



SIMULATION OF FLIGHT THROUGH GUST

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ABSTRACT

A flight simulation programme has been developed on a personal computer using Microsoft FORTRAN to simulate flight trajectories of a light aircraft by using Six-Degree-of-Freedom equation of motion. The simulation has been made realistic through pre-programmed the input to the control surfaces, atmospheric gust during the flight mode. The programme plays an important role in the evaluation and validation of the aircraft design process. A light aircraft (Cessna 182T) has been tested through free flight, gliding flight, flight with gust. The results show good trend and show that the programme could be dependent as a realistic flight test programme.

المخلص:

تم تطوير برنامج محاكاة الطيران على الحاسبة باستعمال لغة الفورتران لمحاكاة مسارات الطيران لطائرة خفيفة الوزن من خلال استخدام معادلات الحركة ذات الدرجة السادسة. لقد تم جعل المحاكاة اقرب الى الحقيقة من خلال البرمجة المسبقة للتحكم بسطوح التحكم، وعند وجود عاصفة جوية اثناء الرحلة الجوية. يلعب البرنامج دور مهم خلال تقييم وتحقيق عملية التصميم للطائرة. الطائرة الخفيفة (سيسزنا) تم اختبارها من خلال البرنامج للطيران الحر، والطيران الانزلاقي، والطيران خلال عاصفة جوية. اظهرت النتائج اتجاه جيد كذلك اظهر البرنامج انه من الممكن الاعتماد عليه كبرنامج اختبار للطيران الحقيقي.

Keywords: six degree of freedom, flight simulation, equations of motion

INTRODUCTION:

With the advent of the new state-of-the-art computers capable of performing several million floating point operations per second, computer simulation provides an inexpensive, powerful and flexible tool to simulate the various aspects of flight. A software has been developed in Fortran language using power station compiler to simulate flight trajectories of a light aircraft .situation that might ask for a simulation are for example Wind effects, Dynamic effects, Transition between different flight stages and needing simulating data of an aircraft part (e.g. lift force on the stabilizer). Wind effects and motion of the atmosphere can be discrete or random; in any case they are usually characterized by only the three velocity orthogonal components. Therefore, to account for atmospheric disturbances such as winds, gust or turbulence, the

forces and moments must be related to the relative motion with respect to the atmosphere. This is accomplished by expressing the velocities used in calculating the aerodynamics in terms of inertial and gust velocities.

Many references deal with equation of motion in a non uniform atmosphere, one of the important references is (Roskam 1972), some of the analytical techniques are available to flight control engineers to study the dynamic response of an airplane to control deflection or atmospheric disturbances. Gust, wind shear and turbulence have been studied and outlined to improve flight safety. (McRuer 1973), discusses the effects causes by non uniform atmosphere where there are a large scale changes in wind speed and direction with altitude which will produce force and moment perturbations on the diving or climbing aircraft. He assumed that the atmospheric properties such as density or speed of

sound are considered negligible for the small altitude perturbations of the usual interest. (Khare 1992), software has been constructed with automatic sortie simulation feature through multiple way points to predict the trajectories of aircraft.

In the present work, six degree of freedom equation of motion has been integrated to predict the trajectories of a light aircraft with new discretization discussed in the next section. This type of discretization simplifies the problem by adding different components to the aircraft model and its effect on the whole motion of aircraft like landing gear or canopy etc. The non uniform atmosphere like gusts is also considered in this study with input command to control surfaces of the aircraft.

MATHEMATICAL FORMULATION:

Firstly some of the assumptions of the problem can be summarized as follows;

- Flat earth surface (no rotation).
- Thrust will be in axial direction through center of gravity.
- Rigid body motion (mass will be constant through flight).
- Wind has no acceleration (constant velocity).

To implement a real-time flight simulator, a new procedure will be done in this work. To calculate the lift and drag forces on aircraft model, the aircraft will be discretized into number of smaller element sections then collect the geometric and performance data for each section. It must be note that the relative air velocity and angle of attack over each element section must be calculated. The wing may be divided into four sections fitted with aileron and flap as shown in Fig (1) and the other sections are the elevator and rudder. Finally you can lump the entire components with the fuselage together as one additional section. The summations of all components contributions are to find the resultant forces and moments with thrust and gravity. The performance data for each section must be presented by using experimental data as a function of angle of attack which is calculated by evaluating the relative velocity in each section (Hoerner 1985) presented many wing shape experimental data of lift and drag.

There are two right-handed coordinate system that are commonly used to characterize the forces and moments applied to the airframe and

the resulting aircraft motion. The primary coordinate systems used are the North-West-Up, or NWU axes (some references used NED which are North, East and Down body axes (Roskam 1972), and the body axes. The NWU axes are defined with the origin at the aircraft center of gravity, x-axis positive north, y-axis positive east, and z-axis positive upward. For purposes of this discussion, "upward" represents the direction from the aircraft center of gravity upward along and reverse in the direction of the local gravity vector. In this simulation, the Earth is considered flat. Therefore, the local gravity vector always points to the earth. The body axes are defined with the center at the aircraft's center of gravity, the x-axis positive through the nose of the aircraft, the y-axis positive through the left wing, and the z-axis positive through the upper of the aircraft. The plane on which the body x-axis and body z-axis lie is called the plane of symmetry. The angle between the body x-axis and the horizontal plane is called the elevation angle, θ , and its sense is positive nose up. The angle between the body y-axis and the horizontal plane is called the bank angle, ϕ , and its sense is positive starboard wing down. The angle between the projection of the body x-axis on the horizontal plane and the north axis of the NWU coordinate system is called the azimuth angle, ψ , which ranges from 0 to 360° with 0 being magnetic north and increasing from north to east. The body axes are useful as an aircraft-fixed reference system for thrust and forces acting upon the control surfaces. The NWU axes are a useful frame for calculating the aircraft motion with respect to the earth and for developing wind velocity profiles.

The angle between the body x-axis and the projection of V in the plane of symmetry is called the angle-of-attack, denoted α . The angle between the stability x-axis and V is called the sideslip angle, β . These coordinate systems are suitable for these calculations because the forces are normal to the airflow across the airframe.

The relative velocity compensates from linear velocity and rotational one. The formula may be used as;

$$\mathbf{v}_R = \mathbf{v}_{cg} + (\boldsymbol{\omega} \times \mathbf{r})$$

(1)

Where \mathbf{v}_{cg} represents the vector of air speed and flight direction of the aircraft, $\boldsymbol{\omega}$ is the angular velocity vector of the aircraft and \mathbf{r} is the distance between the component and the centre of gravity of airplane. It must be noted that any additional velocity like gusts, shear or turbulence could be added to the above equation to account for



atmospheric effects after transformed to the body coordinates.

Preceding by calculation the angle of attack for each wing section is done by evaluation the normal vector for the specified section. The angle between the lift vectors which is perpendicular to the velocity vector represents the angle of attack and this involves taking the dot product between these two vectors.

Once the angle of attack has been evaluated, the resultant forces at each element are calculated from data tables referred previously for each element section. The data sheet for every section consist stall angle where the lift forces are falls down and the drag increased at these points. By assuming the thrust vector in the x-direction only and passes through centre of gravity (it could be made vectoring in any direction and the landing gear drag may be added). Moments at center of gravity can be calculated by multiplying the force vector at each element with aerodynamic center measured from center of gravity of airplane. Thrust will be added to the resultant force. All these forces and moments have been referenced in the body fixed coordinate system. The body forces vector must first rotated from the body space to earth space coordinates and then apply the gravity force.

There is a problem with using three Euler angles in rigid body simulations. So, when numerical pitch angle reaches plus or minus 90° roll and yaw become ambiguous and since Euler angles involving cosines in the denominator the equations becomes singular. One must use some other means of keeping track of orientation in your simulation which is called *Quaternions* (Douglas B. Sweetser).

The loads on the airplane are completed; so that, the next step is to integrate the equations of motion to simulate progressing through time. The integration scheme in this work is simple Euler method. One can advance the work by using fourth order Range-Kutta method.

It must be noted that the angular motion is to calculate the new angular velocity using Euler integration. This is done in body coordinates by using the equation of motion,

$$M_{cg} = \frac{dH_{cg}}{dt} = I \left(\frac{d\omega}{dt} \right) + [\omega \times (I\omega)] \quad (2)$$

The next step is done by another integration to update the airplane's orientation, which is expressed as a quaternion. Since the linear velocity was previously calculated in global coordinates and loads need to velocity in the body

coordinates system, the velocity vector must be rotated to the body coordinate.

The aircraft responses are done by adding disturbances inputs due to gust in the body axes, then,

$$\begin{aligned} u_{disturb} &= u_{gust} \\ v_{disturb} &= v_{gust} \\ w_{disturb} &= w_{gust} \end{aligned} \quad (3)$$

Incorporating constant wind (generated in global NWU coordinate) and total disturbance input (transformed to the global NWU coordinate) to get the total resultant velocity in the global coordinates of reference. The body velocity components of the total velocity can be obtained by transforming the component velocity from global NWU coordinate to local coordinates.

The discrete gust formulation can be summarized as follows (McRuer 1973) (It could be get the data sheets for the wind gust records and put it as a discrete data).

$$W_{gust} = \begin{bmatrix} 0 & 0 \leq x < x_1 \\ \frac{V_m}{2} * (1 - \cos(\frac{\pi(x-x_1)}{dm})) & x_1 \leq x < x_2 \\ V_m & x_2 \leq x < x_3 \\ \frac{V_m}{2} * (1 + \cos(\frac{\pi(x_3-x)}{dm})) & x_3 \leq x < x_4 \\ 0 & x \geq x_4 \end{bmatrix} \quad (4)$$

Where,

$$dm = V/2f,$$

V_T = Aircraft velocity

$$x_2 = x_1 + dm$$

$$x_3 = x_2 + dx$$

$$x_4 = x_3 + dm,$$

dx is the desired gust width

f is the characteristic aircraft frequency,

x_1 is the position of start of gust along global x- axis,

V_m is the maximum gust velocity.

In the present work the gust is divided into two branches the first one is the velocity in the z-direction which is presented in the equ (4) and the other what is called shear velocity (velocity in the direction of y), the same equ (4) is use d in the y-direction. The most important note that the gust must be transformed from global

velocity to body coordinates (it represents vertical velocity only with specified distribution). Gust velocity will be calculated at each element section of the aircraft. This gives more realistic to the flight simulation. Of course you can add cockpit, landing gear and winglets to the model of aircraft and by this way one can get more accurate results (the loads coefficient of these parts must known to be added to the total forces of the aircraft).

NUMERICAL SOLUTION:

As mentioned before in the mathematical procedure the integration will be done using simple Euler Method which needs small time interval to get accurate integration results. Six degree of freedom equation of motion are considered and integrated to predict aircraft trajectories which consisting of three displacements and three orientations of the aircraft. The steps for calculations can be summarized as follows;

- 1- Input geometric information (number of elements of the aircraft and its position, setting angle, mass, moment of inertia, projected area and flap, aileron, elevator and rudder angles).
- 2- Initial conditions with position, flight velocity, maximum gust velocity if consist, angular velocity, thrust force, external forces and/or moments vectors if consist and roll, pitch and yaw angles for the aircraft.
- 3- Summations all global velocities like flight velocity and constant wind velocity and transformed from global NWU coordinate to the body coordinate.
- 4- Evaluate the mass properties like total mass, center of gravity, moment of inertia with respect to the center of gravity. Then compute the inverse of the inertia matrix.
- 5- Time loop begins with appropriate time step.
- 6- Calculation of aircraft load and moments which are done by calculate the normal vector at every section and then calculate the local velocity from equ.(1) with disturbance velocities in eqs.(3,4) at each section. The drag force vector will be along the local velocity vector in opposite direction. The dot product between a unit drag vector and normal vector will give angle of attack at any sections.

- 7- The normal force can be calculated by evaluate the vector normal to the local velocity vector.
- 8- With help of angle of attack, area of each section, velocity and density at known altitude the lift force and drag force will be evaluated at each section from data sheets of aircraft components.
- 9- By multiplying the resultant force with the distances between each component and center of gravity the moment vector at center of gravity is evaluated.
- 10- The resultant force will be summed with thrust force and this force transformed in to the global NWU coordinate to accumulate the gravity force. (Transformation matrix is done by using quaternion).
- 11- The force will be divided by the total mass of the aircraft to find the linear acceleration and the multiply by the time step to find new velocity vector. The velocity vector will be multiplied by the time step to find the new position of the aircraft.
- 12- Using equ (2) to find the angular acceleration vector by multiply the moment and initial angular velocity vector by inverse moment of inertia matrix.
- 13- The new angular velocity and orientation of the aircraft are evaluated by multiplying by time step.
- 14- The loop continues for a specified condition like time interval, specified position etc.

The above procedure is programmed in FORTRAN language and compiled with Microsoft power station compiler. The results are tabled in different files consisting time history of position, orientation, velocities and accelerations, the other data is the force and moment data along flight simulation. All these data are discussed in the next section. The procedure presented here provides a low time consuming because it deals with vectors.

RESULTS AND DISCUSSIONS:

In this section the time history results will be discussed and some of them will be compared with other previously published data.

The properties of the aircraft which is chosen to test the programme result can be found in the (Paul Jackson 2005) Fig (3).



The first group of figures are figures (4 to 7) they show the response of aircraft when the aircraft cruise at speed near 42 m/s ($M=0.124$) and thrust equal to 2560 N and there is no control for flaps, aileron, rudder or elevator. First two figures show the distance that will be travelled by the aircraft, it could be seen that the aircraft moved forward and increasing its height due to lift force as the time progress. All fluctuation at the beginning are due to unsteady behaviour of flight since the aircraft did not takeoff from ground. So that, after this period the aircraft becomes stable and its motion becomes steady. Another thing that the star board motion was not happens because the aircraft in this case have two components only (no gyroscopic motion). Same notes are cleared for the velocity components in x and y-direction.

The most important note is illustrated in the figures 6 for the acceleration components where x and z-direction is shown in this figures, these components became zero for steady state flight (i.e. Cruise flight) this mean the thrust force equal to the drag force and lift nearly equal to the weight of the aircraft. In figure 7 the pitch angle is nose up when the right hand applied to the left side of the aircraft the positive direction when the aircraft pitch angle is nose down. The angular acceleration in yawing and rolling are zero while the pitching is equal to zero after a period of time this make the aircraft has a constant pitch angle.

Figures from 8 to 11 show the response of the aircraft when the thrust increased. The response is going to unstable state and the fluctuation of the aircraft increased and again no control available during the flight. The velocity component in the x-direction was increased and also the pitch angle. The motion will be damped out and steady motion may be obtained after a period of time.

Flaps were tested to illustrate the response of the aircraft for the figures between: 12-15, these devices gives a reasonable stability to the aircraft and also increasing the lift force, so that the elevation of the aircraft increased as shown in figures.

Two type of gust are considered, the first is normal gust velocity with equations shown previously and shear gust represented by same equation with only one difference where the velocity in the y-direction instead of z-direction. It could be seen that z-direction gust could be controlled by aircraft if it affected by this type of gust. But shear wind could not, and the third motion appears in this case (mean in y-direction). The figures from 16 to 26 illustrate the behaviour

of aircraft during these effects. **Fig. (27)** shows the flow chart of the programme.

CONCLUSIONS:

The programme is a useful tool in simulation of flight trajectories of a light aircraft. It is aid for flight visualization during gust and constant wind for various flight conditions within the flight envelope of the light aircraft. A new approach has been developed in this work which simplifies the solution by discrediting the aircraft into component and treats these components separately. This procedure provides to add a multiple component into the model. Input angles of control surfaces gives realistic feel to any flight simulation and the programme provides this facility by pre-programmed inputs to control surfaces. The programme is under development to account for atmospheric turbulence or wind shear and augmented through an autopilot for sortie simulation.

NOMENCLATURE:

u	Velocity in x-direction (m/s)
v	Velocity in y-direction (m/s)
w	Velocity in z-direction (m/s)
M	Moment vector
H	Momentum vector
I	Mass moment of inertia matrix
t	Time (sec)
ω	Angular velocity vector
r	Distance to the center of gravity vector

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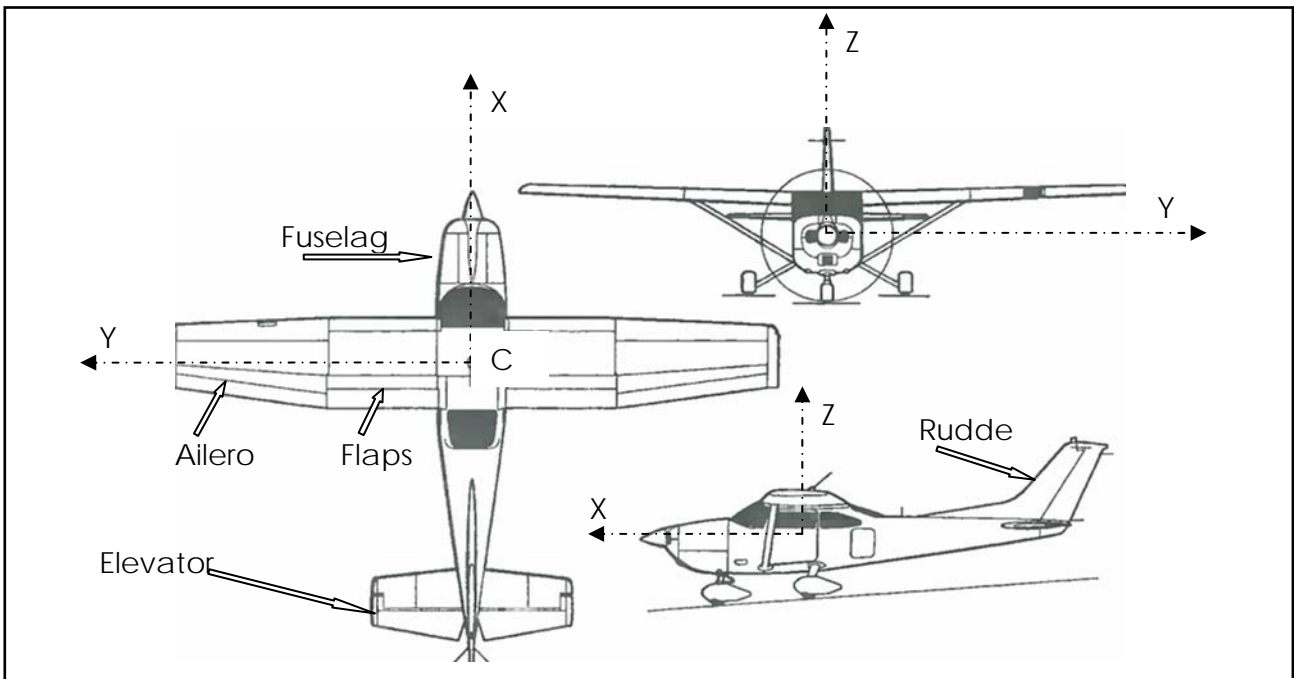


Figure 1: Element Sections of (Cessna 182T) Airplane.

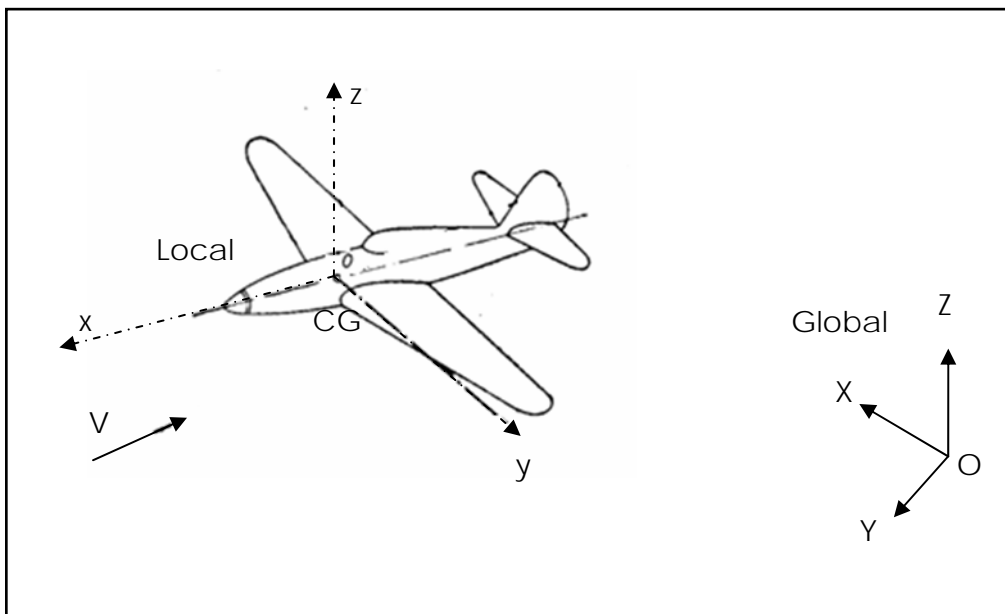


Figure 2: Coordinate Systems.



Performance

Maximum level speed	227 km/h
Cruising speed at 80% power at FL80	226 km/h
Stalling speed, power off	
Flap up	95 km/h
Flap down	87 km/h
Max rate of climb at S/L	219 m/min
Service ceiling	4,115 m
T-O run	288 m
T-O to 15 m	514 m
Landing from 15 m	395 m
Range at 80% power at FL80	1,074 km
Endurance	6 h 36 min

Dimension and weight

Wing span	11 m
Wing aspect ratio	7.5
Propeller diameter	1.9 m
Length overall	8.28 m

Weight and loading

Weight empty	745 kg
Baggage capacity	45 kg
Max ramp: Normal	1,114 kg
Utility	956 kg
Max T-O and landing weight	
Normal	1,111 kg
Utility	952 kg
Max wing loading	68.7 kg/m ²
Max power loading	9.32 kg/kW

Figure 3: Aircraft Dimensions and Properties.

SIMULATION OF FLIGHT THROUGH GUST

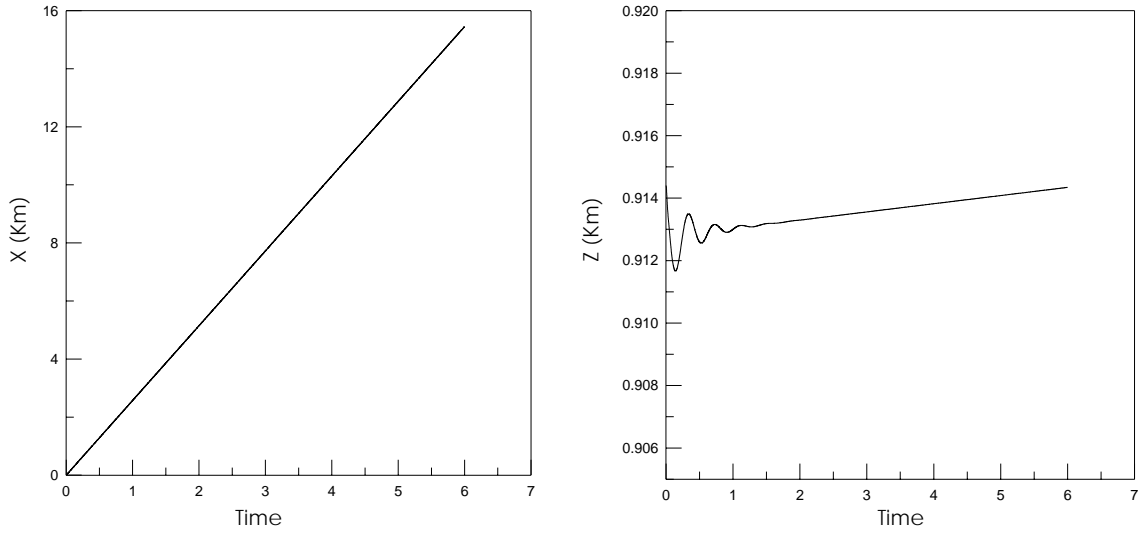


Figure 4: Time History of Aircraft Distance in X and Z-Direction in Cruise Flight.

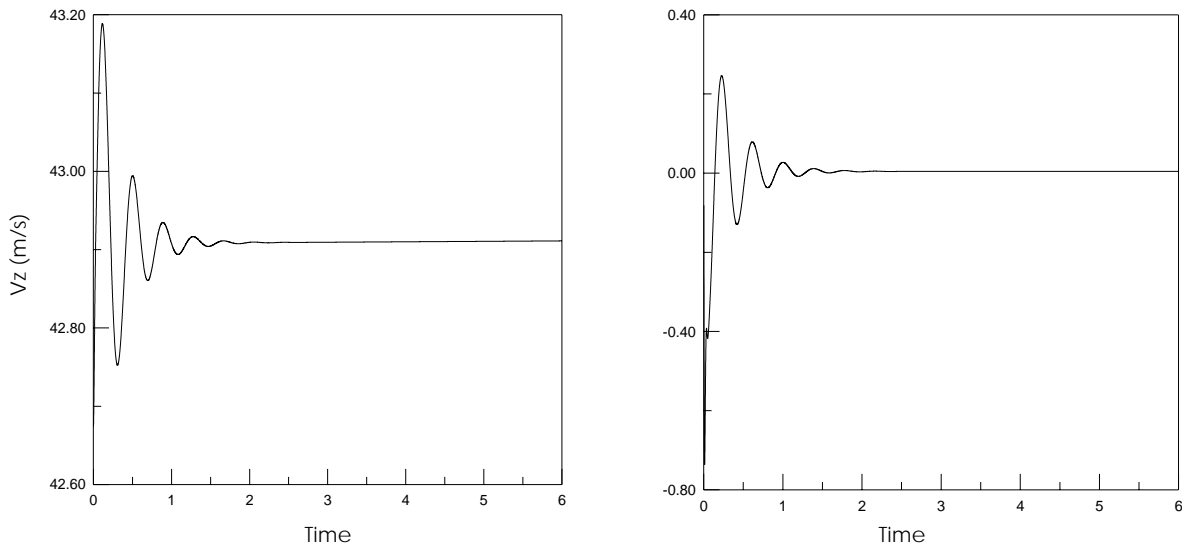


Figure 5: Time History of Aircraft Velocity in X and Z-Direction in Cruise Flight.

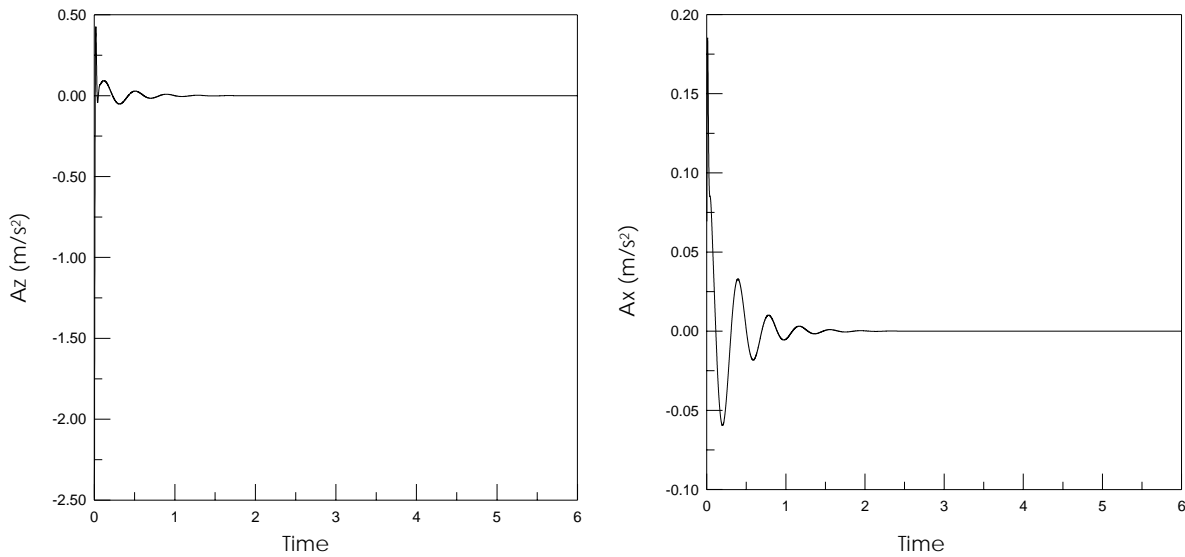


Figure 6: Time History of Aircraft Acceleration in X and Z-Direction in Cruise Flight.

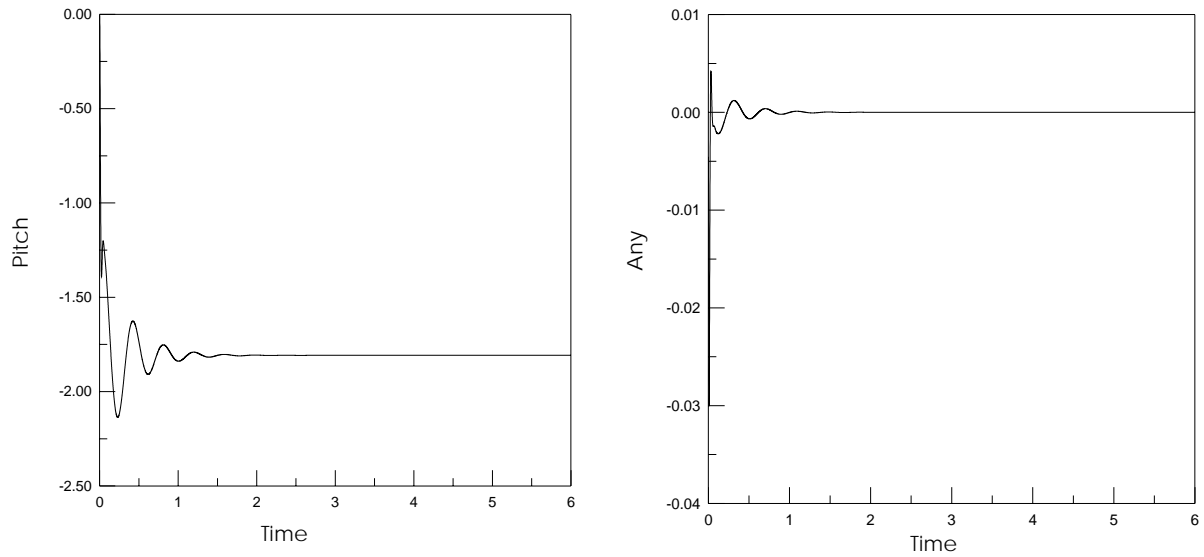


Figure 7: Time History of Pitch and Angular Acceleration of Aircraft in Cruise Flight.

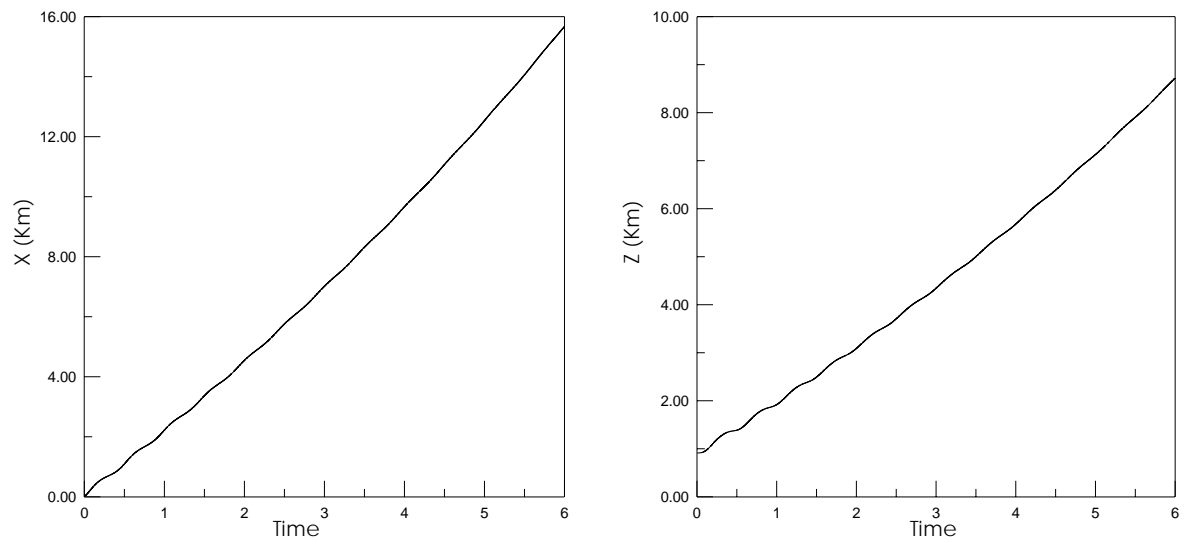


Figure 8: Time History of Aircraft Distance in X and Z-Direction when the thrust increased.

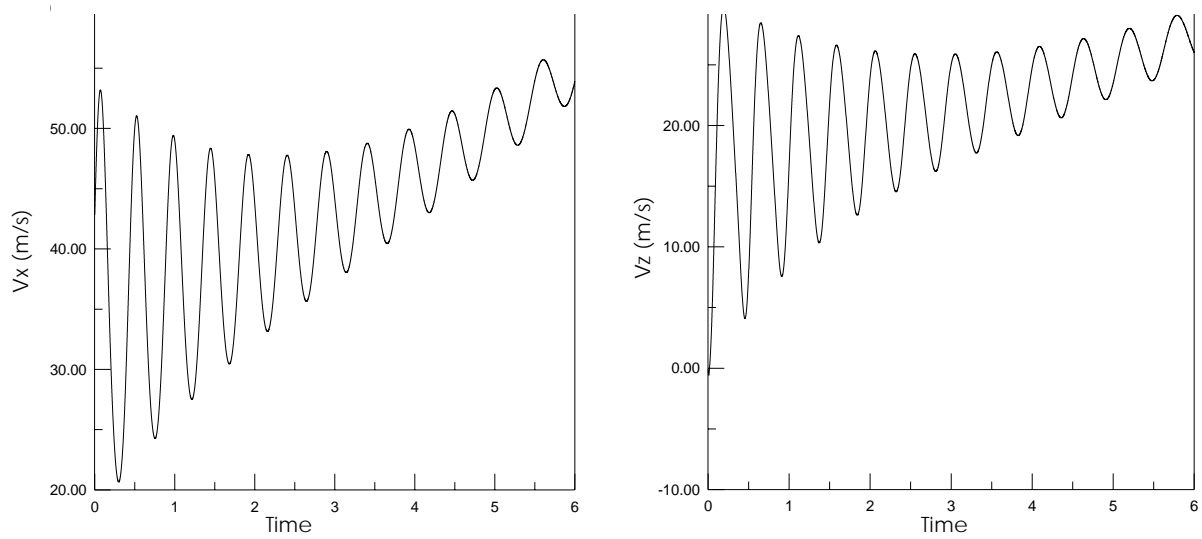


Figure 9: Time History of Aircraft Velocity in X and Z-Direction when the thrust increased.

SIMULATION OF FLIGHT THROUGH GUST

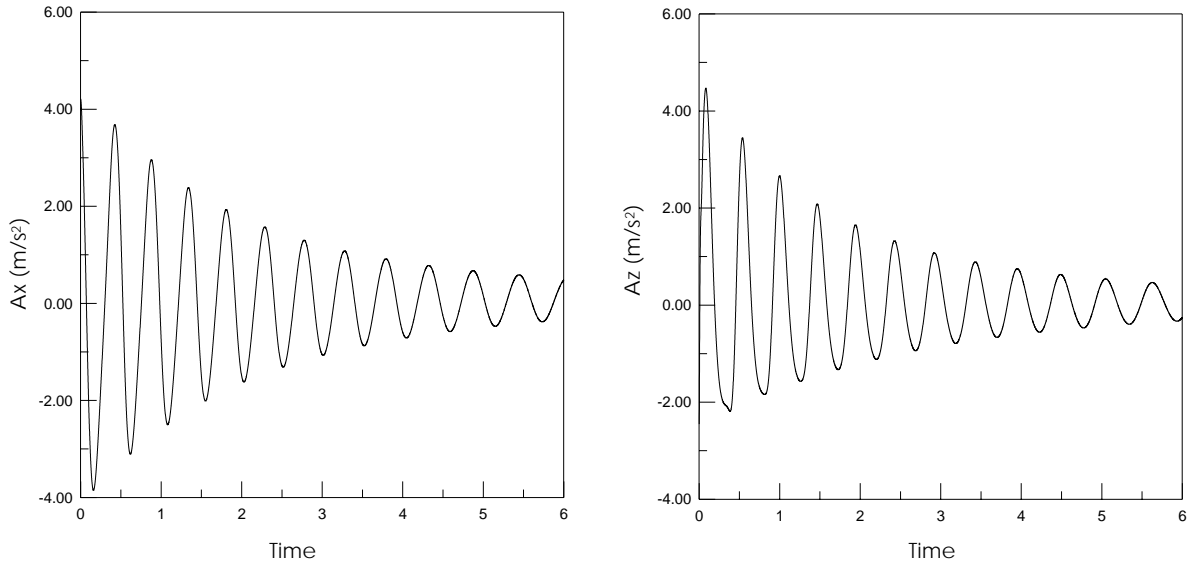


Figure 10: Time History of Aircraft Acceleration in X and Z-direction when the thrust increased.

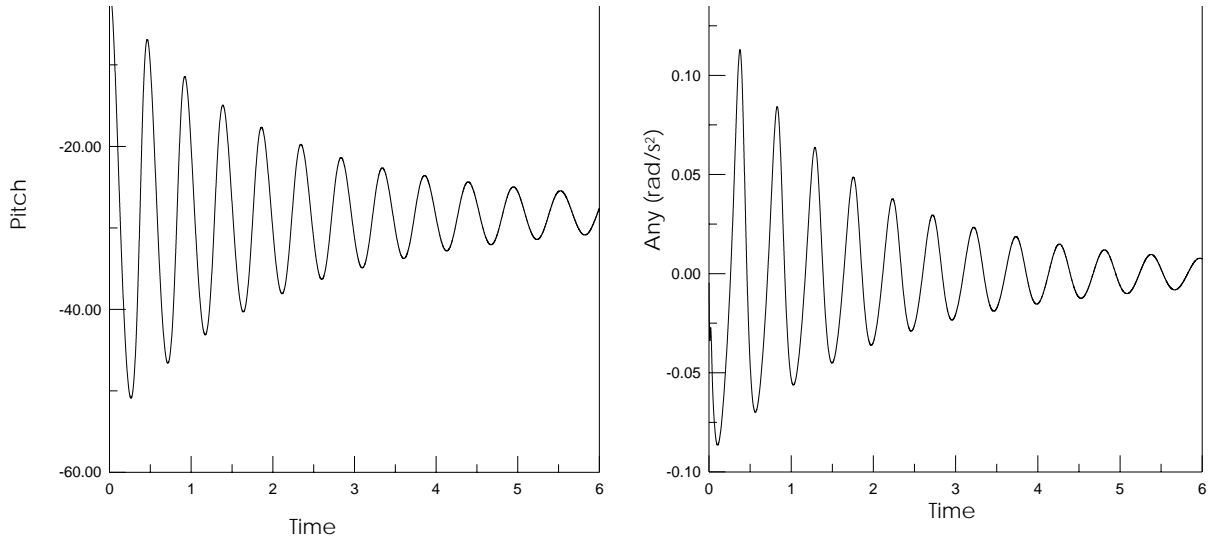


Figure 11: Time History of Pitch and Angular acceleration of Aircraft when the thrust increased.

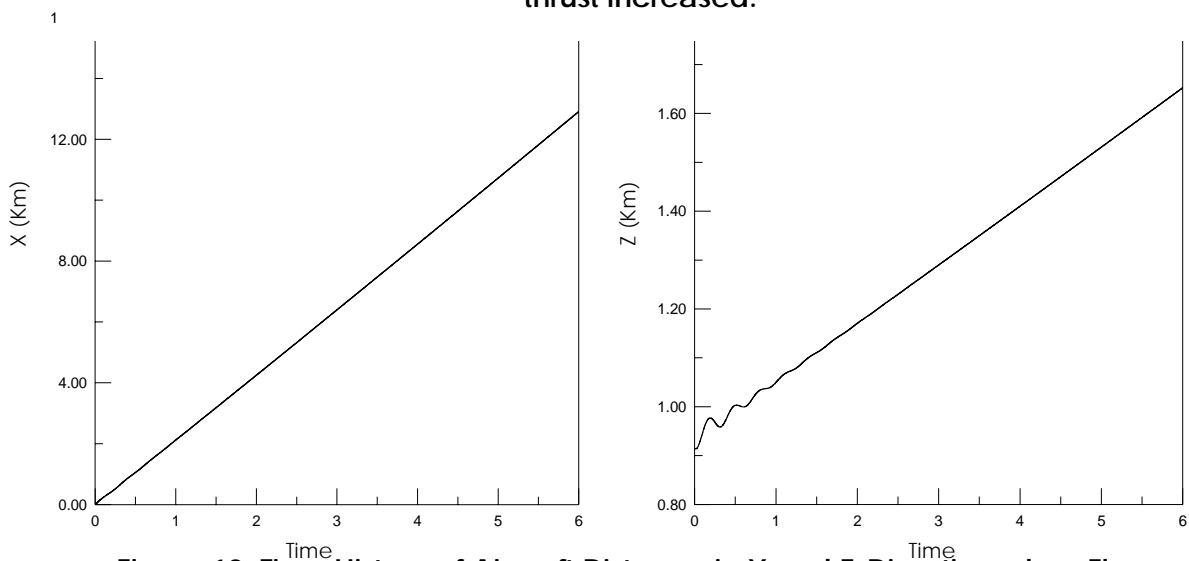


Figure 12: Time History of Aircraft Distance in X and Z-Direction when Flaps

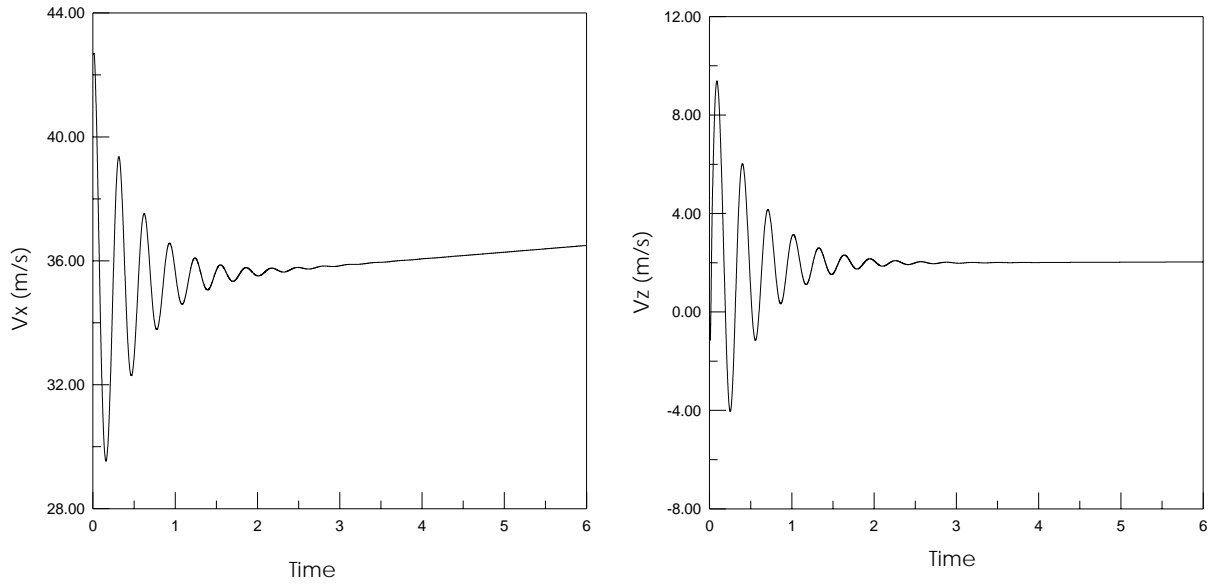


Figure 13: Time History of Aircraft Velocity in X and Z-Direction when Flaps Deflected.

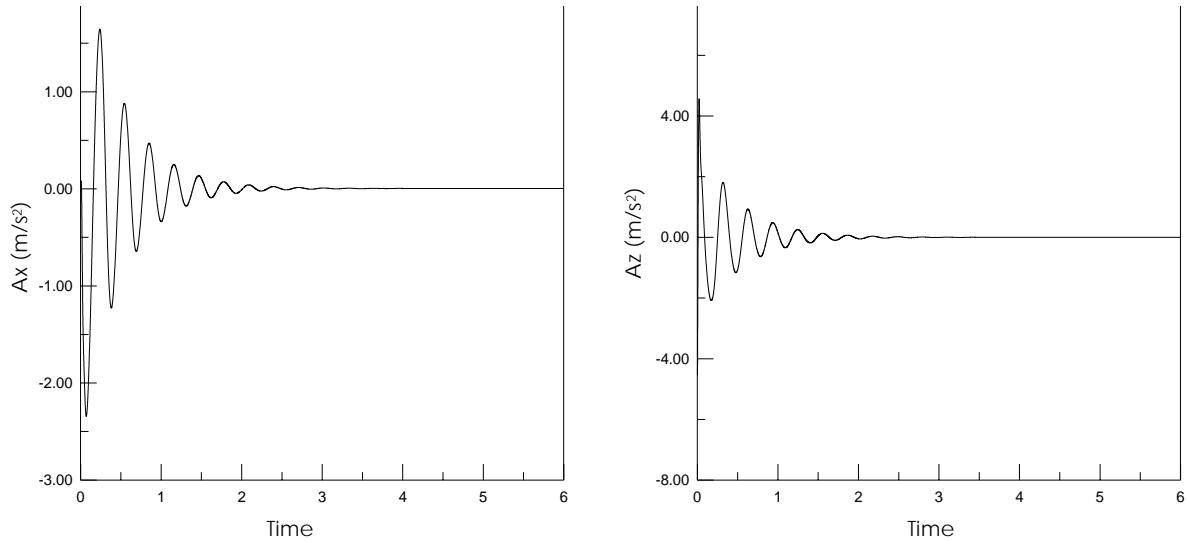


Figure 14: Time History of Aircraft Acceleration in X and Z-direction when Flaps Deflected.

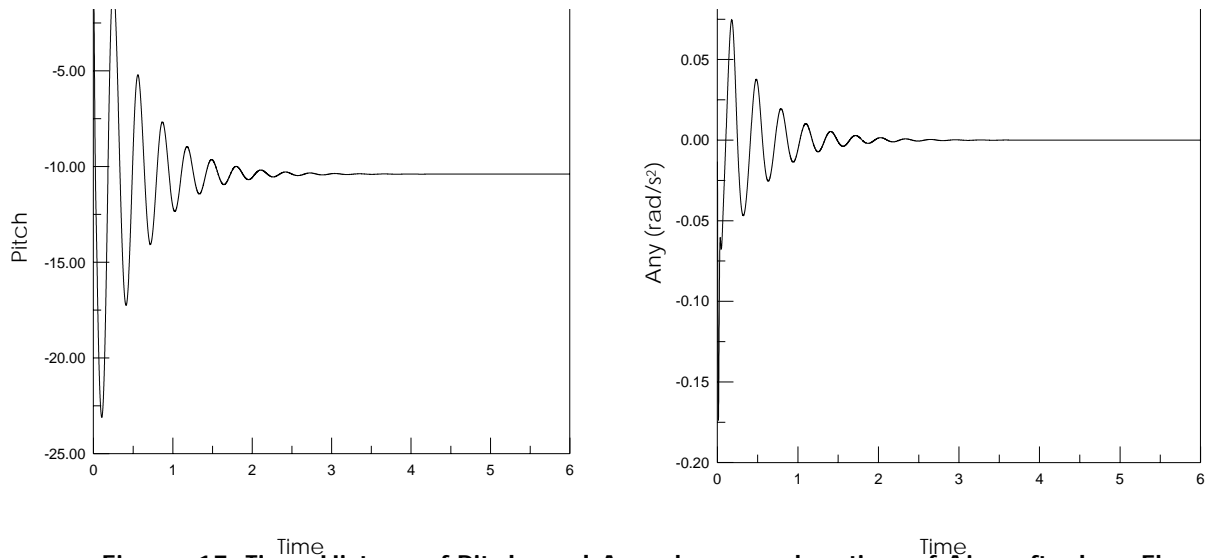


Figure 15: Time History of Pitch and Angular acceleration of Aircraft when Flaps Deflected.

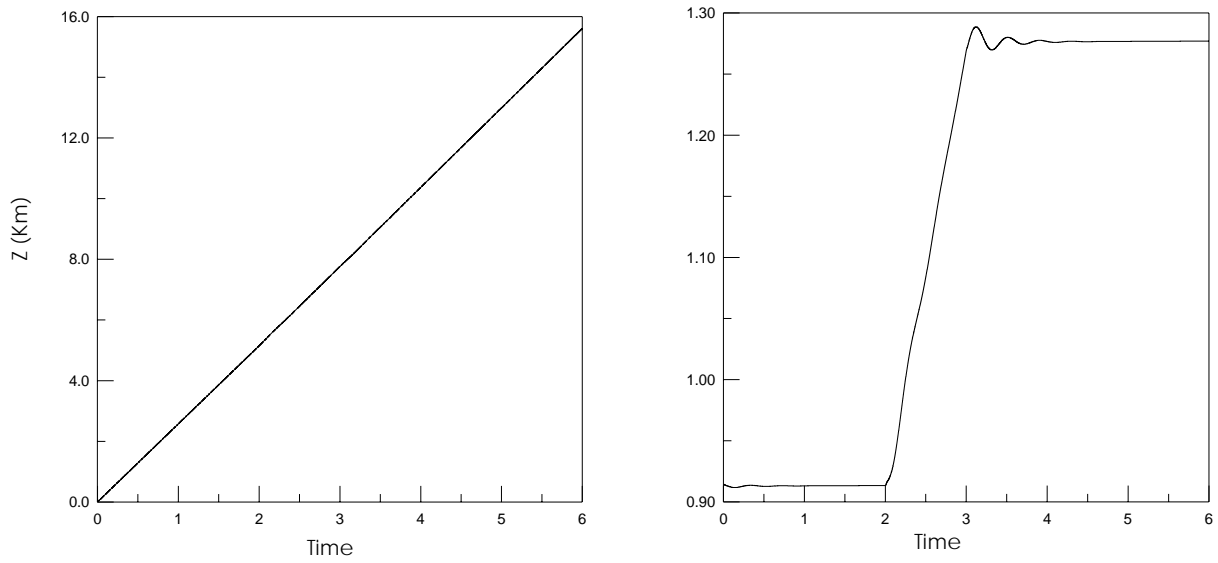


Figure 16: Time History of Aircraft Distance in X and Z-Direction with Normal Gust.

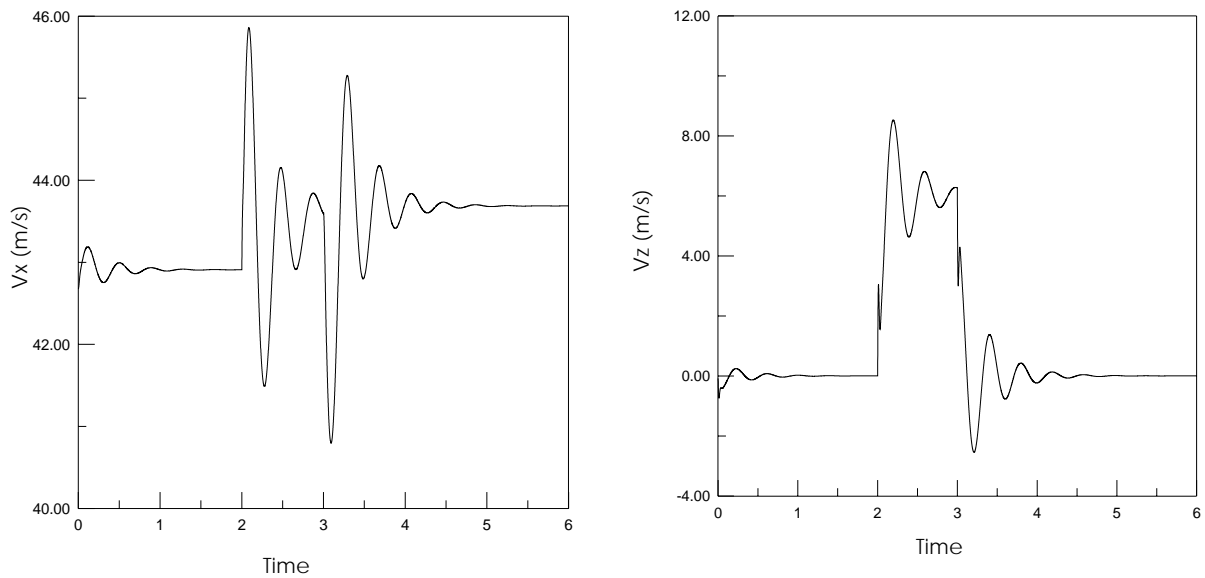


Figure 17: Time History of Aircraft Velocity in X and Z-Direction with Normal Gust.

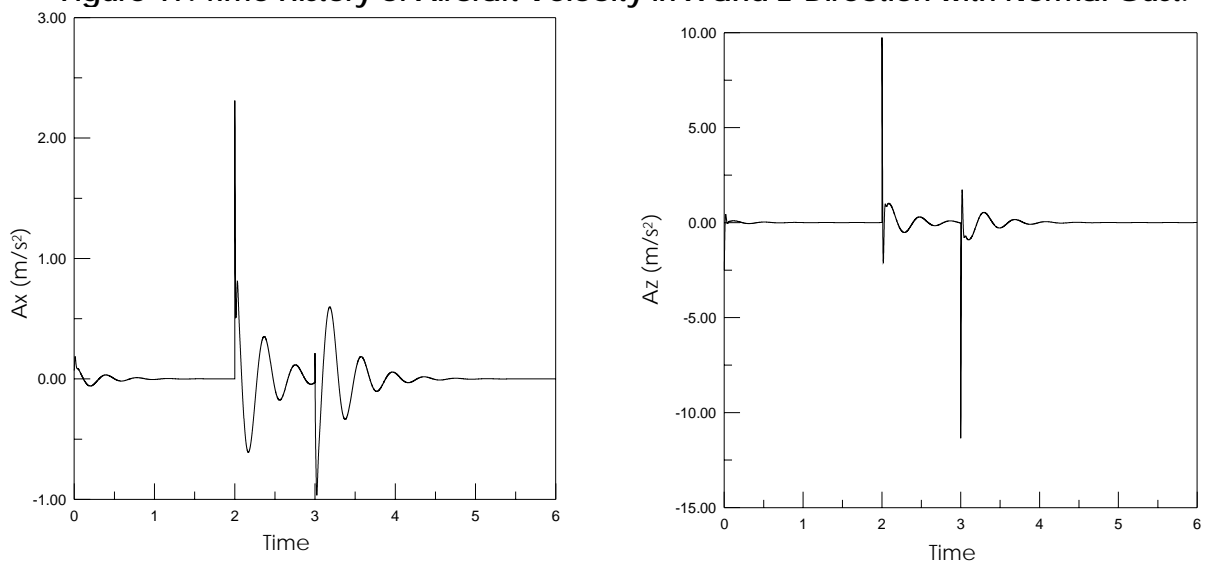


Figure 18: Time History of Aircraft Acceleration in X and Z-Direction with Normal

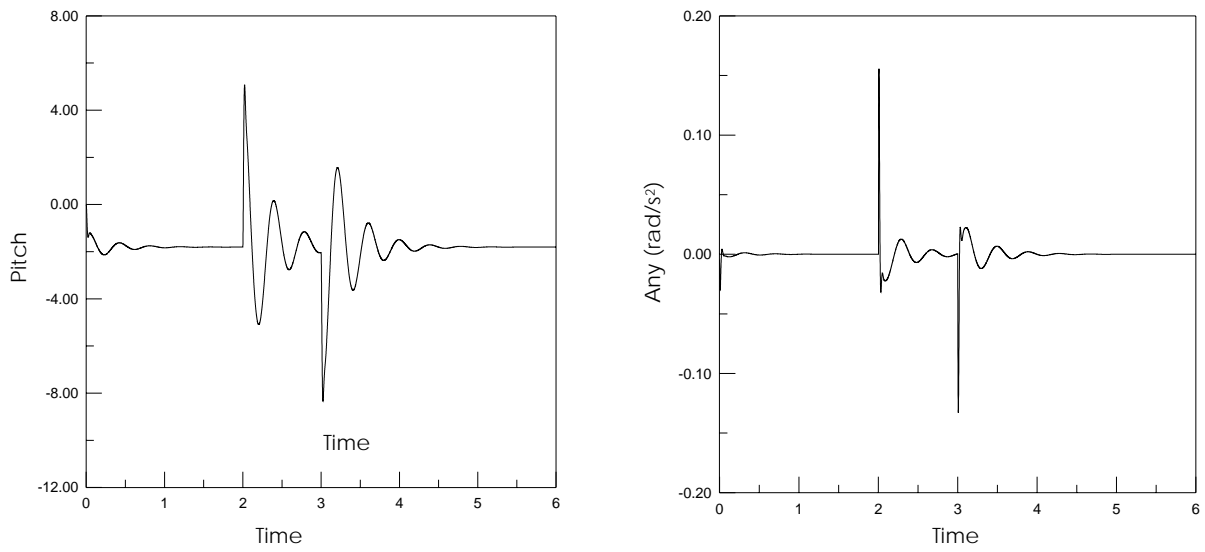


Figure 19: Time History of Pitch and Angular acceleration of aircraft with Normal

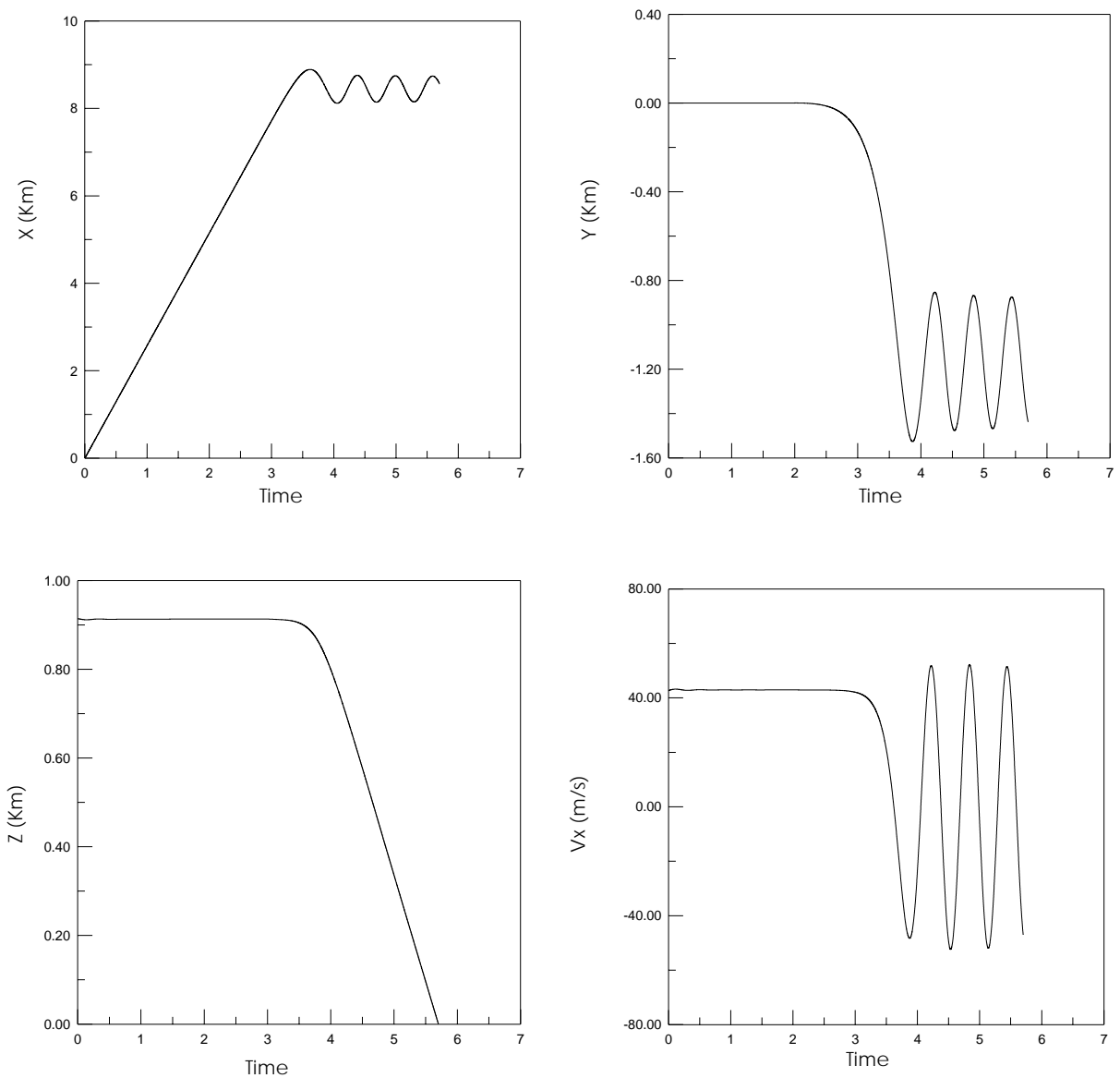


Figure 20: Time History of Aircraft Distances in X and Y-Direction with Shear Gust.

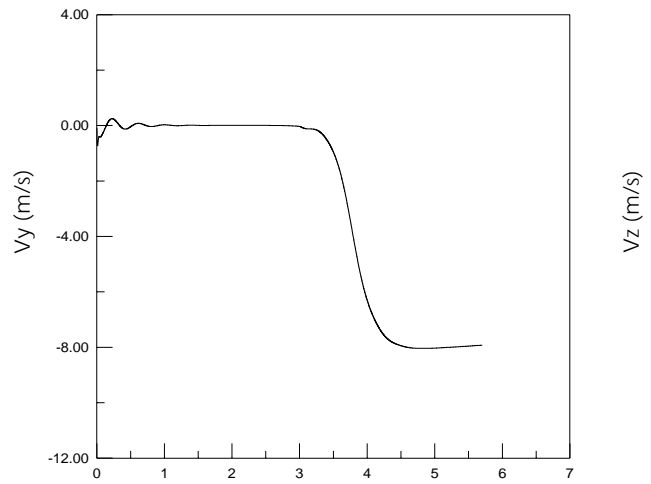
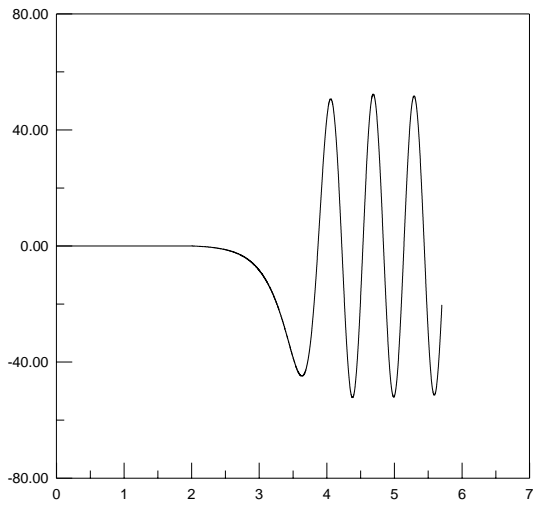


Figure 21: Time History of Aircraft Distance in Z-Direction and Velocity in X-Direction

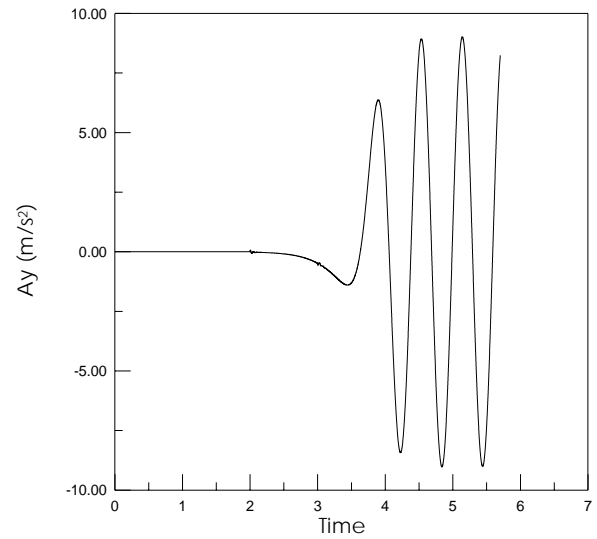
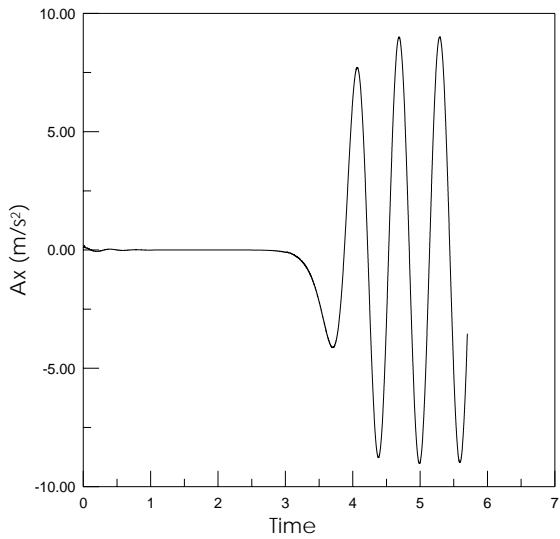


Figure 22: Time History of Aircraft Velocity in Y and Z-direction with Shear Gust.

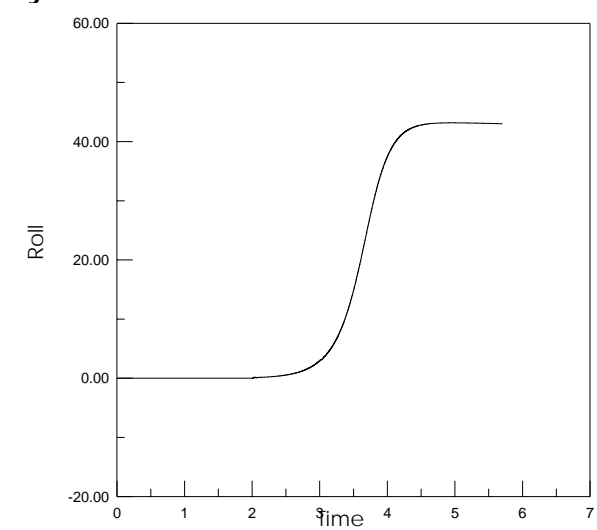
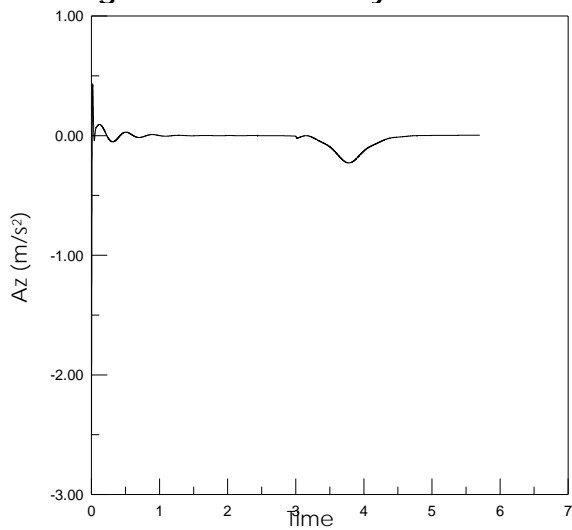


Figure 23: Time History of Aircraft acceleration in X and Y-Direction with Shear

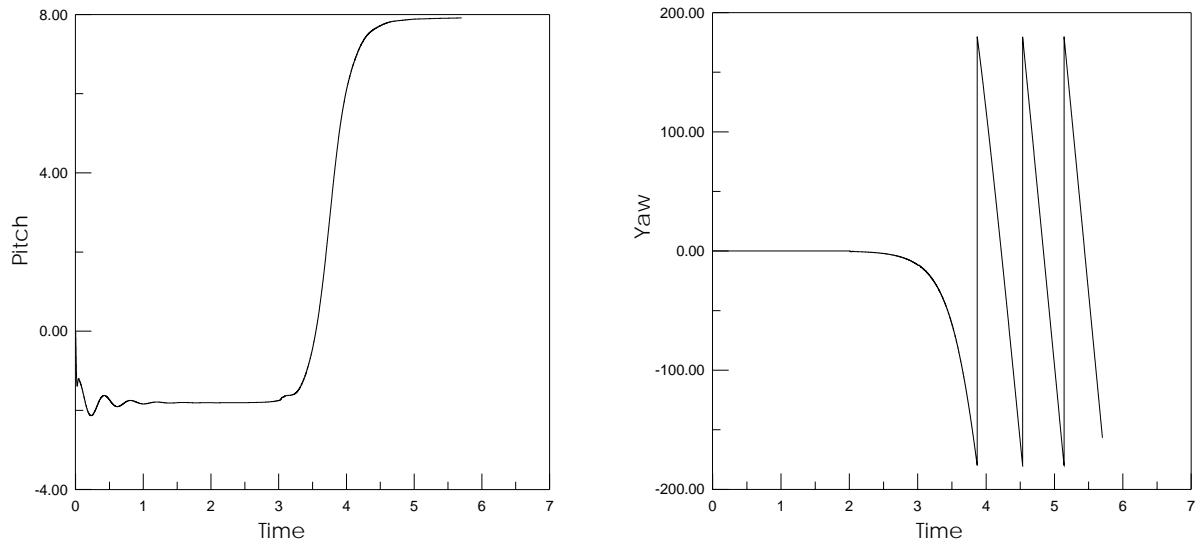


Figure 24: Time History of Aircraft acceleration and Roll angle with Shear Gust.

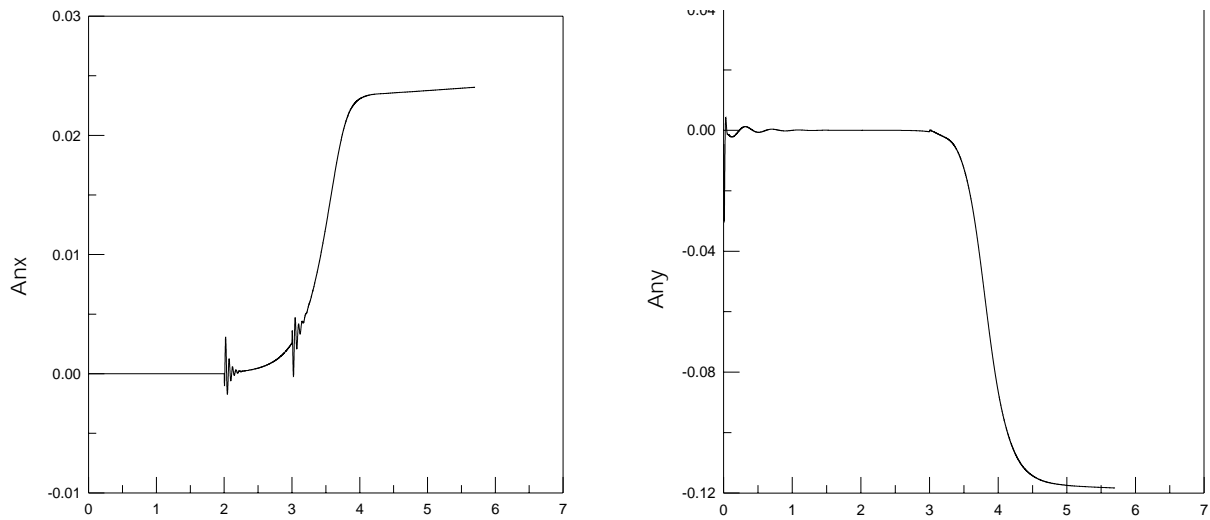


Figure 25: Time History of Aircraft Pitch and Yawing angles with Shear Gust.

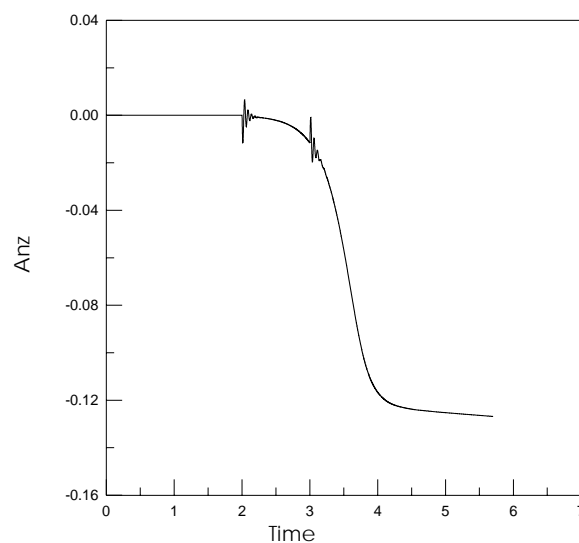


Figure 26: Time History of Aircraft Angular acceleration in X, Y and Z-

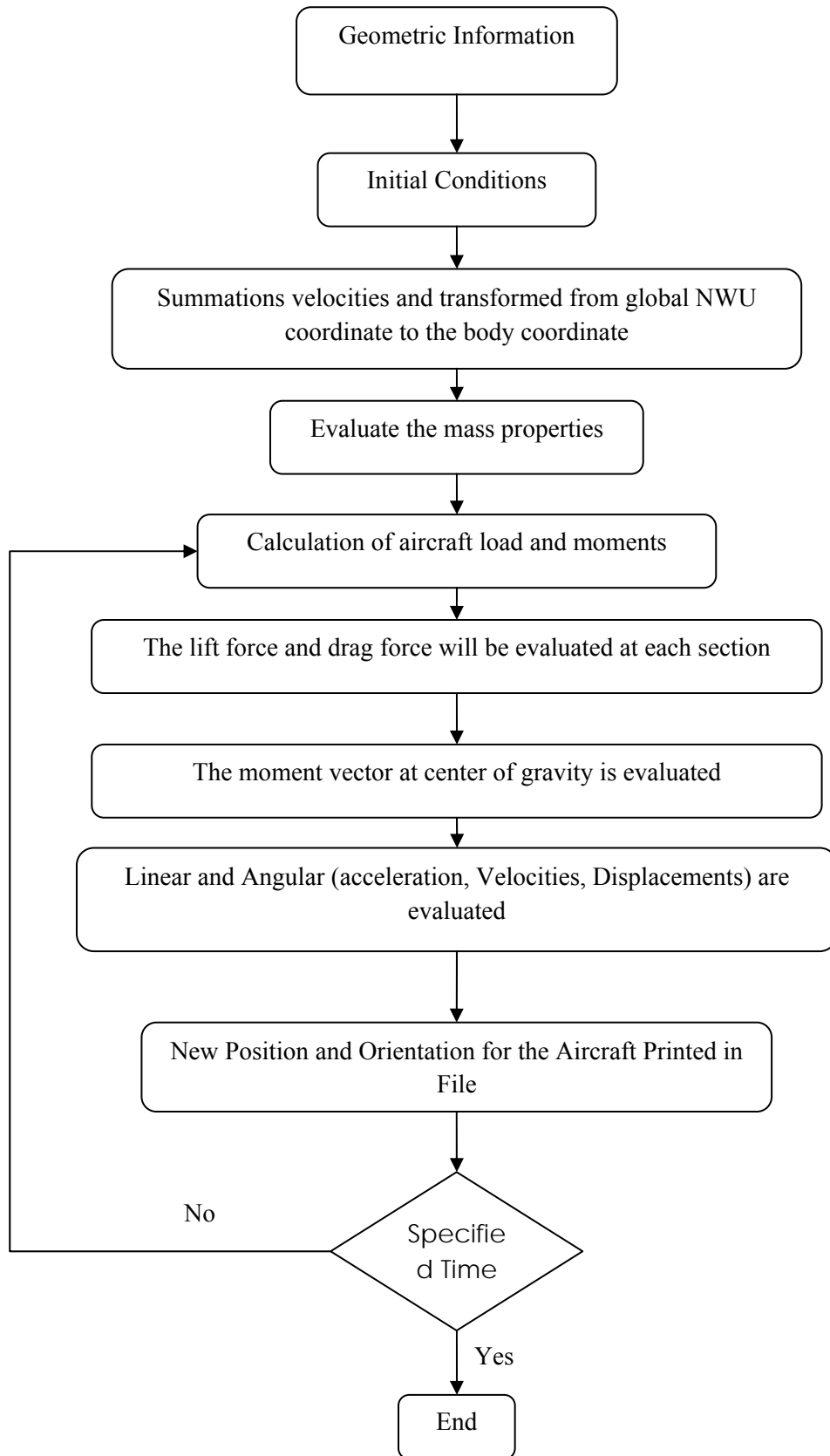


Figure 27: Flow Chart of Programme.