7. ANKARA INTERNATIONAL AEROSPACE CONFERENCE
11-13 September 2013 - METU, Ankara TURKEY

AIAC-2013-035

FLIGHT SIMULATION OF A HIGH WING UNMANNED AERIAL VEHICLE

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ABSTRACT

In this paper the UH-UAS MK.2 an existing Unmanned Aerial Vehicle (UAV) which developed at the University of Hertfordshire is mathematically modelled and its dynamic behaviour is simulated by implementing the model within the computer software, MATLAB and SIMULINK. Longitudinal and lateral stability derivatives were estimated based on method introduced in the United States Air Force Stability and Control Datcom. A SIMULINK model was developed to predict dynamic behaviour of the UAV. In addition a MATLAB program was written to validate the developed SIMULINK model and further analysis. An eigenvalue analysis was performed to investigate the UAV dynamic characteristics. Dynamic responses to various control input, atmospheric disturbances (gust) and initial condition were determined. A brief study of augmenting the lateral motion by utilizing the classic control theory and modern control theory were performed. It was shown that the motion can be controlled and a state feedback is designed to control the spiral instability.

INTRODUCTION

Nowadays UAVs are used widely in civil and military applications. Missions like fire-fighting or detecting radiation levels around nuclear power sites are dangerous and hazardous to be performed by humans, but are obvious applications for UAVs. Increasingly other applications are being considered for economic reasons.

New generations of UAVs will be much more advanced, completely autonomous and independent from being controlled by pilot. They can do any sort of missions at any situation and return to their base safely. Hence, the roles of the UAVs are shifting from only those cannot be performed by manned aircraft to those currently performing by manned aircraft, Cargo or unconventional battle for instance.

These complex missions require more sophisticated UAV with more modern technology. In order to achieve such objective, better understanding of the flight dynamics of UAV and more accurate flight simulation is essential.

UAV CHARACTERISTICS ESTIMATION AND MODELLING

Simulation and modelling the flight dynamics of UAV in Matlab/Simulink, requires consideration of the UAV characteristics such as C.G. location, Moments and product of Inertia, Aerodynamic characteristics and the Stability and Control derivatives.

Moments of inertia can be estimated experimentally by swinging the UAV as a pendulum which relatively simple and convenient to imply on the UAV. The aerodynamic coefficients can be estimated theoretically or experimentally by using Computational Fluid Dynamic software packages or wind tunnel testing.

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Moreover, the non-dimensional stability and control can be estimated empirically based on a method introduced in the United States Air Force Stability and Control Datcom. The method can be used for different configuration, different flight condition and different flight regime.

FLIGHT SIMULATION AND DYNAMICS STABILITY AND CONTROL ANALYSIS

To prevent any damages during test flight it is crucial to predict the response of an aircraft to control or atmospheric input. Furthermore these simulations provide fundamental information to modify the aircraft.

The SIMULINK model named “motion.mdl” is developed to simulate the longitudinal and lateral dynamics of UH-UAS MK.2. Servo motors are assumed perfect in the model. In addition, the MATLAB program named “UHUAV.m” is developed to compute all required parameters of the UAV characteristics. The source code also simulates the longitudinal and lateral motion of the UAV which is used to validate the SIMULINK model.

Table 1 shows the eigenvalues, damping ratio, undamped natural frequency, t1/2 and the period of the oscillation for SPPO mode (short term) and Phugoid (long term) mode.

Table 1, Longitudinal Motion

	SPPO	Phugoid
Eigenvalues	-5.2300 ± 4.5476i	-0.0582 ± 0.4348i
Damping ratio ([illegible])	0.7546	0.1326
Undamped natural frequency([illegible])	6.9306 rad.s-1	0.4387 rad.s-1
t1/2	0.1319 s	11.8593 s
Period	1.3817 s	14.4506 s

As can be seen from the table, UH-UAS MK.2 is stable in longitudinal motion. It can be concluded that the SPPO motion reaches to 0.004 of its initial amplitude in approximately 1 second while the Phugoid motion damps to half of its initial amplitude after approximately 12 seconds.

The eigenvectors V is calculated for further analysis. To interpret this matrix, it is more convenient to compute the magnitude of each component of the eigenvector. The MATLAB source code “UHUAV.m” is used to compute these matrices as follow:

$$V = \begin{bmatrix} -0.0041 - 0.0032i & -0.0041 + 0.0032i & -0.1263 + 0.6157i & -0.1263 - 0.6157i & u \\ -0.0314 - 0.1966i & -0.0314 + 0.1966i & 0.0090 - 0.0423i & 0.0090 + 0.0423i & w \\ 0.9699 & 0.9699 & -0.0414 + 0.3092i & -0.0414 - 0.3092i & q \\ -0.1056 - 0.0918i & -0.1056 + 0.0918i & 0.7112 & 0.7112 & \theta \end{bmatrix}$$

SPPO mode Phugoid mode

$$\begin{bmatrix} 0.0052 & 0.0052 & 0.6285 & 0.6285 & u \\ 0.1991 & 0.1991 & 0.0432 & 0.0432 & w \\ 0.9699 & 0.9699 & 0.3120 & 0.3120 & q \\ 0.1399 & 0.1399 & 0.7112 & 0.7112 & \theta \end{bmatrix}$$

Magnitude of eigenvector matrix V

It can be seen that u and θ are governed by the Phugoid mode since 0.6285>0.0052 and 0.7112>0.1399. In contrary the SPPO mode is dominant in w and q since the magnitudes of SPPO mode for these two variables are much greater than Phugoid mode magnitudes.

The figure 1 shows the UAV response to 1° elevator step input. The axial and normal velocity, AOA, pitch angle, pitch rate and flight path angle are demonstrated respectively. The figure illustrates both SPPO mode and Phugoid mode. The Phugoid mode is visible in all variables, whereas the SPPO mode is visible in the variables angle of attack (α), normal velocity perturbation (w) and pitch rate (q).

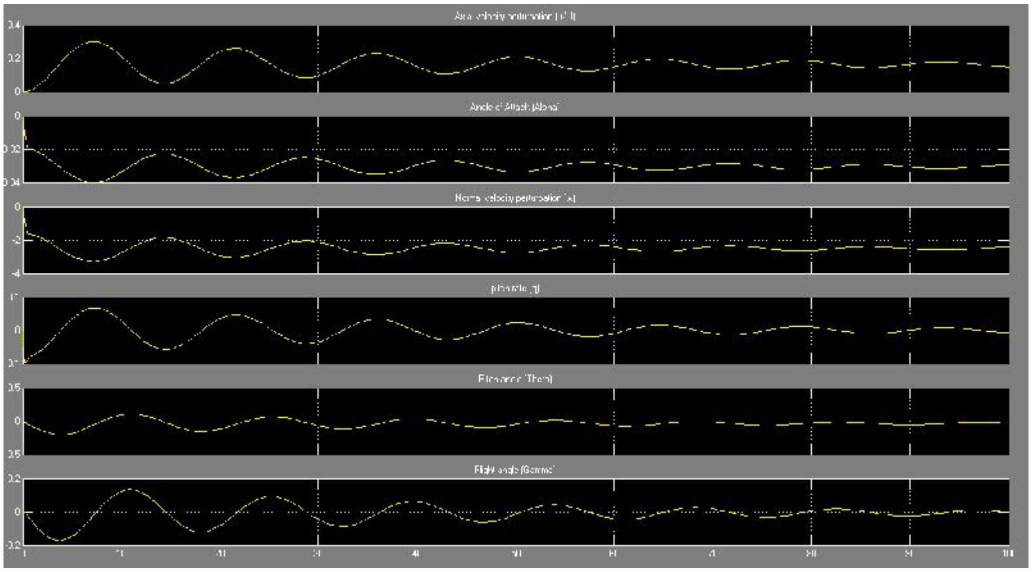

Figure 1: Long term response to 1° elevator step input(SIMULNIK model)

For further analysis the MATLAB source code is developed to provide additional tools to analysis the responses.

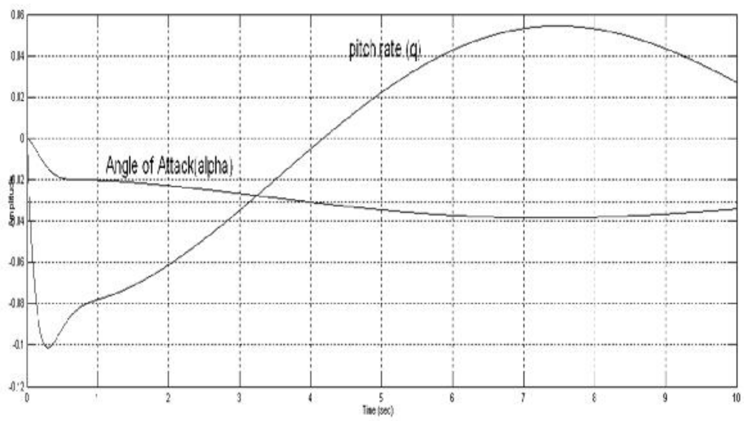

Figure 2: Short time response to 1° elevator step input

The figure 2 shows the UAV short term response to 1° elevator step input. It can be seen from the figure that the SPPO is heavily damped and it is completely died out in less than 2 seconds. Under the effect of the SPPO mode, the pitch rate is reached to a maximum value of -5.8 $deg.s^{-1}$at t=0.3 s. On the other hand the angle of attack is reduced by 1.14° under the influence of SPPO mode.
Figure 3 shows long term response to 1° elevator step input. The developed SIMULINK model can be validated by comparing figure 3 and figure 1. As is shown in the figure the Phugoid mode is damped out in approximately 80 seconds. In addition, it can be seen that this nose-down input left the UAV with reduction in incidence and pitch angle while the velocity is increased.Changes in velocity, angle of attack and pitch angle are as follow:

velocity	14.76 ft/sec
α	-1.77°
θ	-4.01°

As it is expected, the pitch rate, q, reaches a steady state value of zero.

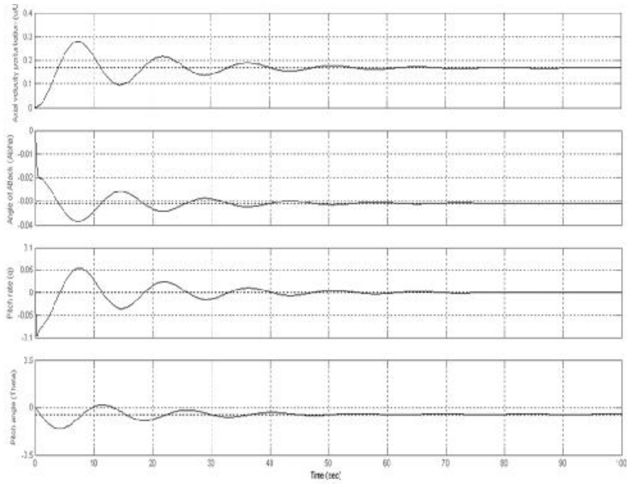

Figure 3: Long term response to 1° elevator step input

The response of the UAV to given initial conditions is computed using the SIMULINK model of the UAV.The given initial conditions are as follow:

Table 2,Given initial condition

Variable	Initial value
$\frac{u}{U}$	0.2
α	4°
[illegible]	8.76°/s-1

The simulation clearly demonstrates that the initial conditions are damped out and the UAV is returned to its equilibrium state after approximately 90 seconds. Figure 5 shows the SPPO response to given initial conditions. As can be seen from the figure, there are considerable changes in both angle of attack and pitch rate and the SPPO mode is damped out in 2 seconds.

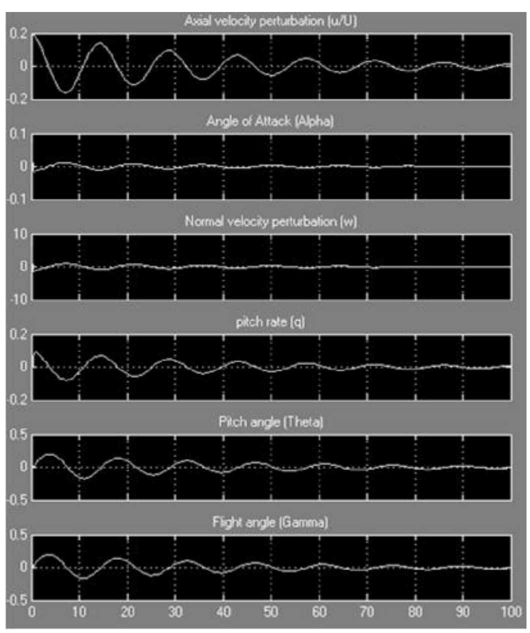

Figure 4: Long term response to given initial conditions (SIMULNIK model)

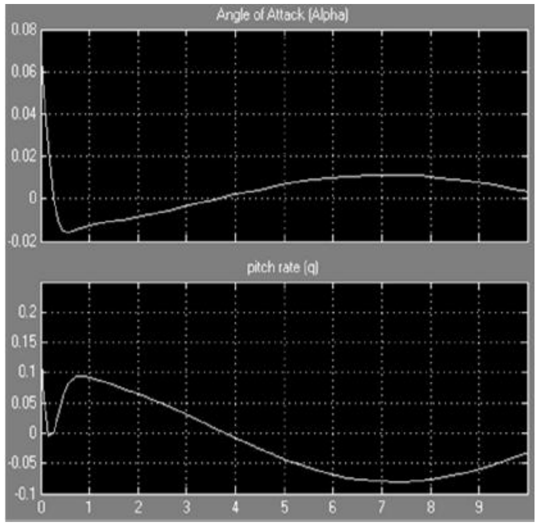

Figure 5: Short term response to given initial conditions (SIMULNIK model)

Moreover, the analysis of the characteristics of the UAV reveals that Roll mode and Spiral mode are overdamped while Dutch roll is lightly damped. The spiral is observed to be divergent with time to double bank angle of 24.9 seconds. From the value of the time to double it may be concluded that the instability experienced by the UAV can be corrected by remote control or piloting. This matter has been proven since the UAV had been flown and tested. In addition, this flight stability problem is dealt in last section of this paper and a modification solution based on modern control theory is proposed.
The UAV lateral responses of the UAV to 1° impulse aileron input is determined and illustrated in figures 6.

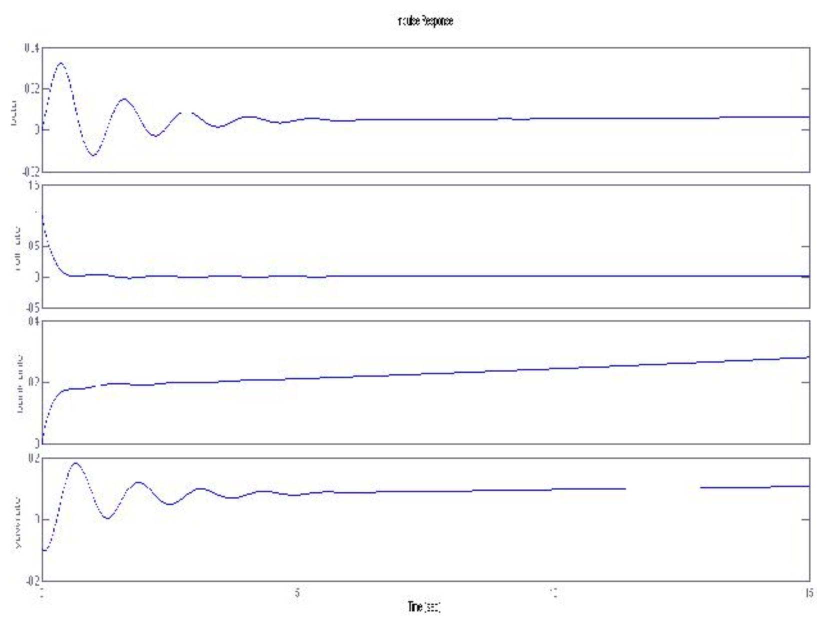

Figure 6: Response to 1° impulse Aileron input

It can be seen from the figure that the UAV is unstable in lateral motion. This instability is caused by the unstable root of spiral mode which was predicted in previous section by eigenvalue analysis.
Further analysis by using SISO transfer functions of the UAV dynamics shows that the classic control theory cannot be applied to control the instability. Hence control using feedback is proposed for the UH-UAS MK.2 lateral stability and control problem. The controllability matrix, MC, is determined for both inputs. Since only one of the eigenvalues of lateral motion is in unstable region, the state

feedback matrix, K, is obtained in manner that only this eigenvalue changes from 0.0277 to -0.002. Table 3 shows the new eigenvalues of lateral motion.

Table 3, Lateral motion with state feedback eigenvalues

-0.7234 ± 5.1512i
- 4.9355
- 0.002

To conclude, the lateral response of the augmented UAV to different control input is simulated. Figure 7 shows responses of the UAV with stat feedback to 1° impulse Aileron input, which evidently is a stable motion.

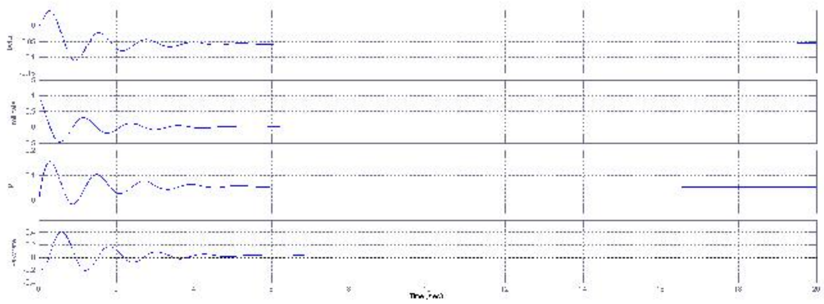

Figure 7: Response to 1° impulse Aileron input (with state feedback)

ATMOSPHERIC DISTURBANCES (GUST)

The response of the UAV to disturbances is predicted without any control input. It is assumed that the gust acts in such a manner so that the UAV moves only in the Z-direction. Thus axial velocity perturbation, pitch angle, pitch rate and control input are set as zero in the Z-force of equation of motion of the UAV. The response of the UAV to two different atmospheric disturbances sharp-edged and Sinusoidal profile are analysed. These two gusts profile are quite common and they can be used to produce arbitrary gust profile. The sharp-edged gust is defined as [Lewis, 2008;Schmidt, 1998; Babister, 1980;Nelson1998]:

$$w_g(t) = \begin{cases} 0 & t < 0 \\ 5 & t > 0 \end{cases}$$

The amplitude of the gust is zero before t=0 and it is 5 ft/sec for t>0.The time constant (τ) of the UAV which shows how fast the UAV responses to the gust is computed (τ= 0.2550). Small time constant indicates that the UAV will respond fast to disturbance while a large one is for a UAV with slow responses. The figure 8 shows the UAV respond after being disturbed with a sharp-edged gust.

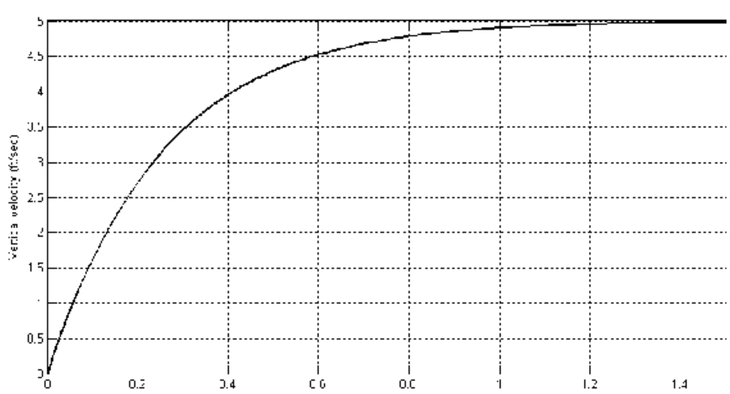

Figure 8: Response to sharp-edged gust

From the figure 8 it can be seen that the UAV approaches to a new steady-state condition after 6τ with a vertical velocity of 5 ft/sec.

In contrary, the sinusoidal gust is no longer constant with time. The sinusoidal profile is defined as [McLean, 1990; Schmidt, 1998]:

$$w_g(t) = -\frac{w_g}{2}\left(1 - \cos\frac{\pi x}{d}\right)$$

Where,

d =gradient distance, $12.5c$

c = wing chord length

w_g =magnitude of vertical gust velocity

The response of the UAV to a sinusoidal gust profile is modelled in the figure 9. The gust amplitude, w_g, is set 2 ft/sec and the simulation is run for 0.25 second. The figure 9 illustrates the changes in load factor after being disturbed with a sinusoidal gust. From the figure it can be seen that the maximum load factor is 1.03 g occurring at t=0.08 s.

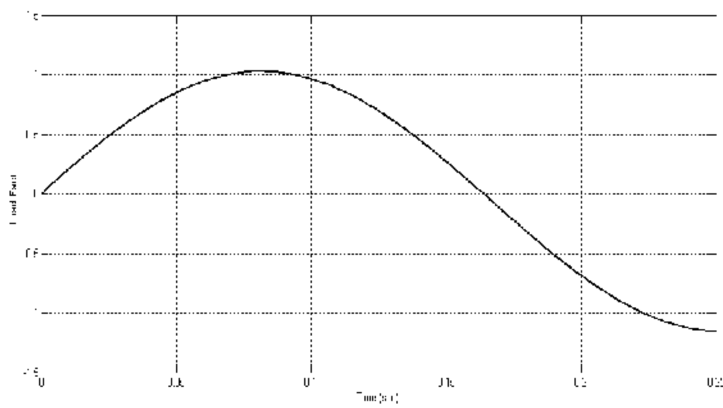

Figure 9: Response to sinusoidal gust

CONCLUSION

In this work, flight simulation and an evaluation dynamic and flight stability of a high wing Unmanned Aerial Vehicles, UH-UAS MK.2, is presented, which can be used for future modification on UH-UAS MK.2. The developed SIMULINK model and MATLAB source code program is flexible to any modification to the UAV or flight condition change and can be modified to simulate dynamics of any conventional UAV. The simulation reveals that the UH-UAS MK.2 is statically stable while it is dynamically unstable. Further eigenvalue analysis shows that this instability is caused by a divergent spiral mode. It was concluded that the divergent spiral mode with time to double bank angle of approximately 25 seconds can be corrected by remote control which this matter has been proven since the UAV had been flown and tested.

It is also demonstrated that the designed augmenting system to incorporate bank angle makes the augmented UH-UAS MK.2 dynamically stable.

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