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STRESS MAGNIFICATION ON THE CONTROL SURFACES DUE TO MANEUVER LOADS BY FINITE ELEMENT FORMULATION

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ABSTRACT

The interaction between a flexible structure and the surrounding fluid is a critical flow field to assess the structural and aerodynamic properties. In the present article, the influence of maneuver loads on the aeroelastic properties of the control surfaces are investigated by Finite Element formulation. The interaction among the structural and aerodynamic forces at various Angle of Attack will produce severe hinge moments. To study the fluid structure interaction phenomena, it requires the modeling of both fluid medium and structure coupled together. An efficient moving grid technique can be used to account for structural deformation in the robust coupled aero elastic model. Fluid-Structure Interaction governing equations are either loosely coupled or strongly coupled models. Here, the structural response lags behind the flow field solution because of the implementation of partly coupled technique. A doublet hybrid method is used to apply the aerodynamic forces in terms of the parameters involved in the Navier stokes equations. The wing model preferred is a flexible high aspect ratio wing that is applicable to a high altitude long endurance flight vehicle. For high Aspect Ratio wings, the geometrical deformation experienced by the structure is high and the computation process is time consuming. Therefore, a methodology to compute the maximum stress exerted by the maneuver loads is implemented through the Finite Element Approach. The control surfaces enhance the flutter suppression modes because of their different locations along the span and by producing required moments.

Keywords: Fluid –Structure Interaction, Aeroelastic stress, Control design, Maneuver loads.

1 .Introduction

Aeroelasticity is a multidisciplinary science dealing with the interactions of aerodynamic forces and structural deformations. As a structure moves through the stationary air, the motion will induce the aerodynamic loads that leading to deformations of the structure. The deformation in turn has a reactionary force on the airflow, thus changing the aerodynamic loading. Aerodynamic and structural interactions occur apparently depending on the physical properties of the structure. Aeroelastic analysis can be divided in two fields of study such as Static aeroelasticity and Dynamic aeroelasticity. Dynamic aeroelastic effects result from the interaction of the aerodynamic, elastic, and inertial forces. When an aircraft is subjected to dynamic instabilities, the interaction of the control system with aeroelasticity must also be considered. Accurate prediction of this phenomenon is complex, but the undesirable effects of aeroelasticity include airframe fatigue, loss of control, unacceptable vibration can be minimized up to certain extend. Therefore, it is most important to predict the aeroelastic characteristics accurately to prevent the aeroelastic instabilities such as control reversal and fatigue.

Several methods have been implemented in the past to predict the aeroelastic instabilities occurring in aircraft and few problems are sorted out by some unique techniques. In the previous studies, the harmonic balance method (exact formulation) and numerical simulation method are adopted with different fractional stiffness on the aeroelastic system. In the prediction of stable boundary, the results of these of methods are in good concord with the aeroelastic system. The change of friction stiffness has little influence on the stable boundary of the system. [1] The non-planar Vortex Lattice Method (VLM) could be used to solve the aeroelastic deformation with great accuracy. [2] Higher order panel method provides a more accurate static aeroelastic response analysis for the initial and detailed design stage of an aircraft. [3]The current work presents a framework to implement the unsteady VLM and how it can be improved for control system optimization. [4] Yang Ning has presented an iterative method for wave investigation with the authority of dynamic stiffness in incidence domain. [5] Nonlinear aeroelastic analysis for such a wing is carried out by using a loosely-coupled method. A non uniform Euler solver and a nonlinear CSD solver are fixed collectively by the 3-D integral constant level tetrahedron interfacing technique. [6] In this article, an attempt has been made to build up a method for high fidelity simulation of aircraft wing with flap combination. [8] The influence of control surface loads on the hinge moment parameters are quantified for a static aeroelastic phenomenon. The airfoil with control surface is prepared using CATIA design tool and the airfoil is prepared with the aluminum material the control surface is made of composite material (Graphite epoxy). To calculate the stresses produced on the Graphite epoxy material, the theoretical strength of Graphite epoxy is computed by MATLAB program. The wing with control surface is subjected to a fluid flow analysis to acquire the varying stress of the wing.

2. Static aeroelastic behavior of a two dimensional flexible airfoil

The aeroelastic problems arise mainly because of the insufficient torsional stiffness and non-uniform load distributions on the wings. Torsional divergence is a critical static aeroelastic phenomenon that is encountered at cruising flight. In this article, partially coupled method is utilized to attain the characteristics of aeroelastic wing divergence. The prediction is made by modelling a high aspect ratio aircraft wing, installed with a control surface (flap). Control surface is fixed with respect to the aerodynamic centre and it will be deflected downwards. It is designed to have up to 3^0 upward deflections to quantify the possibility of control operation at extreme conditions. The flap is designed along with an arbitrary wing using ANSYS and the material properties are assigned as graphite epoxy composite. Aerodynamic lift force distribution acting over a flexible wing that is fixed at the root will be considered for the stress analysis. The control surfaces are deflected against the rigid wing assumption to get the stress distribution at various initial conditions. It is then compared to a flexible wing with fixed control angles to identify the possibility of divergence speed enhancement. The static aeroelastic behavior is considered initially using an iterative approach and then a direct numerical approach.

Iterative Analysis

A 2-D rigid airfoil with unit span and chord 'c' is considered as symmetric with torsional spring of stiffness K_θ at a distance '*ec*' aft of the aerodynamic center on the quarter chord. The slope of lift curve is a_1 and the airfoil has an initial incidence of θ_0 , an elastic twist through angle θ due to the aerodynamic loading.

The lift force acting on the airfoil at the air speed 'V' and initial angle of incidence θ_0 causes a pitching moment of about the flexural axis.

$$M = qec^2 a_1 \theta_o \tag{1}$$

Where, '*q*' is the dynamic pressure. The equation of motion of 2-D airfoil is obtained using Lagrange's equations. Since, only static aeroelastic influences are being considered, the kinetic energy term is ignored. The potential energy '*U*' is found from the angle of twist of the torsional spring, namely

$$U = \frac{1}{2} K_\theta \theta^2 \tag{2}$$

The generalized moment is obtained from the incremental work done by the pitching moment acting through the incremental angle of incidence by Eq. (3),

$$Q_\theta = qec^2 a_1 \theta_0 \tag{3}$$

Then, the application of Lagrange's equation for coordinates θ gives,

$$\theta = \frac{qec^2 a_1 \theta_0}{K_\theta} \tag{4}$$

Thus, the initial aerodynamic loading is applied on the airfoil and it is twisted by angle θ. While doing this calculation it is assumed that the pitching moment is not being modified because of the wing twist. However, as a consequence of twist, the aerodynamic moment changes to allow the new angle of incidence. This new loading in turn causes the change in airfoil twist and again leading to further modification in the aerodynamic loading and so on. The stepping between applications of the aerodynamic load on the airfoil and changing the angle of twist illustrates the fundamental interaction between a flexible structure and aerodynamic forces that gives rise to aeroelastic phenomena.

First iteration

By repeating the above procedure, the updated elastic twist value in the pitching moment and work expression, leading to an infinite series expansion for the elastic twist in the form of Eq. (5).

$$\theta = qR\left[1 + qR + (qR)^2 + (qR)^3 + (qR)^4 + ...\right]\theta_0 \tag{5}$$

The Lagrange's equation gives a revised elastic angle of twist

$$\theta = qR(1 + qR)\theta_0 \tag{6}$$

If advanced static aeroelastic calculation involving the coupling of Computational Fluid Dynamics (CFD) with Finite Element Methods (FEM) is applied for an entire aircraft then it requires a partially coupled approach similar to the iterative process. If the mathematical model for aileron reversal problem is represented in terms of iterative process then it will be strictly static case. To obtain a convenient index for the aeroelastic characteristics of the wing, consider the lift coefficient and coefficient of moment about the aerodynamic centre is

$$C_l = a\alpha + \beta \frac{\partial C_l}{\partial \beta} \tag{7}$$

$$C_m = \beta \frac{\partial C_m}{\partial \beta} + C_{m_0} \tag{8}$$

The elastic moment induced by a rotation of the airfoil through an angle 'α' is α*k. Hence,

$$\alpha k = qc^2 (eC_l + \frac{\partial C_m}{\partial \beta} + C_{m_0}) = qc^2 (ea\alpha + e\beta \frac{\partial C_l}{\partial \beta} + \beta \frac{\partial C_m}{\partial \beta} + C_{m_0}) \tag{9}$$

Hence the reversal speed is

$$U_{rev} = (\frac{1}{a} \frac{\partial C_l}{\partial \beta})^{1/2} (\frac{2k}{\rho c^2})^{1/2} \tag{10}$$

Hence, the rate of change of lift due to aileron deflection is given by

$$\frac{dL^{'}}{d\beta} = \frac{qc[aqc^2 (e\frac{\partial C_l}{\partial \beta} + \frac{\partial C_m}{\partial \beta})]}{(k - qc^2 ea) + \frac{\partial C_l}{\partial \beta}} \tag{11}$$

This shows the mathematical model of the aileron reversal in two dimensional as similar to divergence problem.

3. Wing Model Design

A high aspect ratio wing model with control surfaces such as flap is designed using CATIA V5 with required dimensions as shown in Fig (1). The control surface is fixed at the hinge point at appropriate distances from the root and leading edge. Firstly the NACA airfoil (64- 009) coordinates are plotted and extruded to the specified span by the design tool. Cut sections are prepared about 25% of the chord to locate the flap or aileron control based on the iterative process involved.

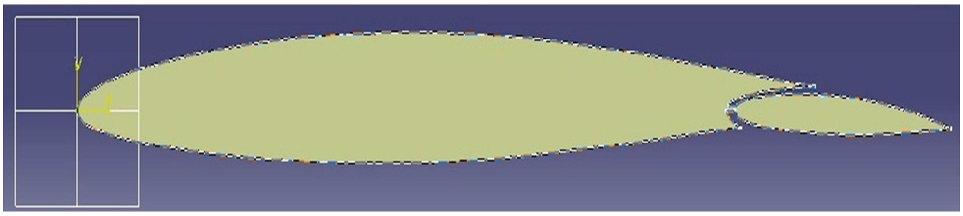

Fig (1). Airfoil with control surface at 3 degree deflection

Flap sections are designed separately using the NACA 0012 coordinate and then assembled with the wing occupying the space provided. To deflect the flap control, suitable hinge with appropriate length is fixed at about 25% of the cut section. The wing model is then imported to the analysis tool to carry out mesh and for applying the boundary conditions. Fig (1) is a sample image and all degree of control deflection is being taken into account in the current analysis.

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4. Results and Discussion

The FEM analysis is done for various flap deflections and the corresponding stresses, strains and deformations are evaluated. The results show the variation of these physical properties against each deflection angle of the control surface. A sample normal stress output for each control deflection angle is illustrated below. Fig (2) presents the normal stress distribution at 0^0 flap deflection case. Here, the maximum stress is produced about 2.5 MPa near the mid-chord location of the flap. The angle of incidence of the oncoming wing is the critical reason behind this finite stress build-up.

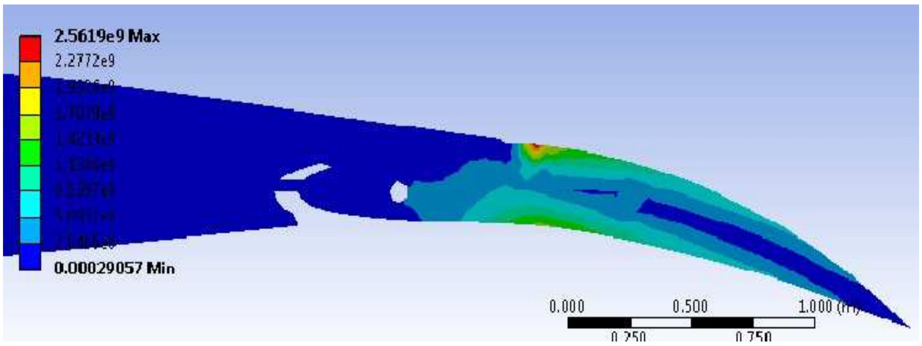

Fig (2). Stress at 0 deg flap deflection with 5^0 angle of incidence

The main wing airfoil is assigned with aluminium 2024-T3 alloy material properties. The main wing airfoil is meshed with coarse mesh and the control suface meshing is fine one. The stress regions of interest are meshed with adaptive mesh generation technique to quantify the spatial variation of stress at each angle of incidence.

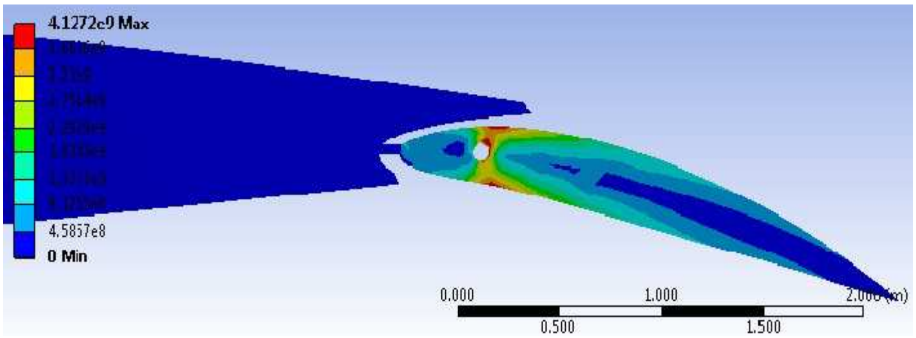

Fig (3). Stress at 3 deg flap deflection with 5^0 angle of incidence

The deformation profiles of the controls about its hinge also computed using ANSYS to ensure its rigidity at various aerodynamic pressures. All the stress levels are computed at 5^0 angle of incidence to give an insight about the influence of wind direction on the control stress. When the flap is deflected about 3 degrees the stress magnitude increases to 41.2 MPa. This is an expected result because the control is deflected downwards. A linear stress increment is observed from 1^0 and 2^0 control deflections which conveys the influence of control rotation. The applied pressure on the control surface is the ¾ th flap deflection load usually computed for its model selection. The corresponding strains are significant because of the varying atmospheric characteristics.

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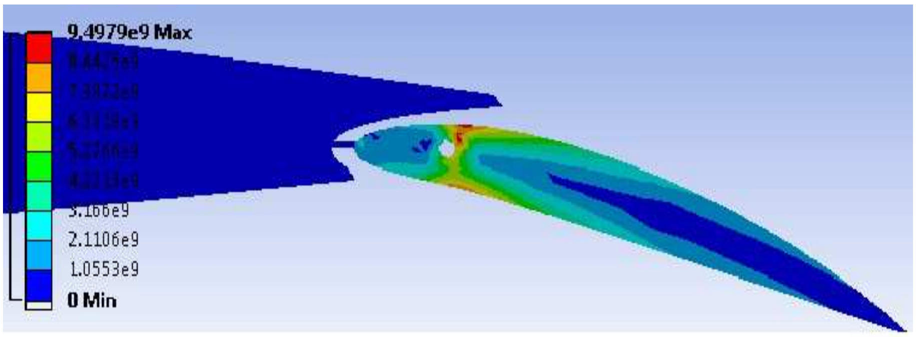

Fig (4). Normal stress at 6 deg flap deflection with 5^0 angle of incidence

At high angle of deflections the mesh is further refined since the load magnitude is very severe. For this iterative process, the model design and meshing is performed separately for each angle of deflection. It is a tedious process but the less computing power is sufficient to attain optimum solutions. At 6 deg flap deflection the stress level reaches 94.9 MPa. It is almost two times of the previous case and the stress concentration is very high near the hinge point. This result focuses the importance of aerodynamic balancing in the stability characteristics of any airplane at high cruising speeds.

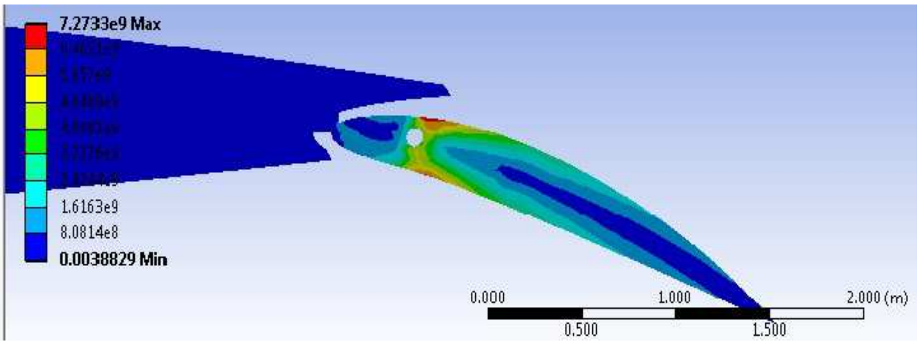

Fig (5). Normal stress at 9 deg flap deflection with 5^0 angle of incidence

S.No	Deflection angles	Stress values	Strain values ($\mu\varepsilon$)	Deformations (cm)
1	0 degree	25.619e9	0.016652	0.061675
2	3 degree	41.272e9	0.0268277	0.1969
3	6 degree	94.979e9	0.061732	0.43683
4	9 degree	72.733e9	0.33018	0.33018

Table (1). Results for stresses, strains and deformations

As the control surface is deflected about 9 degree and the main airfoil is fixed to the aerodynamic centre the stress level decreases (Fig 5). Because of the initialization of elastic rotation produced on the wing structure the resulting normal stress decreases. It reveals an important fact that the maximum control deflection can induce the elastic rotation in opposition the wind induced twist. However, for high aspect ratio wings it is

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difficult to incorporate this methodology because of its flexibility nature. However, for better maneuvering capabilities it is vital to assess the control loads to avoid the over balancing and loss of control.

5. CONCLUSIONS

In the present article, the influence of control surface loads on the static aeroelastic phenomena is discussed. Here, initially the aircraft wing with flap as control surface is modeled in CATIA using specific coordinates. Then the model is meshed with tetrahedral elements using ANSYS work bench. It is assumed that the arbitrary wing is said to be fixed and the flap is movable. The structural analysis is carried out at fixed Mach number and at fixed angle of incidence to quantify the control stresses. The airfoil designed using aluminum material to provide the practical insights about the implementation. Flap control is assigned with graphite epoxy material properties because of the high strength to weight ratio requirements. The aerodynamic pressure load is applied on the flap and corresponding stresses are evaluated at various chord points. Corresponding strains and deformations are computed for different angle of attacks to ensure the reliability of this approach. The stress value is kept in minimum while the flap is deflected about 0 degree compared to the other angles. The increased angle of incidence enhances the stress value and has significant influence on the aeroelastic wing divergence.

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