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Investigation on the Effect of Wind Turbulence in the Cruising Flight of an Airplane

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***Abstract* – The prime focus of this article is to compute the effect of atmospheric turbulence on the dynamic vibration frequency of an aircraft wing. Flutter is an unstable self – excited vibration in which the structure extracts energy from the outside airstream. It facilitates to build up the amplitude and often result in an unpredicted damage to structure can occur easily within few seconds. Aircraft wing structure is commonly flexible in nature and this flexibility of the airframe makes aeroelastic study as an important aspect of aircraft design. The displacement of wing against the oncoming flow field plays an important role in dynamic stability characteristics. To maintain the aircraft stability at high speeds, distance between the aerodynamic centre and the elastic axis of aircraft wing should be kept in minimum. An analytical procedure is developed based on Theodorsen method to forecast the speed and frequency at which the gust occurs. Scope of this article is to increase the dynamic stability of the aircraft at the impact of non-linear gust. The gust induced vibration is investigated by numerical simulation on a swept wing to eliminate or identify the flutter boundary.**

***Keywords* – Flutter, Theodorsen Method, Gust Response, Dynamic Response Analysis.**

I. Introduction

Modern airplane structures are flexible and this elasticity is inherently responsible for the various types of aeroelastic phenomena arise in the cruising flight segment [2]. Static aeroelastic phenomena contain the study of the relations between aerodynamic forces and elastic forces [10], [11], [12]. Gust load plays an important role in aircraft structural design as a variable dynamic load. The effects of gusts and that the gust components normal to the flight path was most effective in imposing loads on the airplane [6]. The basic gust load equations were formulated almost at the beginning of gust load studies, and it has continued to the present time. In the middle of 1930's, National Advisory Committee for Aeronautics (NACA) and various researchers, such as Theodorsen and Garrick [4, 9], were made few advances in this field. Theodorsen's theory of unsteady aerodynamics still remains an essential tool for aeroelastic analysis. The Sharp-Edge Gust (SEG) concept was introduced in the year of 1931 and it was a guide for the first gusts load regulation in 1934. After 1934, maneuver load factor for transport airplanes was reduced to the range of 2.5 to 4.0 *g* [6].

In 1952, research efforts did begin by NACA to apply the method of generalized harmonic analysis to aircraft gust loads. There are two main types of gust loads [12]; the discrete gust is solved in the time domain method and continuous turbulence gust (Fig.1) response is solved in the frequent domain method. In describing the atmospheric turbulence, a distinguished property of power spectrum for a gust velocity is used. To measure the quantity of resulting airplane dynamic elastic responses, power spectra approach is valid. Power spectral density (PSD) had been used to minimize the noise in the communications industry and telephone circuits.

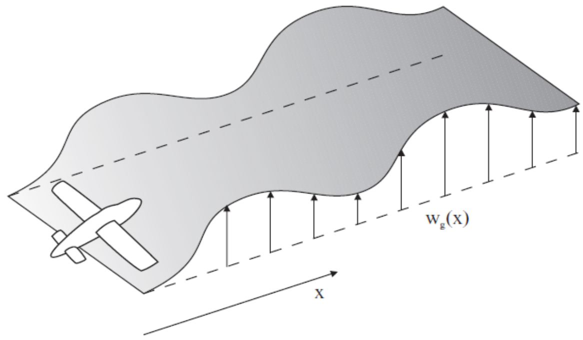

Fig.1. Continuous Turbulence gust

Nowadays, aircrafts are designed to be highly maneuverable in order to attain high-performance mission objectives increasingly. Aircraft design thoughts that take the advantage of wing elasticity to increase maneuverability have been examined systematically. Towards this purpose, aircraft designers adopt, flexible light-weight, high aspect ratio wings in modern aircrafts [8]. By twisting an aircraft wing structure, an aerodynamic moment can be produced to enable an aircraft to perform a maneuver using traditional control surfaces.

Limit-cycle oscillation (LCO) is appeared to be an aeroelastic motion with structural non-linearity. The LCO analysis is performed on a basic aeroelastic model by holding only two structural modes [1]. Aeroelastic instability and response of modern aircraft wings add up non-classical effects at subsonic flight speeds. The effects such as warping restraint, transverse shear and the 3-D strain effects are built-in the structural model.

A method is developed based on the Galerkin method to calculate the speed and frequency at which flutter phenomena occurs [3]. The Finite Element Method (FEM) incorporated for the structural model is a three Degrees of Freedom (DoF) cantilever beam. Here, one coordinate is linked to the vertical displacement and the other two are equivalent to bending and rotation.

Flutter invention method is more complicated but it has been simplified by the use of series of researches on different fundamental sections. Focus of this article is to develop a methodology for 3-D wing-flutter prediction with coupled fluid-structure interaction. The modal analysis is used to compute the structural response. It is helpful to reduce the flutter occurrence in a commercial aircraft by encountering the gust loads acting on an aircraft wing.

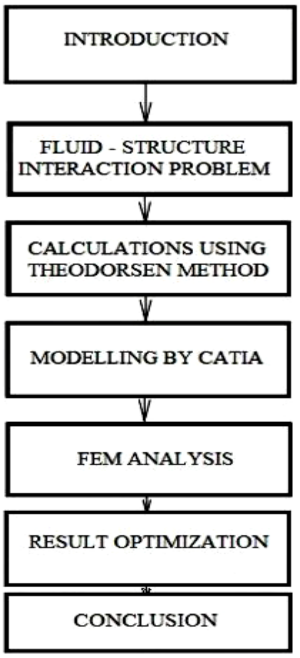

Fig.2. Flow chart for Problem description

II. Mathematical Model

A. Gust

In general, the wind gust is the maximum wind speed recorded over a specified time period. The wind speeds are calculated and the peak wind speed in the measuring period is approximately 10 knots more than the normal wind speed.

It is a well known fact that in the feature of air travel aircrafts regularly experience atmospheric turbulence with high degrees of severity. Turbulence may be considered as movement of the non-uniform air through which the aircraft passes.

Where the discrete gust velocity varies in a resolving manner, time and gain is in the form of an idealized discrete component that the aircraft encounters.

The continuous turbulence is assumed to vary in an unsystematic manner. The discrete gust response is worked out using the time domain method. The continuous turbulence response is normally determined in the frequency domain method.

B. Types of gust

(i) Sharp Edge gust (or) Step gust

The early work on gust response was considered the gust input to be in the form of a sharp-edged or step gust where the aircraft entered into a uniform gust velocity field defined spatially by

$$w_g(x_g)=\begin{cases}0, & x_g<0,\\ w_{g0,} & x_g\ge 0,\end{cases} \qquad (1)$$

(ii) '1-Cosine' gust

The expression governing the spatial behavior of the '1-cosine' gust, where the variation in the velocity of the air normal to the path of the aircraft is,

$$w_g(x_g)=\frac{w_{g0}}{2}\left(1-\cos\frac{2\pi x_g}{L_g}\right),\quad 0\le x_g\le L_g, \qquad (2)$$

Where x_g is the position of the aircraft in the spatial description of the gust relative to a convenient fixed origin, wg_0 is the value of the peak, or design, gust velocity and L_g is the gust length. The design gust velocity w_{go} varies with gust length, altitude and speed.

(iii) Continuous Turbulence gust

Continuous turbulence is represented by a random variation in velocity of the air normal to the flight path of the aircraft (Fig 3). A sinusoidal gust of amplitude wg_0 and wavelength λ_g, defined spatially by the expression,

$$w_g(x_g)=w_{g0}\sin\frac{2\pi x_g}{\lambda_g} \qquad (3)$$

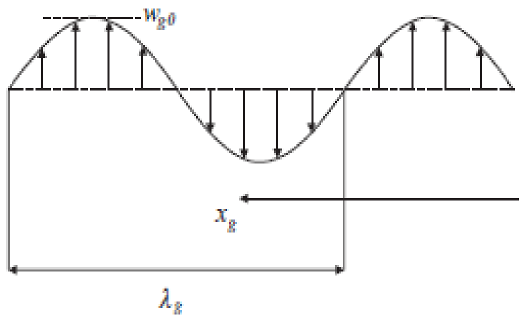

Fig.3. Sinusoidal gust representation

Since, the spatial variation of gust velocity at the wing is transformed into a temporal variation at frequency $\omega=\frac{2\pi V}{\lambda_g}$ rad/s,

$$w_g(t)=w_{g0}\sin\frac{2\pi V}{\lambda_g}t=w_{g0}\sin\omega t=w_{g0}\exp(i\omega t) \qquad (4)$$

C. Theodorsen's function

For flutter calculations, the general unsteady aerodynamic behavior in the time domain is rarely used. Since, the motion at a single oscillation frequency is of more interest, as the frequency increases, the unsteady force amplitude decreases and the phase lag changes. Further investigation shows that the amplitude attenuation and phase lag are a function of the dimensionless frequency parameter ν, defined as $\nu=\frac{\omega c}{V}$

This can be interpreted as the number of oscillations undergone by the aerofoil during the time taken for the airflow to travel across the chord of the aerofoil, multiplied by 2π. However, often the so-called *reduced frequency k* [12] is used.

$$k=\frac{\omega b}{V}=\frac{\omega c}{2V}=\frac{\nu}{2} \qquad (5)$$

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Theodorsen's function is used to model the changes in amplitude and phase of the sinusoidal unsteady aerodynamic forces relative to the quasi-steady forces for different reduced frequencies. The function behaves, effectively, as the Fourier transform of Wagner's function, and can be thought of as a filter that modifies the input to a system to give an output depending upon the reduced frequency. Theodorsen's function

C (k) = F (k) + i G (k) [11], where C (k) is a complex quantity, is expressed as a function of reduced frequency such that

$$C(k) = F(k) + iG(k) = \frac{H_1^{(2)}(k)}{H_1^{(2)}(k) + iH_0^{(2)}(k)} = \frac{K_1(ik)}{K_0(ik) + K_1(ik)} \quad (6)$$

Where K_j (I k) (j = 0, 1 . . .) terms are Bessel functions of the second kind and $H_n^{(2)}$ (k) are Hankel functions of the second kind. Although an explanation of Bessel and Hankel functions is beyond the scope of this article, these functions are included in many software libraries and are easy to calculate. Approximate expressions for C (k) have been found as

$$C(k) = 1 - \frac{0.165}{1 - \frac{0.045}{k}i} - \frac{0.335}{1 - \frac{0.30}{k}i}, \quad k \le 0.5, \quad (7)$$

$$C(k) = 1 - \frac{0.165}{1 - \frac{0.041}{k}i} - \frac{0.335}{1 - \frac{0.32}{k}i}, \quad k > 0.5 \quad (8)$$

When 'k' increases the magnitude decreases, and the phase lag increases up to a value of around k = 0.3 and then reduces again.

For the quasi-steady aerodynamics case then ω = 0, thus k = ν = 0 and hence F = 1 and G = 0, so the unsteady lift may be seen to tend towards the quasi-steady values. In the limit as $k \to \infty$, then F → 0.5 and G → 0, but typically for full size aircraft k has a maximum value of the order of unity.

III. Design and Analysis

A. Wing Model Geometry

The wing model is created with designing software is shown in Fig (4). The aerofoil used in this model is NACA 64-009.The wing model is shown below with dimensions. A specification for CATIA model is discussed in this section, for analysis NACA 64-009 is taken. Normally the mid-sized aircrafts use this airfoil. The semi-span of the wing is 28.2 m and sweep angle is 25 deg. The root chord and tip chord values are 6.4 m and 2.5 m. The mean Aerodynamic chord is placed at 6.75 m from the root chord. The taper ratio (λ) for this airfoil is 0.3906.

B. FEA Analysis

A Finite-element analysis package is used broadly in industry to simulate the response of physical systems to electromagnetic effects and thermal and structural loading. FEM tool uses to work out the basic governing equations and the related problem boundary conditions.

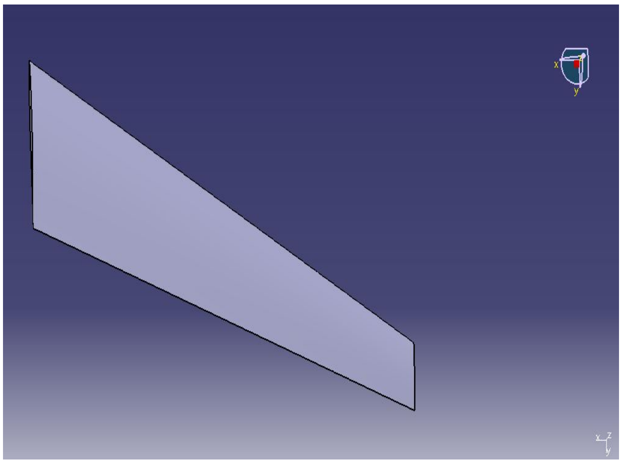

Fig.4. Wing model designed using CATIA tool

FEM is a numerical technique, well suited to the computer systems, which can be concerned to solve problems in heat transfer, solid and fluid mechanics. The procedure to solve problems in all of these fields is parallel; but this discussion will address on the application of finite element methods to problems of solid mechanics. In models, displacements in every element are directly linked to nodal displacements. The nodal displacements are related to the stresses and the strains in the elements. The finite element methods try to select the nodal displacements so that stresses in the models are in equilibrium with the applied loads. The nodal displacements should be constant with any constraints on motion of the structure model.

C. Theoretical analysis

Development in computer speed and memory, as well as advances in computer architectures, have allowed numerical model to be used more often to give support to the design process. These simulations are extremely useful; it must calculate quantitatively the features of the actual model under concern in both an economical and reliable manner. An aircraft is subjected to complex interactions between structures, aerodynamics, controls, and propulsion. Aeroelastic analysis plays a most important role in aircraft structural design. Flutter, Maneuver loads, gust response and LCO are the aeroelastic phenomena that measured in aircraft structural design and certification processes.

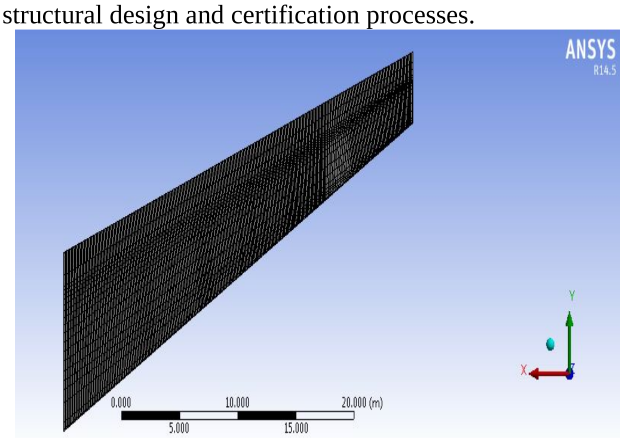

Fig.5. Meshed Model of the wing

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Aeroelastic analysis is based on the coupling of a structural dynamics model and an aerodynamic model. The structure is modeled by a finite-element model and the aerodynamic properties are modeled by a linear panel aerodynamic model. Linear aerodynamic tools are also limited in modeling complex geometries. The use of linear panel methods in aircraft structural design might result in a structure that is inadequate when subjected to the actual flight loads, often requiring significant structural redesign at a late stage of the design process.

Nearly 70 years ago, Theodorsen published, at the present famous details outlining, in detail, an analytical technique by which the flutter characters of airfoils with two or three degrees of freedom might be theoretically calculated. This development placed the groundwork for what has turn into a rich area of study in theoretical aero elasticity. In current work, Theodorsen function is used to calculate the flutter characteristics. Compute the natural frequency and frequency changes due to non linear gust load impact on aircraft wing.

IV. Results and Discussion

The lift load is acting on top of the aircraft wing. Wing is a cantilever beam, so DoF in root is arrested. The wing span is divided into five segments by finding the aerodynamic center. The load is acting in aerodynamic center.

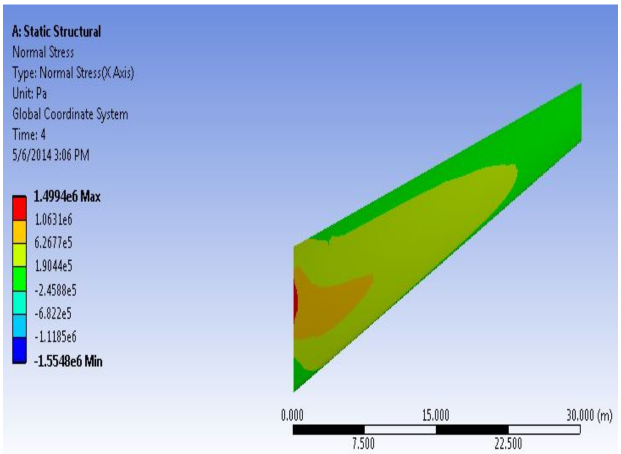

Fig.6. Stress distribution

The Fig (6) shows the stress distribution in an aircraft wing and the stress is highest at the root on the upper side. The graph gives an idea that the stress is linearly increasing. The Stress is validated by comparing the ultimate strength of the aluminum alloy material.

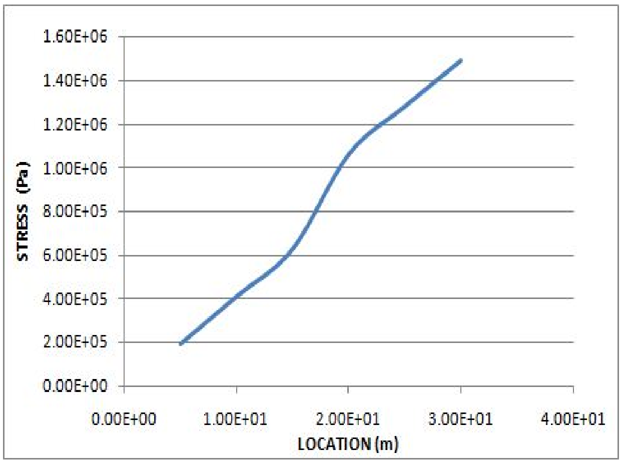

Fig.7. Stress Vs Location of a wing span

The graphical illustrations are used to compute the maximum and minimum deformations exist in the aircraft wing structure. The deformation is maximum in wing tip and minimum in wing root.

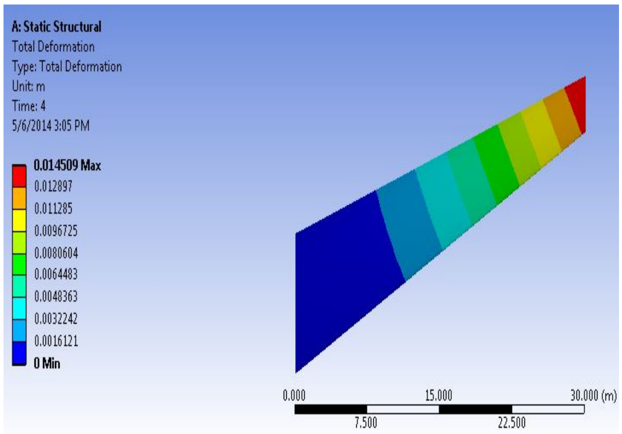

Fig.8. Total Deformation contour

By using different types mode shapes can find the natural frequency and frequency for an aircraft wing. The frequency plays an important role in aeroelasticity. There are five mode shapes shown here and discussed below,

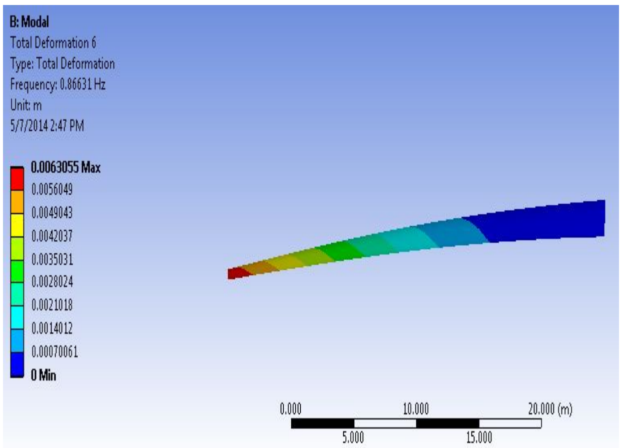

Fig.9. First Mode shape

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In fig (9) the first mode shape is displayed. The frequency of this mode shape is 0.866 Hz and the natural frequency also find. The deformation is small only compare to other mode shapes.

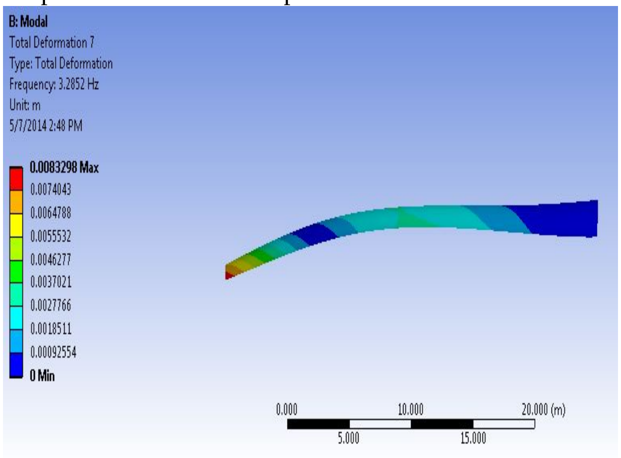

Fig.10. Second mode shape

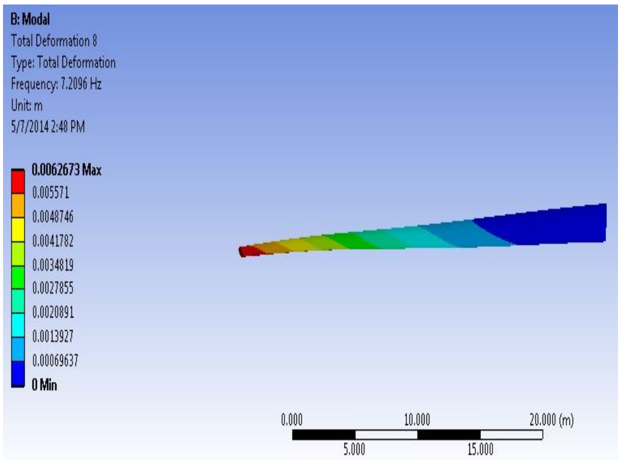

Fig.11. Third mode shape

The frequency in second mode shape is 3.28 Hz shown in fig (10). In the middle of wing structure has average deflection occur. The maximum deformation takes place in the tip chord of wing. In mode shapes; the frequency gradually increases because the loading point will varies. The frequency occurred in this mode shape is 7.3 Hz.

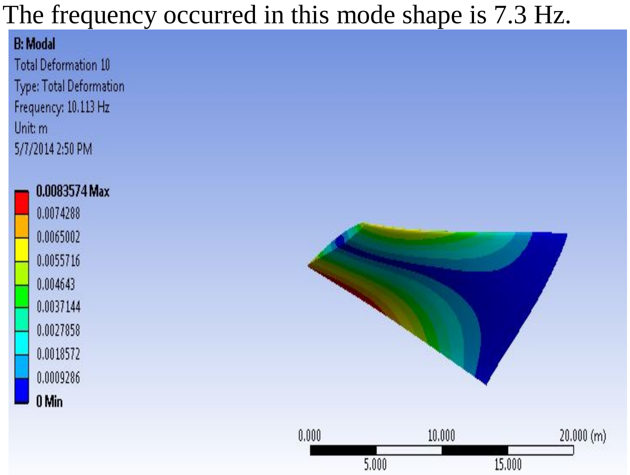

Fig.12. Fourth mode shape

When the frequency increases, it affects the wing structure by creating damages. As well as it depends on the material property also. In this Al is used for the structure. 10.1 Hz is obtained in the fourth mode shape.

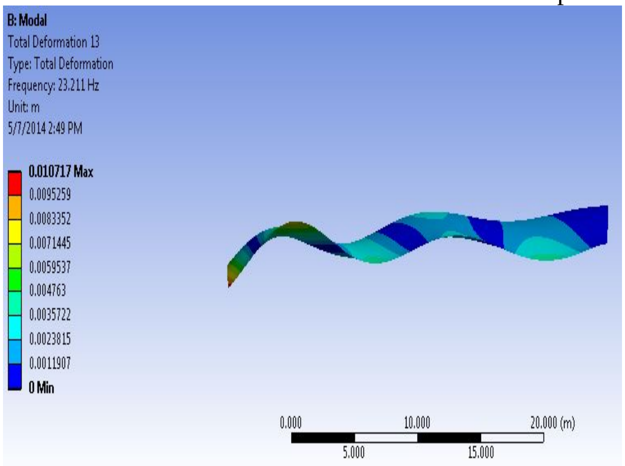

Fig.13. Fifth Mode Shape

The frequency is large compare to first mode shape, if frequency increases continuously creates severe damage in aircraft wing structure. The main purpose of finding the mode shape is to find the strength of the material through frequency. In a fluid-structure interaction analysis, the major area utilized by means of natural frequency. Frequency about 23.21 Hz is occurring in fifth mode shape. The modal frequency and natural frequency are obtained from FEM analysis.

V. Conclusions

A non-linear gust load is calculated and validated using the stress and deformation variation by FEM approach. The excitation frequency and natural frequency also calculated from different mode shapes. The frequency mode and stress variation was computed from the calculated load using FEM software and the model was developed in CATIA. For the given load an aircraft wing is optimized against the gust occurrence. In comparison with theoretical result, the obtained results are matched to the tapered wing. Therefore, flutter speed is rising from wing root to tip. So the displacement at wing tip is high compared to the wing root. This displacement variation brings on the severe instability of an aircraft.

Future work is to vary the loading conditions to find the stress and deformations in the wing structure. It is required to ensure the stability of an aircraft, which is subjected to the non-uniform turbulence forces.

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