FLYING QUALITY STUDY UNDER THE INFLENCE OF CLEAR AIR TURBULENCE

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Abstract

Clear air turbulence (CAT) is one of the most influential factor in flight safety and flight quality consideration. In this work we attempt to simulate CAT wind velocities, invent 3-D turbulence measuring and prediction parameters (indices), and using genetic algorithm (GA) to find the optimum escape trajectory. Results show moderate success and it is hoped that the concepts and techniques implemented in this work could be used in future airborne Doppler radar research and flight simulation practice.

1 Introduction

Flight safety and flying quality both are extremely important to modern day aviation industry. The two most hazardous weather phenomena to flight safety and flying quality are the low level wind shear and clear air turbulence (CAT). Due to the large amount of research effort put into wind shear alert in last fifteen years [1,2,3,4,5], the wind shear related accidents have greatly reduced. But as the amount of civil aviation passenger transport increase 5 to 6 percent annually, the incidents caused by turbulence phenomenon become more frequent, and the general public's expectation in flying quality and ride comfort is also higher than before.

Clear air turbulence (CAT) is probably one of the most influential factor in flying quality consideration, one unique thing about CAT is that it basically can not be seen or predicted, the blue clear sky may lead to some severe turbulence situation [6,7]. Generally speaking, turbulence or gust has random fluctuating behavior, associated with strong vorticity and mixing effect. Thunderstorm, vertical convection, mountain lee waves, non-uniform heating, etc. are the most common causes of turbulence. Among the many different kinds of turbulence, CAT may be the most severe one and difficult to predict. It is believed that CAT is directly caused by high altitude jet stream phenomenon, it can lead to unexpected severe vertical/lateral motions and pitching moments, and cause disastrous effect on flight attendants and/or passengers. Statistics shown that there are hundreds of aircraft injury/death accidents every year caused by CAT phenomenon [8].

Due to the ever increasing importance of CAT phenomenon, the work in this paper is concentrated in first simulate turbulence/gust three-dimensional wind profiles, then compare with some actual wind profiles, and calculate the newly invented turbulence prediction parameters T_1, T_2 and T_3. Finally, an optimum flight dynamics trajectory can be found via the genetic algorithm real value approach. It is believed that the concept and methods used in here can one day be used in designing the next generation airborne Doppler radar, and greatly enhance the future aviation flight/ride quality.

2 Turbulence Profiles and Parameters

There are several different kinds of turbulence/gust wind generation models currently in use, namely, the von Karman model and Dryden model [10]. They all use the power spectrum density (PSD) approach, express in frequency domain, and somewhat difficult to use in the flight dynamics equation direct solver. In this work we try to use two different approaches to simulate 3-D turbulence wind profiles. The first approach is to use the Dryden PSD model, input a sine or cosine function and create a continuous oscillatory wind profile. After a fifty function randomly combination and inverse transformation, we can get the velocity profiles in three directions:

$$V_u = \left[\frac{A\sqrt{K_u}}{\varpi^2+\lambda^2}\left(B\lambda + C\varpi\right)\right]\cos\left(\varpi t\right) + \left[\frac{A\sqrt{K_u}}{\varpi^2+\lambda^2}\left(B\varpi - C\lambda\right)\right]\sin\left(\varpi t\right) - \left[\frac{A\sqrt{K_u}}{\varpi^2+\lambda^2}\left(B\lambda + C\varpi\right)\right]\exp^{(-\lambda t)} \quad (1)$$

$$\begin{aligned} V_v = & \left[\frac{DE\sqrt{K_v}\left(\beta\varpi^2 - \beta\lambda^2 - 2\lambda\varpi^2\right)}{\left(\varpi^2+\lambda^2\right)^2} - \frac{DF\varpi\sqrt{K_v}\left(\varpi^2 - \lambda^2 + 2\lambda\beta\right)}{\left(\varpi^2+\lambda^2\right)^2}\right]\exp^{(-\lambda t)} \\ & + \left[\frac{DE\lambda\sqrt{K_v}\left(\left(\varpi^2+\lambda^2\right)\left(\lambda-\beta\right)\right)}{\left(\varpi^2+\lambda^2\right)^2} - \frac{DF\varpi\sqrt{K_v}\left(\beta-\lambda\right)}{\left(\varpi^2+\lambda^2\right)}\right]\times t\times\exp^{(-\lambda t)} \\ & - \left[\frac{DE\sqrt{K_v}\left(\left(\beta\varpi^2 - \beta\lambda^2\right) - 2\lambda\varpi^2\right)}{\left(\varpi^2+\lambda^2\right)^2} - \frac{DF\varpi\sqrt{K_v}\left(\varpi^2 - \lambda^2 + 2\lambda\beta\right)}{\left(\varpi^2+\lambda^2\right)^2}\right]\cos\left(\varpi t\right) \\ & + \left[\frac{DE\varpi\sqrt{K_v}\left(2\lambda\beta + \varpi^2 - \lambda^2\right)}{\left(\varpi^2+\lambda^2\right)^2} - \frac{DF\sqrt{K_v}\left(2\lambda\varpi^2 - \beta\varpi^2 + \beta\lambda^2\right)}{\left(\varpi^2+\lambda^2\right)^2}\right]\sin\left(\varpi t\right) \end{aligned}$$

(2)

A, D: input signal amplitude
B, E: input signal cosine phase shift
C, F: input signal sine phase shift
All other parameters have same meaning as Dryden model

Vertical velocity V_w has the same form as V_v shown above.

The second approach is to use the Matlab tool and directly combine more than fifty sine function waves. The principle is to employ small amplitude for higher frequency waves, large amplitude for low frequency waves, and randomly select their phase shift. The following are the three different velocity profiles (real, inverse transformation approach, Matlab approach) for vertical and lateral direction, and showing good agreement in fluctuating behavior.

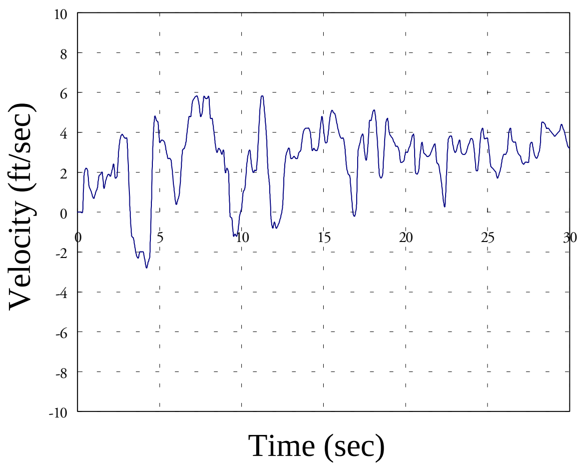

Fig.1 Real wind profile in vertical direction

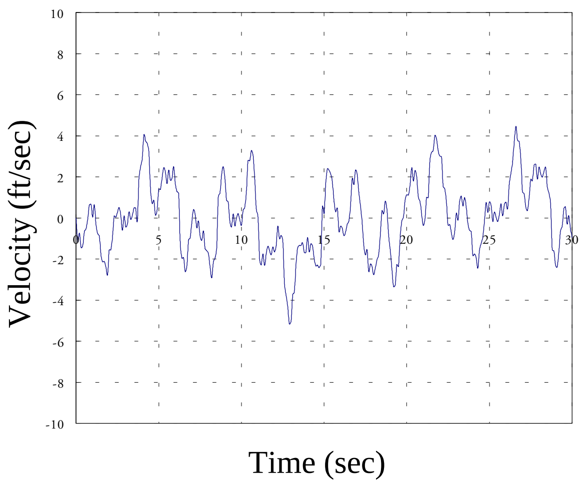

Fig.2 Inverse transformation wind profile in vertical direction

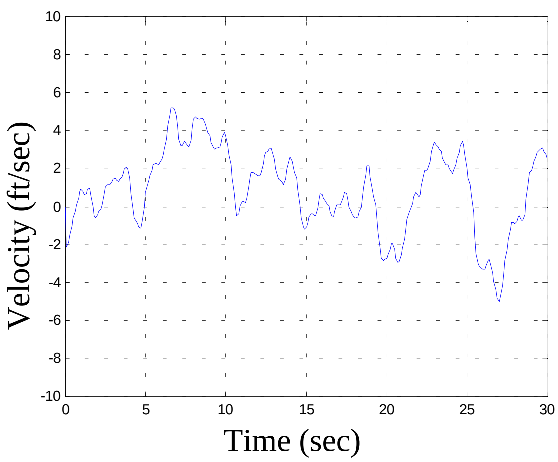

Fig.3 Matlab wind profile in vertical direction

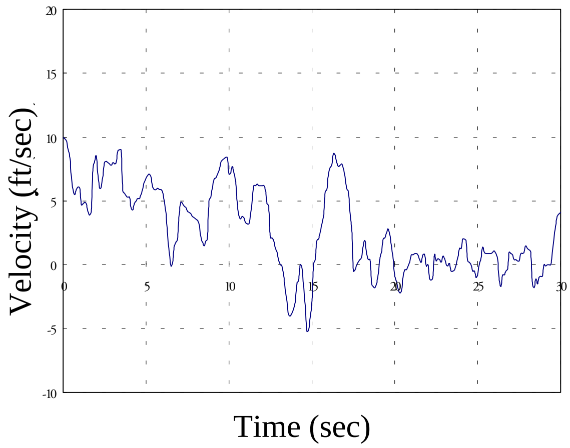

Fig.4 Real wind profile in lateral direction

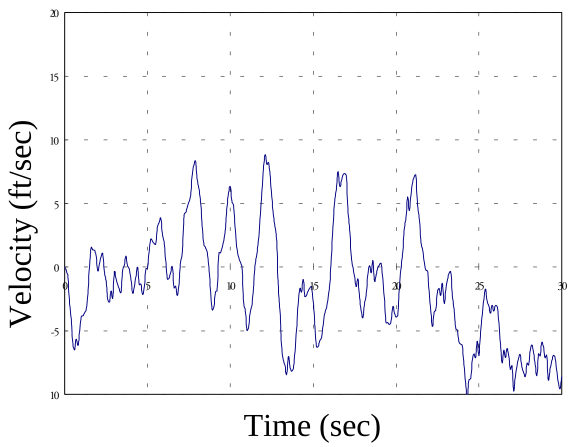

Fig.5 Inverse transformation wind profile in lateral direction

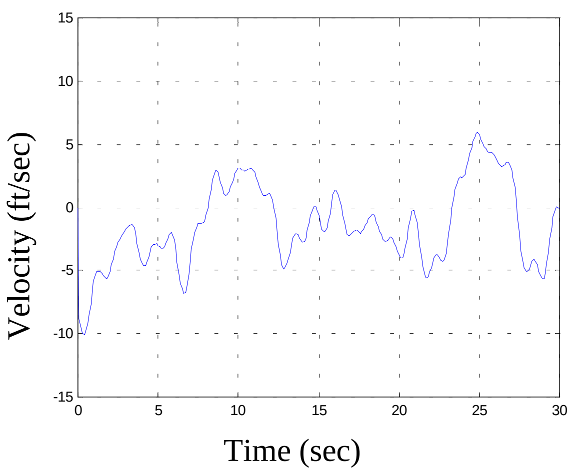

Fig.6 Matlab wind profile in lateral direction

In this research a set of CAT prediction parameters have been proposed to quantify the three-dimensional wind input severity (T_1), the aircraft response in linear transformation (T_2), and angular transformation (T_3).

$$T_1 = \sum_{i=1}^{3} \left| \frac{\dot{W}_i}{g} \right|$$
$$T_2 = \sum_{i=1}^{3} \left| \frac{\dot{V}_i}{g} \right| \quad (3)$$
$$T_3 = \sum_{i=1}^{3} \left| \frac{\dot{\omega}_i}{\overline{\dot{\omega}}_i} \right|$$

where W_i is turbulence wind velocity in different direction, V_i is aircraft flight velocity, $\overline{\dot{\omega}}$ is the mean value of all angular acceleration. The idea of these parameters is that we have to consider the atmospheric turbulence in all three directions, and include its response both in linear and angular motion. But what it matter the most is the force (acceleration) rather than momentum (velocity). Finally, we need to non-dimensionalize all these physical quantities. Result shown here are the T_1 parameter for three wind profile (Fig. 7-9), and aircraft's response T_2 and T_3 (Fig. 10,11).

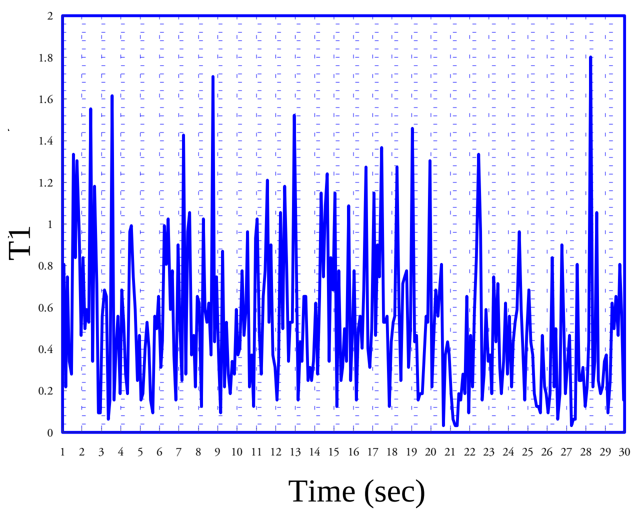

Fig.7 Real wind T_1 value

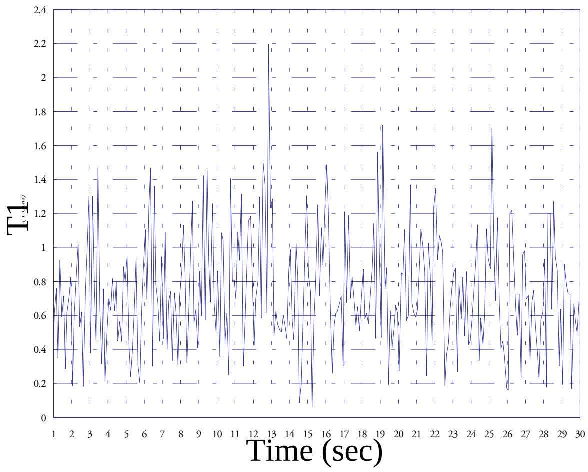

Fig.8 Inverse transformation wind T_1 value

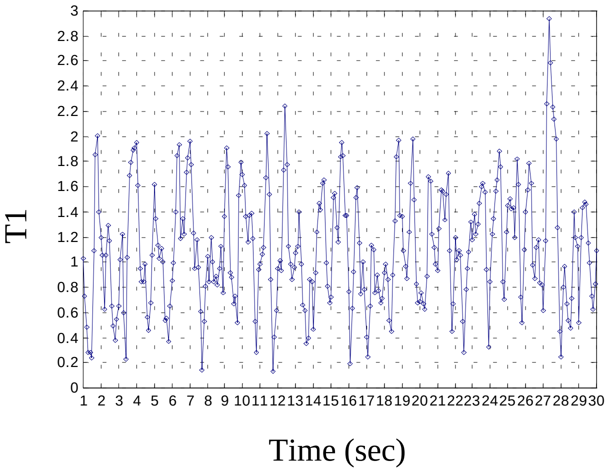

Fig.9 Matlab wind T_1 value

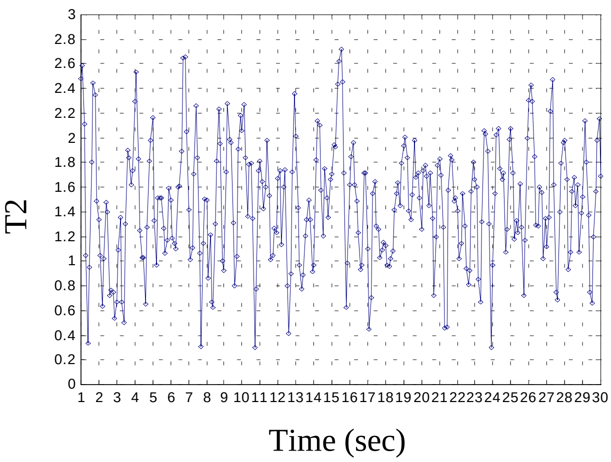

Fig.10 Matlab wind T_2 value

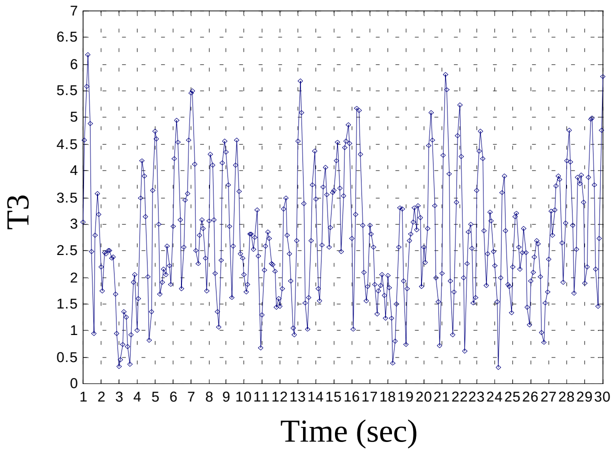

Fig.11 Matlab wind T_3 value

Again, the three T_1 parameters show excellent agreement, combine with the total T_2 and T_3 values, they can be employed to measure and to predict the detrimental effect of CAT on transport aircraft.

3 Flight Simulation

Assuming that the aircraft is a rigid body with flat-earth, mass and mass distribution are constant, and symmetry with respect to body axes' XY plane. After considering the thrust, gravitational force, aerodynamic forces & moments, the equations of motion become

Force:

$$\begin{aligned} \sum X &= m((\dot{u} + \dot{W}_X) + q(w + W_Z) - r(v + W_Y)) \\ \sum Y &= m((\dot{v} + \dot{W}_Y) + r(u + W_X) - p(w + W_Z)) \\ \sum Z &= m((\dot{w} + \dot{W}_Z) + p(v + W_Y) - q(u + W_X)) \end{aligned} \quad (4)$$

Moment:

$$\begin{aligned} \sum L &= \dot{P} I_X - \dot{R} I_{XZ} + QR(I_Z - I_Y) - PQI_{ZX} \\ \sum M &= \dot{Q} I_Y + PR(I_X - I_Z) - R^2 I_{XZ} + P^2 I_{XZ} \\ \sum N &= \dot{R} I_{XZ} - \dot{P} I_{XZ} + PQ(I_Y - I_X) + QRI_{ZX} \end{aligned} \quad (5)$$

Kinematic equations:

$$P = \dot{\Phi} - \dot{\Psi}\sin\Theta$$
$$Q = \dot{\Theta}\cos\Phi + \dot{\Psi}\cos\Theta\sin\Phi \qquad (6)$$
$$R = \dot{\Psi}\cos\Theta\cos\Phi - \dot{\Theta}\sin\Phi$$

Navigation equations:

$$\dot{X} = u\cos\Theta\cos\Psi + v(-\cos\Phi\sin\Psi + \sin\Phi\sin\Theta\cos\Psi) + w(\sin\Phi\sin\Psi + \cos\Phi\sin\Theta\cos\Psi) + W_{XE}$$
$$\dot{Y} = u\cos\Theta\sin\Psi + v(\cos\Phi\cos\Psi + \sin\Phi\sin\Theta\sin\Psi) + w(-\sin\Phi\cos\Psi + \cos\Phi\sin\Theta\sin\Psi) + W_{YE}$$
$$\dot{Z} = u\sin\Theta - v\sin\Phi\cos\Theta - w\cos\Phi\cos\Theta + W_{ZE} \qquad (7)$$

These set of equations represent twelve ODE as a function of time, and its rather nonlinear behavior can be solved by standard 4th order Runge-Kutta method.

4 Optimum Flight Trajectory

To solve the above twelve flight dynamics equations and achieve an optimum condition (trajectory) is rather a difficult task. After review the classical and modern optimal control methods, we select the genetic algorithm (GA) as the steering tool. This method is first proposed by Professor John Holland in 1975, and has been widely used in mechanical, electrical, information, and business optimal selection processes. The basic idea is to abstract and explain the adaptive processes of natural systems, and to implement the selection logic on some artificial system. GA has three different processes: reproduction, crossover, mutation, and use payoff information (objective function) rather than derivatives or other auxiliary knowledge. We first design our objective function according to our solution constraint, the higher the objective function value, generally the closer to the optimum solution. After the reproduction process in the mating pool, different species than go through the crossover and mutation processes to create the next generation species, and this will continue until the convergence criteria is satisfied.

There are two different kinds of GA method: discrete GA and real-valued GA. In our case we select the real-valued approach due to its computation efficiency and its similarity to the natural world. The reproduction process also contain some noise addition (bomb effect); and the crossover process will lead to the distance between two species become farther or nearer:

If $x_2 > x_1$,

$$\text{Nearer:} \quad \begin{cases} x_1' = x_1 + \sigma(x_2 - x_1) \\ x_2' = x_2 - \sigma(x_2 - x_1) \end{cases}$$
$$\text{Farther:} \quad \begin{cases} x_1' = x_1 + \sigma(x_1 - x_2) \\ x_2' = x_2 - \sigma(x_1 - x_2) \end{cases} \qquad (8)$$

where x_1, x_2 are first generation species before crossover, x_1', x_2' are second generation species after crossover, σ is randomly selected small real value.

Finally, the mutation process can be achieved by adding flexible amount of noise:

$$x = x \pm s \times random\_noise \qquad (9)$$

where s is the weighting factor to control the amount of noise.

The adjustment of objective function is through the use of linear scaling and power law scaling, and both can lead to farther distance of different species' objective functions.

5 Results and Discussion

The case we consider here is for a Boeing 747 transport cruising at 40000ft altitude with M=0.85 and turbulence last for 30sec. As mentioned before, the simulated wind profile seems reasonable and the T_1, T_2, T_3 parameters can be used to measure the severity of turbulence level (i.e. T_1>1.5 is very severe) and the response of aircraft in linear and angular motions. It is well known that same level of turbulence will have different effects on different sizes' aircraft, and only through the computation and consideration of T_2 and T_3, we can then fully appreciate the detrimental effect of CAT on aircraft flying quality. The larger value of T_3 is mainly due to the improper use of angular acceleration reference value $\bar{\dot{\omega}}$, and it is hoped that further improvement can be achieved if we change $\bar{\dot{\omega}}$ to the mean value of angular acceleration corresponding to T_2=1 cases (i.e. when $\dot{V}_i$ equals gravitational acceleration).

The GA process is implemented as follow: T_2 is assigned as the objective function, and four flight directions are put as initial species (right-0°, up-90°, left-180°, down-270°), crossover parameter is in between 0.01 to 1, mutation rate is about 0.01 to 5, and the convergence criteria is (1) summation of every trajectory's T_2 value is minimum; (2) the difference between all four "better" trajectories should always less than 0.001. We use Matlab as our GA computation tool, and after 113 iterations, the optimum trajectory can be found as follows:

Number	Search Parameter (Flight Direction)	Objective Function (T_2)
1	194.59206444	2.6686415456
2	189.94986616	2.6678045391
3	186.72217850	2.6677406429
4	191.36690202	2.6679667294

Table 1 Results of Generic Algorithm Search

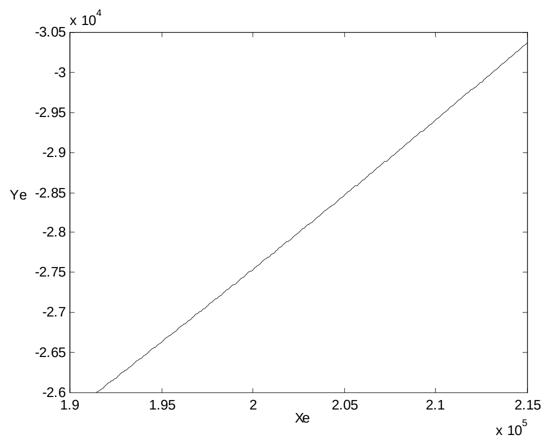

Fig.12 Optimum trajectory on XY plane

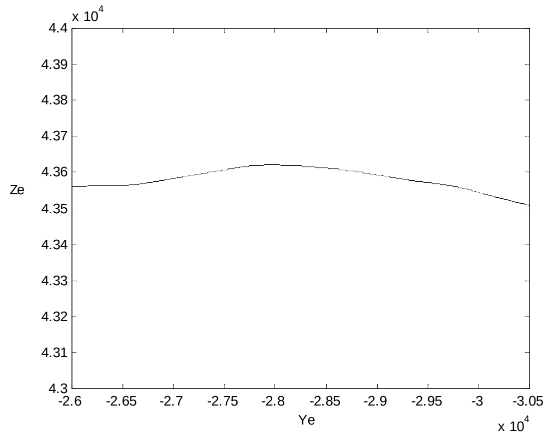

Fig.13 Optimum trajectory on YZ plane

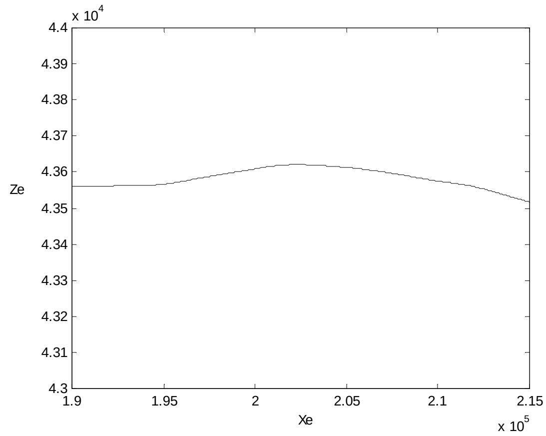

Fig.14 Optimum trajectory on XZ plane

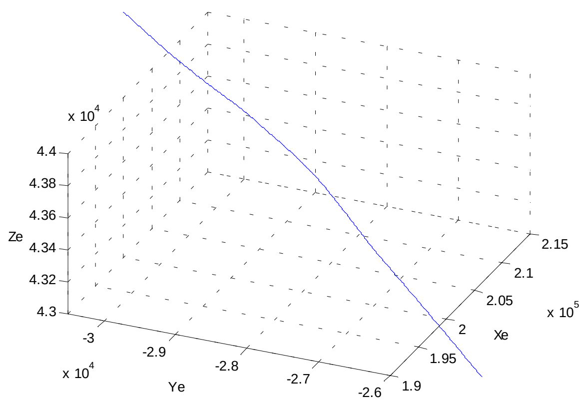

Fig.15 3-D optimum trajectory

It is shown that the optimum direction is 186.6722°, and represents that if the aircraft escape through the left direction, then the influence of CAT on its linear acceleration will be minimum.

Through the use of classical wind profile generation, newly created turbulence prediction parameters, flight dynamics solver, and the modern GA optimum search tool, we try to investigate the CAT influence on flight quality a little further. Future improvements can be accomplished as follow:

(1) T_3 angular acceleration reference value should change.

(2) Trim the aircraft for different condition or for a different aircraft.

(3) Try to use different search parameter such as acceleration escape direction, thrust level; and objective function could change to T_2/T_3 combination or minimum flight time.

(4) Existing experimental and/or computational data should be pursued and compared to justify our results.

Nevertheless, it is felt that the concepts proposed in this research might someday lead to the creation of next generation airborne Doppler radar, we can detect and calculate the influence of CAT, and automatically choose a safest trajectory to escape if necessary. If that come true, ride/flight quality will be greatly improved for passenger transport aircraft, and we no longer need to worry about clear air turbulence influence in our journey!

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