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ANALYSIS OF A LIGHT AIRCRAFT RESPONSE TO GUST WIND BASED ON NONLINEAR MODEL

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ABSTRACT

This work simulates and analyzes the behavior and performance of a light aircraft in steady level flight subjected to gust wind. A home-made code is developed using MATLAB to simulate the aircraft behavior using the nonlinear 6-DOF and the aerodynamics and engine model were utilized in this code. The gust model used in this analysis is sine-wave shaped gust.

The aerodynamic behavior of this aircraft was investigated using CFD at different angles of attack and side slip angles. The x, y and z forces and moments were calculated at a flight speed of 50m/s and at sea level conditions. Lift and drag curves for different angles of attack were determined. The maximum lift coefficient for this aircraft was 1.67 at angle of attack of 17°; the maximum lift to drag ratio (L/D) was found to be 13 at α=2°, and the zero lift drag coefficient was 0.0342. Also, the yawing moment coefficient was determined for different side slip angles as well as rolling moment. The static stability of the aircraft was analyzed based on these results. Also, USAF digital DATCOM was used to estimate the dynamic derivatives of the vehicle. The engine was modeled by a simple model such that engine power and thrust vary with altitude and speed.

The simulation results indicate that the aircraft is stable, controllable and the gust wind effect is eliminated and damped in a few seconds. In addition, the load factor increment due to gust effect is not critical.

KEY WORDS

Nonlinear 6 DOF equation of motion, CFD, aerodynamics model, and gust wind.

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NOMENCLATURES

A	Aspect Ratio	C_n.	Yawing Moment coefficient
b	Wing Span (m)	e	Oswald Span Efficiency
C	Wing Chord (m)	L	Lift force (N), Rolling Moment (N.m), Length (m)
c_D	Drag Coefficient	M	Pitching Moment (N.m), Mach No.
c_L	Lift Coefficient	N	Yawing Moment (N.m)
C_l	Rolling Moment coefficient.	p	rolling rate (rad/s)
C_m.	Pitching Moment coefficient	q	Pitching rate (rad/s)
S	Wing Area (m^2)	r	Yawing Rate(rad/s)
x, y, z	Coordinate System		

INTRODUCTION

Atmospheric turbulence is air movement on a small scale. It is caused by the instabilities of pressure and temperature distributions in clouds, near the ground, and in the wind-shear regions of the jet stream [1]. The mechanism of turbulence is such a varied and complicated process that statistics offer only manageable method to handle gust design problem.

Early models characterized turbulence as a discrete gust and the “sharp edge gust” was of this type. Then, this model modified into Power Spectral Density method PSD. In this method, the gusts were regarded as random fluctuations in a continuous random process. The PSD was essentially a decomposition of the energy of the random process with respect to frequency or wave length . This method will be applied in this paper [1].

Consequently, The Federal Aviation Administration has supported the development of the Statistical Discrete Gust (SDG) Method, for use as an alternative procedure of estimating severe gust and turbulence loads, The SDG method has been identified as a possible method, which can handle both discrete gust events and relatively continuous turbulence, and which moreover can be used to evaluate highly nonlinear systems [2].

Simulation of flight vehicle trajectories and its behavior is renewed interest due the current development of UAV’s and advanced air vehicles. The first known flight simulation device was to help pilots fly the Antoinette monoplane [3].

Aircraft response to atmospheric gust was studied by Sharma and Gosh [1]. They presented a robust technique to design the flight controllers for the aircraft to fly under turbulent atmosphere as well as to perform maneuvers incorporating the whole highly nonlinear dynamics of the aircraft system. Another study done by Hahn

Schwarz [2] where analyzed gust effects on passenger comfort and the safety of aircraft.

In the present work, nonlinear equations of motion was utilized to simulate the gust effect on the aircraft. The aerodynamics model was investigated using CFD techniques to evaluate all longitudinal and lateral static stability. Regarding dynamic derivatives coefficients, DATCOM method has been applied. Moreover, the engine model assumes that engine power linearly decreases with altitude increment.

MATHEMATICAL MODEL OF THE AIRCRAFT

A light aircraft were constructed with following specification presented in Table 1.

Table1. Aircraft Specifications.

Aircraft Specifications		Units
Weight	700	*Kg*
Cg	0.25 MAC	
Wing Reference area, S_{ref}	15.87	*m^2*
Span, b	10.6	*m*
MAC, $\overline{C}$	1.495	*M*
I_{xx}	989	*Kg. m^2*
I_{yy}	981	*Kg. m^2*
I_{zz}	1895	*Kg. m^2*

Aerodynamics Model

A simulation of the flow field around this light aircraft using numerical solution of the Reynolds Averaged Navier-Stokes equations coupled with K-ω turbulent model has been used in order to calculate the steady state aerodynamics coefficients.

Furthermore, a calculation to the aircraft aerodynamics behavior was done for different angles of attack and side slip angles. A calculation for *x, y* and *z* forces and moments were done at flight speed of 50m/s and sea level conditions .A plotted for lift and drag curves for different angles of attack were done. The maximum lift coefficient at an angle of attack of 17° for this light aircraft was 1.67. Maximum lift to drag ratio (L/D) occurs at $\alpha=2^{\circ}$ was 13 as shown in Fig. 6, and the zero lift drag coefficient was 0.0342.

DATCOM method had been applied to calculate the dynamic stability derivatives and control surface derivatives.

Mesh creation

Figure 1 shows the mesh elements around this light aircraft body, a fine mesh is focused near a/c surface to smooth surfaces as well as considering the boundary layer effect, the interval size of the element is almost 2.5 (mm), which is created using CFD preprocessor software GAMBIT.

Unstructured grid with triangles and tetrahedral in the surface and volume meshes, approximately 4 million cells is created in the computational domain of the aircraft.

The mesh was created on the faces and surfaces of the domain in GAMBIT, and in order to construct the 3-D volume element, this surface mesh file is exported to TGRID software to construct tetrahedral element type mesh that will be exported to solver in FLUENT.

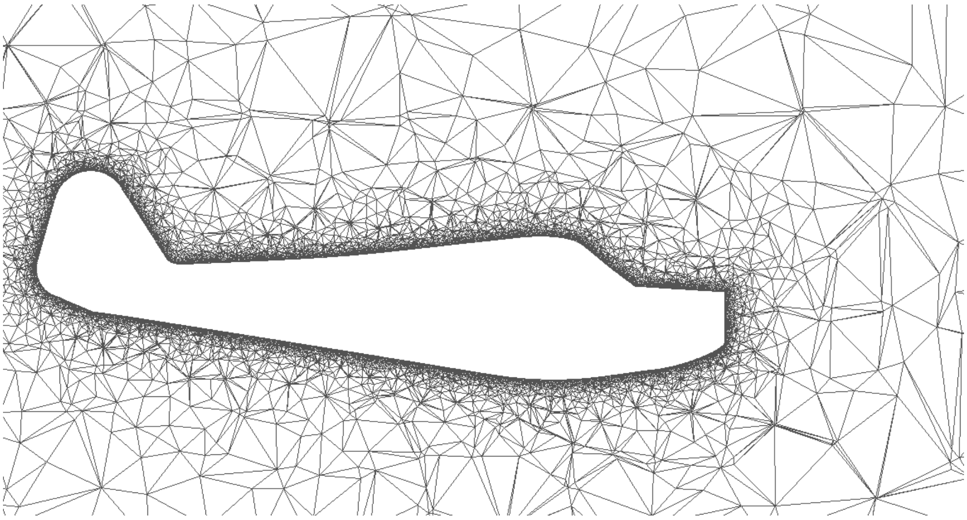

Fig. 1. Mesh Elements Around Aircraft.

Specifying boundary conditions

Computational domain is shown in Fig. 2 with specified boundaries. The domain is created big enough to set farfield values of velocity and pressure. Farfield boundary conditions require the lower effect of wing downwash and wake behind wing and a/c, the domain dimensions are 6 times the wing span in the radial direction and 11 times the wing span behind the a/c .

Figure 2 also illustrates the boundary conditions specified to the computational domain; the outlet boundaries define the outlet as zero variable gradient, except fixed value of pressure. The inlet and outlet flow field variables (pressure, density, viscosity and temperature) tabulated in Table 2.

A/C surfaces split into different segment or parts named by a/c surfaces parts i.e *wing, Body, Vertical Tail and Horizontal Tail.* wall boundary condition specified to the

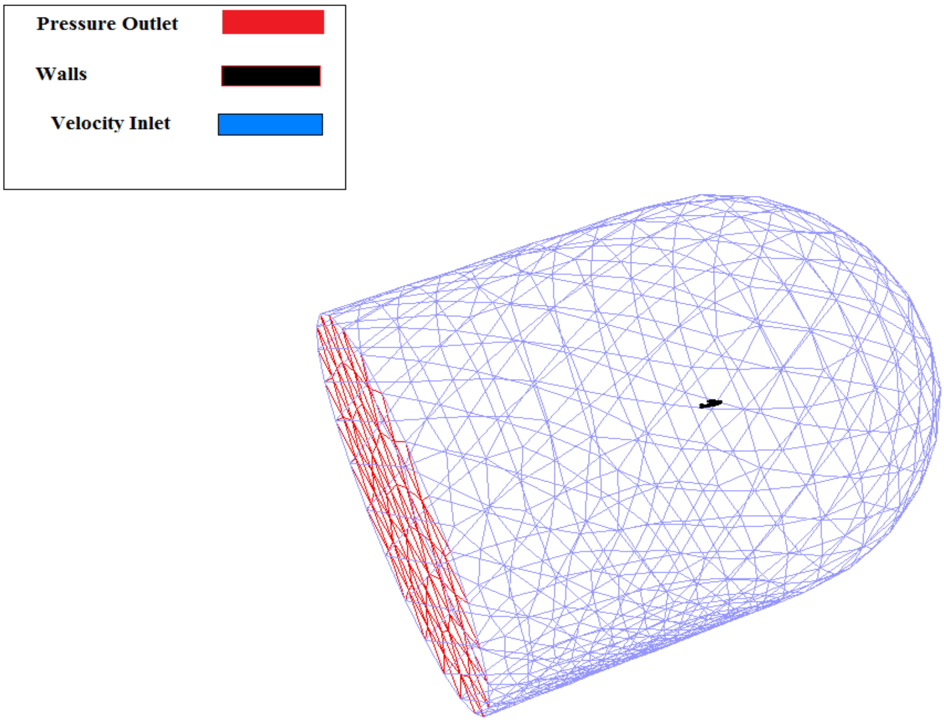

Fig. 2. Boundary Conditions and Domain.

Table 2. Free Stream Values.

Alt (m)	Density (kg/m^3)	Pressure (Pa)	Viscosity (kg/m/s)	Velocity (m/s)
0	1.225	101325	1.7894×10^{-05}	50

A/C surfaces, the *Non-slip wall* is applied on a/c surfaces (zero velocity relative to the wall; wall stress computed by viscous-stress or wall-function expressions).

The operating condition and farfield velocity are defined according to Table 2, the incompressible solution coupled with K-omega SST turbulent model is selected to solve the current analysis. Several angle of attack and side slip angles are solved.

The output from this analysis is lift, drag, side forces and pitching moments , yawing moments , and rolling moments coefficients variations with angles of attack and side slip angles only.

For estimating dynamics derivatives DATCOM method is used, the aircraft model and dimensions are specified in the DATCOM files and the results are acquired and sorted out. The DATCOM software main features are the low computing time comparing with CFD simulations, and wind tunnel results.

The aerodynamic force and moment coefficients are calculated based on the following equations [6,7]:

$$C_D = C_{D_1}(\alpha) + C_{D_{\delta_e}}\delta_e + C_{D_q} q \frac{\overline{C}}{2V_\infty} \tag{1}$$

$$C_L = C_{L_1}(\alpha) + C_{L_{\delta_e}}\delta_e + C_{L_q} q \frac{\overline{C}}{2V_\infty} \tag{2}$$

$$C_y = C_{y_\beta}\beta + \left[C_{y_p} p + C_{y_r} r\right]\frac{b}{2V_\infty} + C_{y_{\delta_a}}\delta_a + C_{y_{\delta r}}\delta_r \tag{3}$$

$$C_l = C_{l_\beta}\beta + \left[C_{l_p} p + C_{l_r} r\right]\frac{b}{2V_\infty} + C_{l_{\delta_a}}\delta_a + C_{l_{\delta r}}\delta_r \tag{4}$$

$$C_m = C_{m_1}(\alpha) + C_{m_{\delta_e}}\delta_e + C_{m_q} q \frac{\overline{C}}{2V_\infty} \tag{5}$$

$$C_n = C_{n_\beta}\beta + \left[C_{n_p} p + C_{n_r} r\right]\frac{b}{2V_\infty} + C_{n_{\delta_a}}\delta_a + C_{n_{\delta r}}\delta_r \tag{6}$$

A look up table is constructed and then interpolated at given flight data to give an accurate value of the aerodynamic forces and moments acting on the aircraft at each time step.

Propulsive Model

The engine represented by a simple model that the power is assumed constant and the thrust is calculated as function of relative wind speed. The throttle position is set to 0.5, that the cruise setting of the throttle.

Atmospheric Turbulence

The pure pitching (plunging) gust model will be applied on the nonlinear equations of motion. The analysis of this motion is described in Refs. [5,6,7]. In the following, the vertical velocity of the gust is described as a sin-wave harmonic motion and represented by:

$$w_g(t) = A_g(1 - e^{-t/\tau}) \tag{7}$$

Nonlinear Equations of Motion

The motions of an aircraft are affected by external forces and moments resulting from flight through the atmosphere and engine thrust, acting on the airplane [6]. The airplane motions are calculated using the equations of motion as derived from Newton’s laws. By adding all forces acting on all parts of the aircraft as well as the moments due to these forces about the centre of gravity of the aircraft, the resulting general earth-flat equations of motion of an aircraft at the fixed coordinate system [7]:

$$
\begin{aligned}
\dot{u} &= rv - qw - g\sin\theta + (X_A + X_T)/m \\
\dot{v} &= -ru + pw + g\sin\phi\cos\theta + (Y_A + Y_T)/m \\
\dot{w} &= qu - pv + g\cos\phi\cos\theta + (Z_A + Z_T)/m
\end{aligned}
\tag{8}
$$

$$
\begin{aligned}
\dot{\phi} &= p + \tan\theta(q\sin\theta + r\cos\phi) \\
\dot{\theta} &= q\cos\phi - r\sin\phi \\
\dot{\psi} &= (q\sin\phi + r\cos\phi)/\cos\theta
\end{aligned}
\tag{9}
$$

$$
\begin{aligned}
\Gamma\dot{p} &= I_{xz}(I_x - I_y + I_z)pq - [I_z(I_z - I_y{}^2)]qr + I_z l + I_{xz} n \\
I_y\dot{q} &= (I_z - I_x)pr - I_{xz}(p^2 - r^2) + m \\
\Gamma\dot{r} &= [(I_x - I_y)I_x + I_{xz}{}^2]pq - I_{xz}[I_x - I_y + I_z]qr + I_{xz} l + I_x n \\
\Gamma &= I_x I_z - I_{xz}^2
\end{aligned}
\tag{10}
$$

$$
\begin{bmatrix} \dot{p}_n \\ \dot{p}_e \\ \dot{h} \end{bmatrix} =
\begin{bmatrix}
C_\theta C\psi & S_\phi S_\theta C_\psi - C_\phi S_\psi & C_\phi S_\theta C_\psi + S_\phi S_\psi \\
C_\theta S_\psi & S_\phi S_\theta S_\psi + C_\phi C_\psi & C_\phi S_\theta S_\psi - S_\phi C_\psi \\
S_\theta & -S_\phi C_\theta & -C_\phi C_\theta
\end{bmatrix}
\begin{bmatrix} u \\ v \\ w \end{bmatrix}
\tag{11}
$$

This set of ordinary differential equations are solved using Runge-Kutta method. A home-made MATLAB based code is generated to solve these equations simultaneously.

RESULTS AND DISCUSSIONS

The results of the present work divided in to.

- Aerodynamics analysis results.
- Nonlinear flight simulation results.

Aerodynamics Analysis Results

CFD analysis has been conducted in order to investigate nonlinear aerodynamics flow field variables mainly stall progress. More details can be found in ref [8] that summarizes and gives details on the present analysis.

The static (forces and moments variations with respect to angle of attack and side slip angles), these derivatives or coefficients were calculated using CFD, the dynamics derivatives were determined via Digital DATCOM methods specified previously.

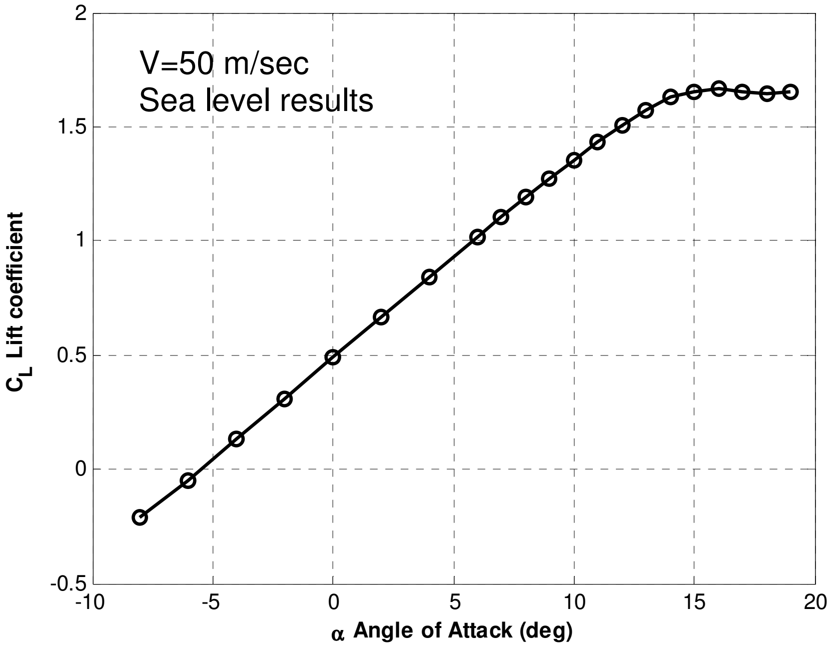

Fig. 3. Lift coefficient Vs angle of attack.

Figure 3 illustrate the relation between lift coefficient and angle of attack, this figure calculated using CFD and the stall is occurred at α=16°.

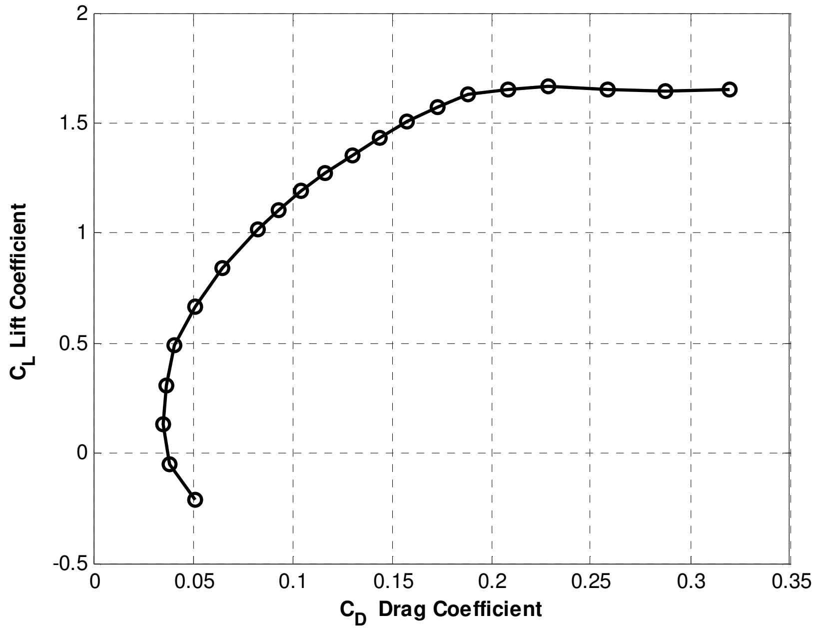

Fig. 4. Drag polar diagram.

The drag polar curve is plotted in Fig. 4, this figure is also obtained using CFD analysis. The zero lift drag coefficient is equal 0.0374. Usually CFD solution predicted higher drag due to the assumption of fully turbulent flow.

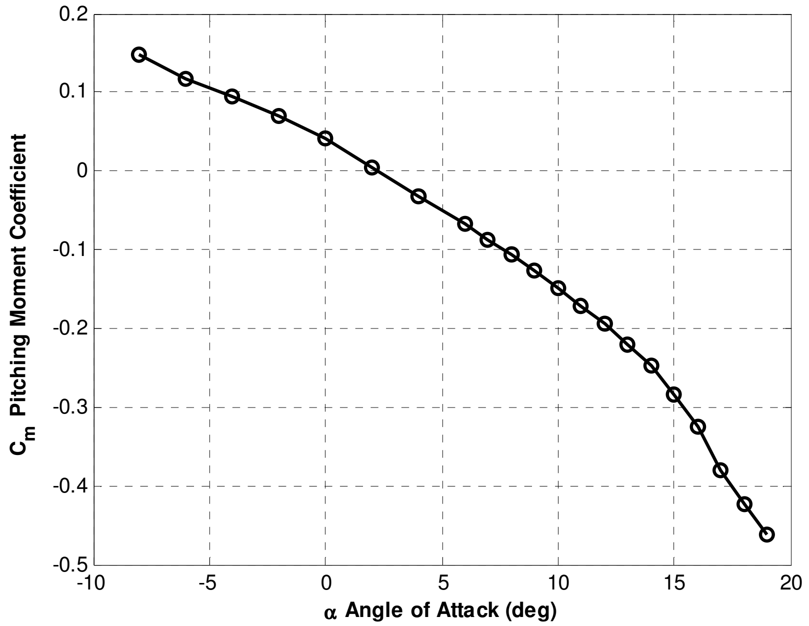

Fig. 5. Pitching moment coefficient C_m Vs angle of attack *α* (°).

Figure 5 illustrates the known C_m-α relationship. This figure reveals that this aircraft is statically stable since that the slope is negative.

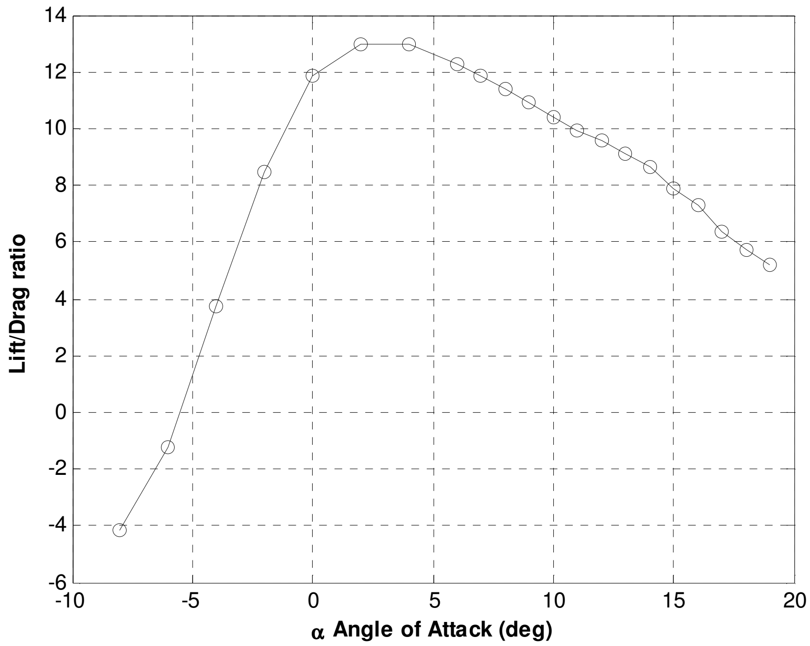

Fig. 6. Lift to drag ratio Vs angle of attack *α* (°).

Figure 6 illustrates the lift to drag ratio, the maximum L/D is 13 which corresponding to α=2º, the cruise L/D is 12. No doubt the L/D ratio is Important to analyze the performance behavior during cruise and decent specially.

Regarding the dynamic derivatives were calculated based on DATCOM method specified in ref [9, 10, 11]. The aircraft input file in DATCOM defines the flight conditions (speed, altitude, and angle of attack), aircraft geometry and units. The output file illustrate the forces and moments coefficients and derivatives variations with α, β, p, q, r. also the control surfaces effectiveness are calculated. A summary of the output results from DATCOM is shown in Table 3.

Table 3. Stability and Control Dervatives.

Dynamic Stability Derivatives (1/rad)						
C_{L_q}	C_{m_q}	C_{lp}	C_{yp}	C_{np}	C_{nr}	C_{lr}
5.3	-8.2	-0.48	0.01	-0.04	-0.046	0.14
Control Derivatives (1/rad)						
$C_{L\delta e}$	$C_{m\delta e}$	$C_{l\delta_a}$	$C_{l\delta_r}$	$C_{n\delta_a}$	$C_{n\delta_r}$	$C_{y\delta_r}$
0.43	-0.37	0.229	0.013	-0.05	-0.085	0.187

Nonlinear Flight Simulation Results

This section will summarize all the flight variables that are gathered from this analysis. The trim data were as follow: control surface deflections=0, no flap deflected and the cruise condition of throttle position is set to 0.5.

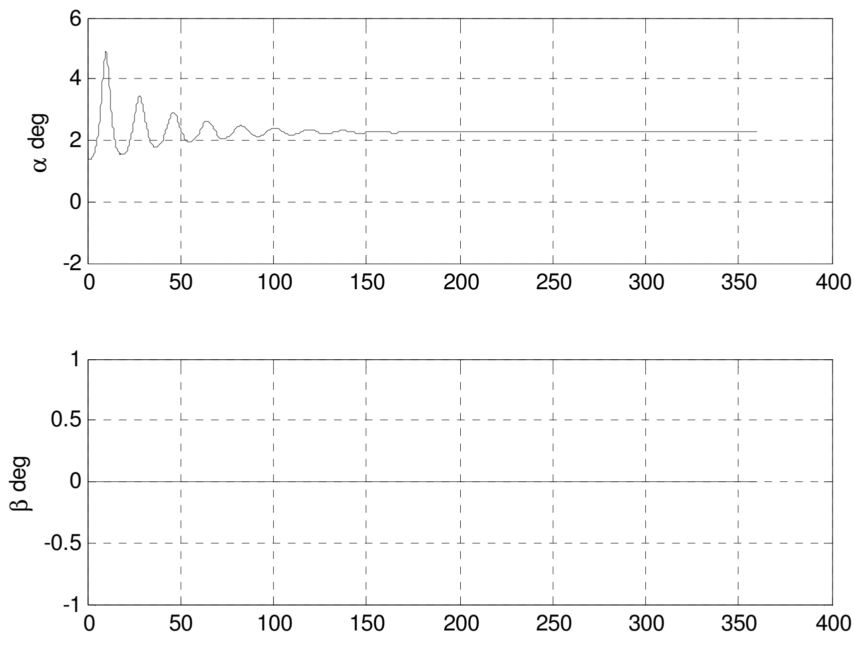

Fig. 7. Angle of attack and side slip Vs time (x axis).

At the beginning, the effect of the vertical gust on the flight angle of attack, this shown clearly in Fig. 7. But after 50 sec this effect is eliminated and damped well.

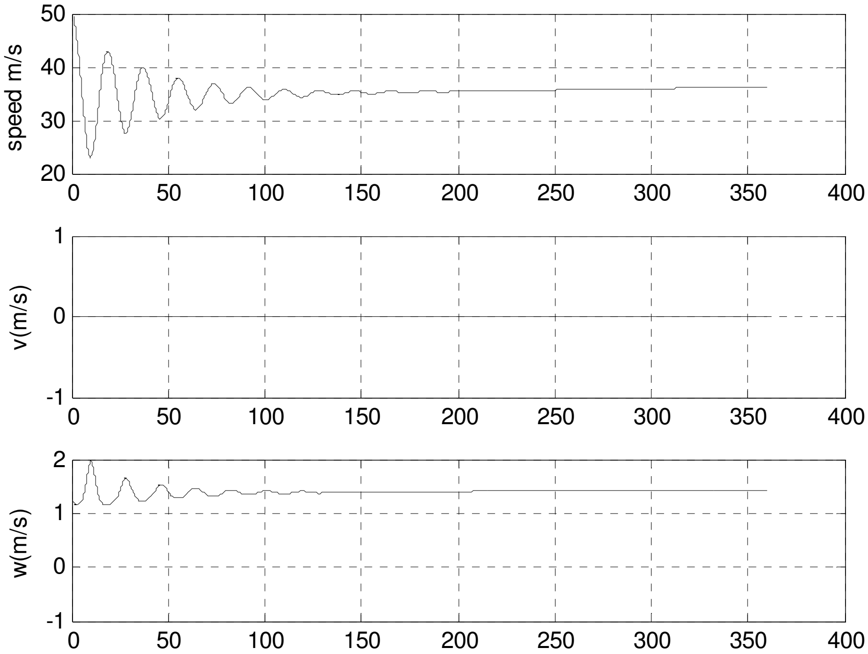

Fig. 8. Velocity in x, y, z (u,v,w)(on y-axis) Vs time (on x axis).

Figure 8 shows that there is no any lateral motion, and also only vertical plunging motion occurs which is damped, w has the same trend of angle of attack damping since they are affecting each other.

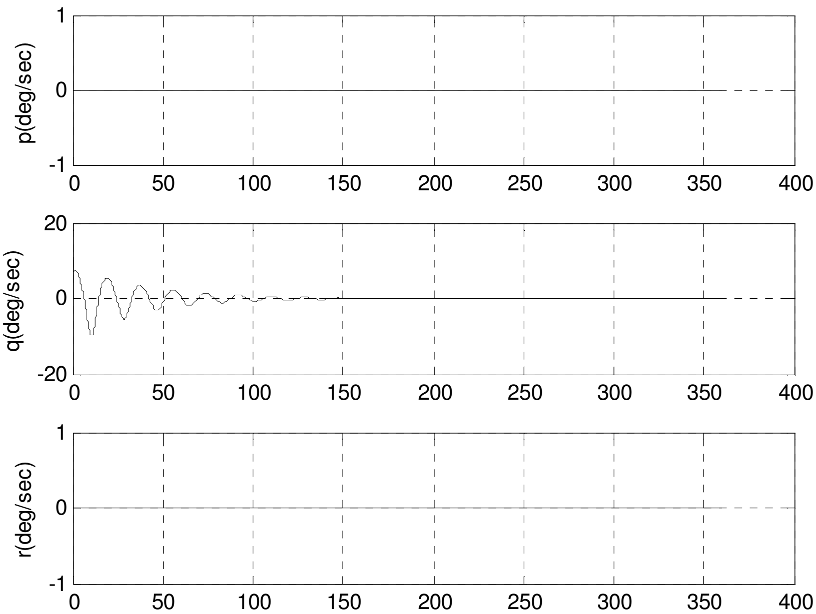

Fig. 9. p,q,r Vs time (x axis).

Figure 9 shows the nondimensional rate of roll, pitch and yaw p, q, and r respectively. This figure reveals that q is damped in about t 100 sec. the increment in the pitch rate is due to the incremental pitch angle of the airplane, now we can say that the aircraft is damped and dynamically stable.

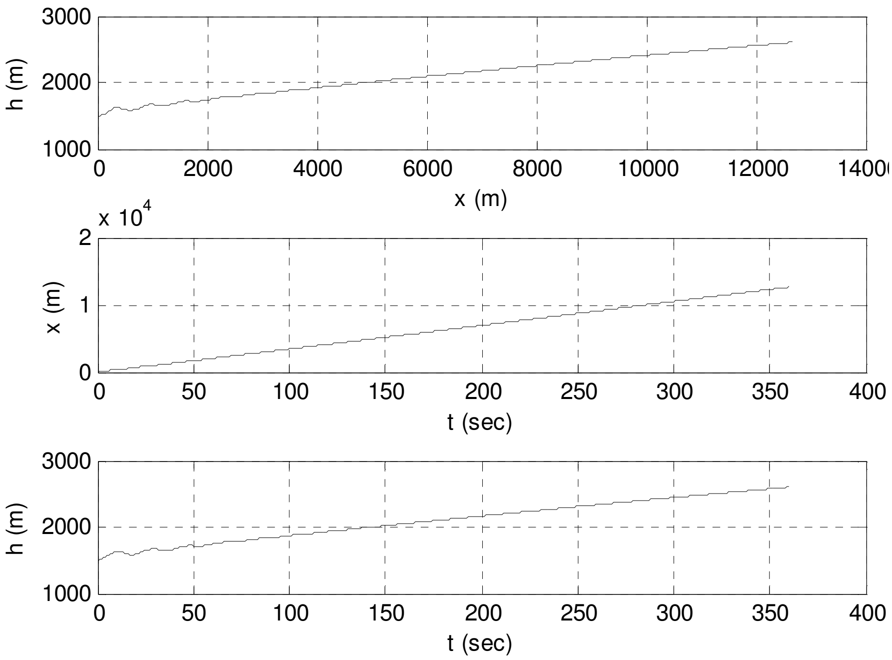

Fig. 10. Altitude Vs time and cross distance. Crossed distance Vs time, altitude Vs time

In Fig. 10, it is obviously that the aircraft raise it's height by 1000 (m) in 6 minutes.

The introduced results indicate that the aircraft has an ability to damp the vertical gust oscillatory motion. But the height of the aircraft will be increased due to the presence of vertical gust velocity,

CONCLUSION

This paper analyzed a light aircraft subjected to a vertical gust, the simple harmonic gust model is integrated with the nonlinear equation of motion. The aerodynamics forces and moments coefficient are estimated using state of the art CFD, also digital DATCOM software is used in order to estimate dynamics derivatives of the airplane and control effectiveness.

The results obtained from this simulation shows the vertical gust will cause an increment in the angle of attack and the pitch rate (q), also the altitude will be affected, this simulation do not consider any deflection in the control surfaces, so a trim function need to generated in the next simulation, to optimize the control surfaces deflection with respect to speed and angle of attack, also the throttle position hold fixed during this simulation, a more accurate propulsion model is need to be constructed.

A recommended work to be handled experimentally to validate the obtained aerodynamics forces and moments coefficients and derivatives from CFD and DATCOM. Also we recommend analyzing the short period and long period oscillations as well as Dutch roll.

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REFERENCES

[1] Sunil Sharma, A.K.Ghosh, “Simulation and Control of Highly Maneuverable Aircraft under Turbulent Atmosphere using nonlinear Dynamics” Chaotic Modeling and Simulation (CMSIM), pp 499-507, 2012.

[2] Klaus-Uwe Hahn, Carsten Schwarz, “Alleviation Of Atmospheric Flow Disturbance Effects On Aircraft Response”, 26th International Congress Of The Aeronautical Sciences, 2008.

[3] Peter H. Zipfil,”Modeling and Simulation of Aerospace Vehicle Dynamics”, 2nd Ed,. AIAA Education Series, pp. 447, 2007.

[4] Elijah E.Turner, “An Exposition On Aircraft Response To Atomespheric Turbulance Using Power Spectral Density Analysis Techniques”,Technical report, 1977.

[5] J.G.Jones, “Documentaion of The linear Statistical Discrete Gust method”, T echnical report, 2004.

[6] C. Nelson,”Flight Stability and Control”, 2nd Ed.

[7] Brain Stevens & Frank Lewis, “Aircraft Control and simulation”, Wiley Inter-science, New York, 1992.

[8] M. Mahdi, “Computational Aerodynamics Analysis of Light Aircraft”, MSc Thesis, Karary University, Apr 2012.

[9] “The USAF Stability And Control Digital Datcom User Manual”, , McDonald Douglas Astronautics Company, USAF, 1979.

[10] “USAF Digital DATCOM Theoretical Manuall Part 1” McDonald Douglas Astronautics Company, USAF, 1960.

[11] “USAF Digital DATCOM Theoretical Manuall Part 2” McDonald Douglas Astronautics Company, USAF, 1960

[12] Frederico R. Garza, Eugene A. Morelli, “A Collection of Nonlinear Aircraft Simulations in MATLAB”, NASA Report,NASA /TM-2003-212145.