{yy}}\dot{\psi}\dot{\emptyset} + \frac{M_{tot,y}}{I_{yy}} \quad (26)$$
$$\ddot{\psi} = \frac{I_{xx} - I_{yy}}{I_{zz}}\dot{\theta}\dot{\emptyset} + \frac{M_{tot,z}}{I_{zz}} \quad (27)$$

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The fundamental goal of this dynamic modeling is to bring the required numerical outputs (fig.1) for flight motion for the given inputs conditions[1].

B. Model Testing on XFLR5 Simulation Environment

In this model testing, the time consuming process of model making and testing in wind tunnel was replaced by using sophisticated XFLR5 numerical simulation software which can generate and manipulate data significantly on computational aerodynamic.

The output parameters of UAV (i.e– displacements, velocities and accelerations) have been tested on various flight conditions and the model verified on its stability and control in the XFLR5 simulation software[11]. And the results are discussed in the next chapter.

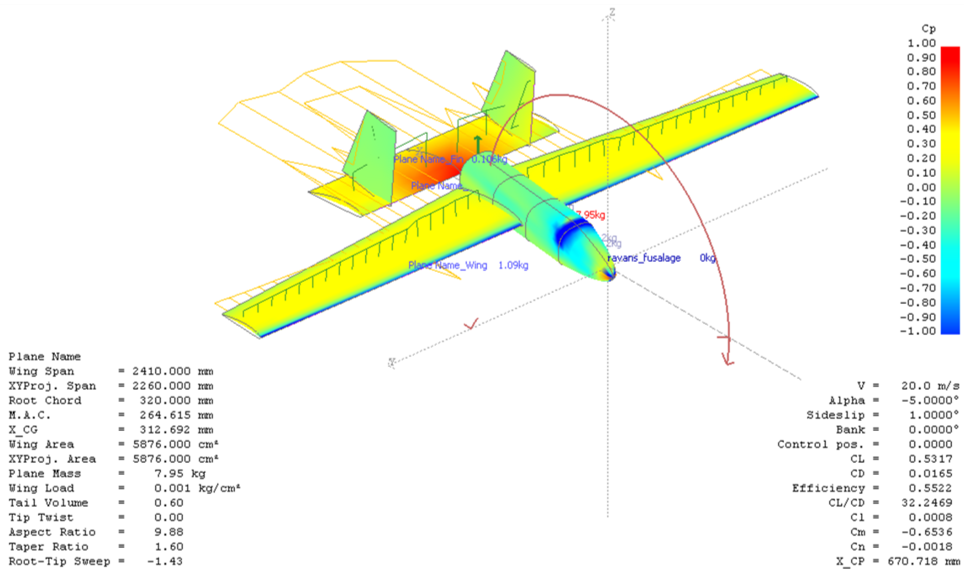


Fig.2-Forces and moments are on the airframe

III. MODEL IMPROVEMENT THROUGH STABILITY

This stability test was done for model improvement for the existing twin boom vertical stabilizer UVA. It wasn't fulfilled the trimmed condition in terms of, basic stability and control characteristics. The major issue that it had was the center of pressure and the center of gravity was confused with natural point. Therefore, a small transient upsets from equilibrium it couldn't stable in climbing.(Fig.3).Obviously, the gradient is zero from -5˚ to 5˚ and it was positive at 7˚ in the previous model. Therefore it is unstable while it is claimbing.

To control the downwash lag the elevator incidence angle was changed from 5° to 16° and the wing incidence angle was changed from 15° to 8°.The condition for longitudinal static stability can be determined by plotting pitching moment coefficient *Cm*, for variation in incidence α. The nose up disturbance increases α and takes the aircraft to the out-of-trim point where the pitching moment coefficient becomes negative and is therefore restoring. Clearly, a nose down disturbance leads to the same conclusion. As indicated, the aircraft is stable when the slope of this plot is negative[5].

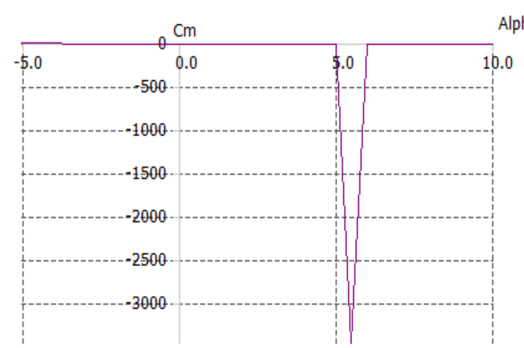


Fig.3-Pitch angle Vs Moment coefficient in UAV before the model improve

Flying condition and handling qualities are interpreted to describe in terms of, stability and control characteristics of the UAV. In this application, flight model has been tested for four natural longitudinal stability modes and four natural lateral stability modes on XFLT5 simulation environment. There are two symmetric phugoid and two short period modes for longitudinal motion and one spiral , one roll damping and also two Dutch roll modes for lateral motion[5].

As for the longitudinal stability modes, whenever the UAV is disturbed from its equilibrium trim state the lateral–directional stability modes will also be excited. Again, the disturbance may be initiated by Autopilot, a change in power setting, airframe configuration changes, such as flap deployment, and by external influences such as gusts and turbulence.

The following graphs have been generated using UAV air frame geometry and aerodynamic stability predictions are based on it. The magnitude of the gradient (Fig-4) determines the degree of stability in the airframe for a given disturbance in alpha (AoA). The corresponding pitching moment C_m curve is showing negative slope (fig.4) in stable aircraft. Therefore, when the angle of attack is changed the tendency to return to its stable position is high in this UAV[5].

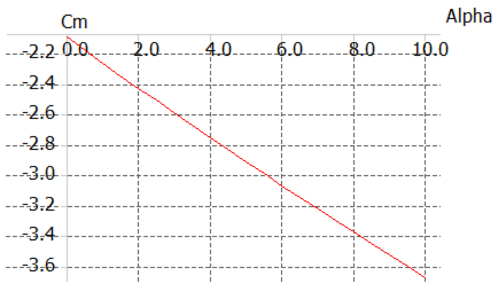


Fig.4-Pitch angle Vs Moment coefficient in UAV after the model improvement

It is shown below that the condition for UAV to possess static stability at a given trim condition is that the gradient of the C_l Vs Alpha (AoA) plot is positive. Obviously, a very large range of values of the gradients is possible and the magnitude of the gradient determines the degree of stability possessed by this UAV. Variation in the degree of longitudinal static stability is illustrated in Fig.5. This means, the tendency of center of gravity to move forward from natural point of the air frame is high[1].

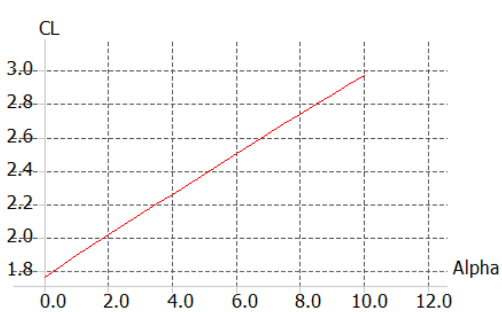


Fig.5- Pitch angles Vs Lift coefficient in UAV

A. Root Locus Plot for UAV

Root Locus interpretation for the UAV lateral and longitudinal modes are shown below and analyzed the pitch attitude feedback on UAV at the same flight condition [1].

The typical root locus graphs are plotted for four natural lateral modes (fig.6) and four natural longitudinal (fig.7) modes. These illustrate the negative damping constants in both modes then also the degree of stability is more [11].

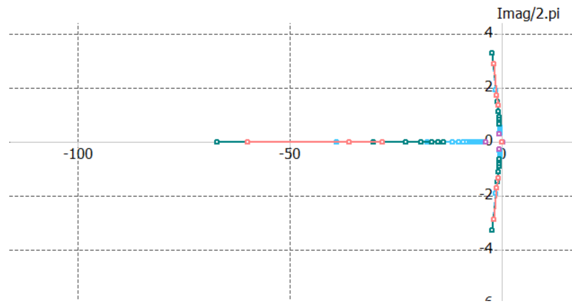


Fig. 6- Lateral mode

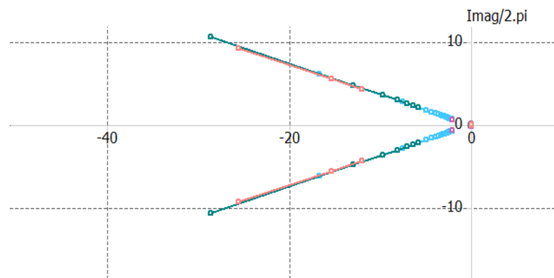


Fig.7- Longitudinal mode

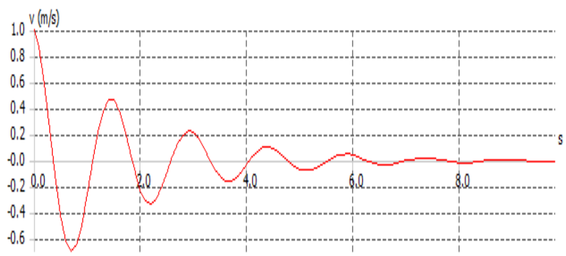
B. Short Term Response for the Dynamic Model

The UAV handling qualities are mainly concerned with the dynamics of the initial, or transient, response to controls [1]. Thus since the short term dynamics are of the greatest interest and it is common practice to conduct handling quality studies using reduced order dynamic models derived from the full order equations of motion [9].

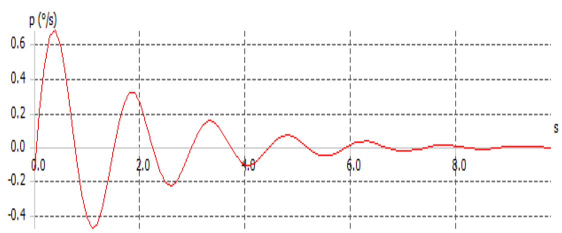
The advantage of this approach is that it gives maximum functional visibility to the motion drivers of greatest significance. The lateral behavior is described by four variables.

The spring lateral stability analysis has been done for this UAVon XFLR5 simulation software environment. When it was flying in steady state position at an altitude of 8000 ft the head angle turned down from 2˚ due to the unexpected perturbation and the spiral lateral mode stability is described as follows. When the UAV was in its steady state, the roll rate and the yaw rate were equal to zero. But, for the sudden deviation of the head angle these were fluctuating and progressively returned to zero with in very short period. The results are shown in fig .8.

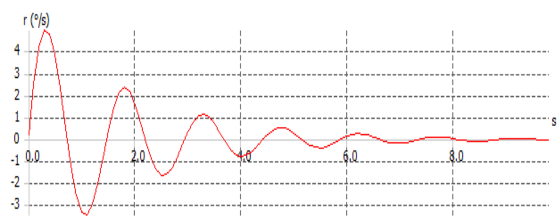
A well designed UAV should be tested for twenty odd different modes for the stability. Among these twenty, four natural longitudinal and four natural lateral modes are the most important[4]. The procedure for investigating and interpreting the other lateral modes and longitudinal modes of this UAV are much similar to lateral spiral mode. Therefore it is not repeated at the same level of detail in this paper because of the pages limitation. But this UAV has tested for the twenty odd stability modes and it has shown a good stability in open loop after few flight geometrical changes.



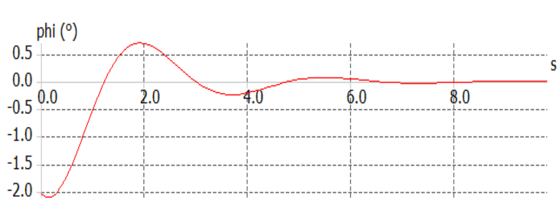
Lateral speed variation v= dy/dt about the steady state value V = (U_0,0,0)



Roll rate diviation P = dθ/dt



Yaw rate variation r = dψ/dt



Heading angle variation φ

Fig.8 – Air frame response for spring lateral stability mode

IV.CONCLUSIONS

Through this stability analysis, model of this UAV and its stability could be increased from its previous position. And this is very important practice for any newly developed UAV to avoid the unnecessary money waste and to decrease the period of time for the project.

But, there are some limitations in this method because of high non-linear behavior of the flight dynamic modeling. Therefore the smart autopilot is crucial to overcome this problem and achieve a long flight endurance and quality fly.

V.ACKNOWLEDGEMENT

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