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The coupling mechanism and damage prediction of carbon fiber/epoxy composites exposed to lightning current

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ABSTRACT

Numerical implementation of carbon fiber/epoxy composites exposed to simulated lightning current is presented in order to elucidate coupling mechanism and damage prediction caused by a lightning strike. In order to accurately simulate lightning load, the coupling simulation of lightning electromagnetic fluid and composite plate is used to study lightning damage. Multivariate interpolation scheme for coupling procedure is necessary to transfer information of fluid-solid coupling interface. A complete set of computational models are established that contains magneto hydro dynamic (MHD) model, Structural finite element (FE) model and the corresponding interpolation procedure for non-matching mesh points. Different radial basis methods are discussed for interpolation scheme, which show that volume spline function has an advantage in terms of precision and efficiency for mesh points in this paper. Based on numerical results, damage mechanism of carbon fiber/epoxy composites is revealed and temperature dependency of electrical/thermal material parameters is assumed. According to numerical results of carbon fiber/epoxy composites and thermal decomposition behavior, the damage area and depth estimated from numerical results are predicted.

1. Introduction

Aircraft are struck by lightning in flight with some regularity and are required to have demonstrated protection against this threat. The aim of lightning protection is to avoid accident and increase aircraft safety after lightning strike [1]. Lightning analysis methods mainly include laboratory test and numerical simulation method at present. Recently, researchers have proposed some lightning damage models of composite materials combined with lightning test. Ogasawara [2] reported the coupled method of finite element (FE) simulation between electromagnetic and thermal behaviour when subject to lightning strike. Abdelal [3] introduced material parameters with the change of temperature such as char material properties to simulate material status after decomposition and gas material properties to simulate material ablation status. At the same time, complex physical characteristic of protection systems was modeled using UMATH material subroutine of Abaqus software. Chemartin [4] coupled Maxwell's equations and Navier-Stokes equations to simulate discharge process of lightning magnetic liquid, which presented some specific features of lightning arcs observed in flight or laboratory and direct effects of lightning on aircraft skins. Base on this method, Tholin [5] researched lightning swept process and its duration. However, Ogasawara uses a technique of applying electric arc load to a node that may produce inaccurate results. Explanation of a more accurate method to apply electric current is discussed later in this paper. Chemartin cannot analyze aircraft structure response of lightning strike due to lack of structure calculation domain. In order to study lightning strike accurately, it should be regarded as a multiple field coupling problem.

Lightning problem can be described as a coupled field formulation. Since fluid and structure show different mathematical and numerical properties, different numerical solvers and commercial analysis software are available. A conventional serial staggered (CSS) method has been applied to research fluid–structure interaction problems [6,7]. For lightning coupling problem, lightning channel and composite response modules are solved independently, in which different modules will exchange boundary information on contact interface in each time step. However, it requires different mesh type and density to solve each module with different physical field. How to deal with non-matching between different meshes becomes a key problem to resolve.

In this paper, CSS method to exchange boundary information is put forward for structure and liquid interface nodes in space. In recent years, physics theory and mathematical interpolation methods have been more abundant. Approximation methods based on radial basis have been caused for concern [8]. In this contribution, interpolation scheme use the globally supported radial basis function to build the coupling matrix, which can transfer structural response such as

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displacement and temperature, and lightning load such as lorentz force, lightning current and high temperature. Here, computational accuracy and time efficiency of different radial basis functions is compared in Section 4.1. In addition, most mesh interpolation schemes require node connection information and search algorithm, which will take up plenty of computer memory. Our approach will solve this problem and only need node coordinates without superposition.

For long electric arc columns and lightning channels, their motion appears chaotic and tortuous. Therefore, lightning channel can be considered as a long gap discharge. Discharge model of long gap is mainly related to resistive Magneto Hydro Dynamics (MHD) [9], in which motion of lightning plasma is driven by electromagnetic force and temperature gradient. Lightning load calculated by MHD method is passed to structural model through above interpolation procedure. The coupled thermal-electric characteristic of carbon fiber/epoxy composites is analyzed in structural model when exposed to lightning load [10–12]. Transient temperature distribution in composites is analyzed to illustrate damage behavior in Section 4.2.

In Section 2, the coupling field problem is formulated and a solving procedure is explained. The solving process is divided into three parts such as finite volume analysis (FVA) based on MHD theory provided from Fluent software, a multivariate interpolation program of radial basis function (RBF) method written through Matlab software, and finite element analysis (FEA) of the coupled structural-thermal-electrical behavior provided from Ansys software. Finally, the lightning damage mechanism of composite materials is discussed through numerical simulation.

2. Implementation of coupling for transient lightning strike calculation

Assumption is made that CFD and Ansys models already exist. The main coupling steps are summarized as follows. Platform extracts mesh information of coupling surface in fluid and structural model, calculating time is synchronized. In CFD model, temperature boundary of the coupling interface is set to room temperature and the coupling potential boundary is set to zero. Current, heat flow and force of coupling interface is obtained in order to interpolate to Ansys model. In Ansys model, the coupling boundary of the coupling interface is set to heat flow, current and force which are interpolated from CFD results through interpolation subroutine. Then Ansys ablation model is solved. Boundary information in CFD model is modified by profile files which contain temperature, displacement and potential distribution of coupling interface in Ansys model. Time steps and dynamic grids are updated. Iteration is repeated until the total calculation time is over.

The coupling calculation platform transfers data information and synchronizes between various software. Multivariate Interpolation subroutine based on RBF is written for non-matching mesh of coupling interface. This platform contains Ansys, Fluent and Matlab software. The operating environment is win7. Fig. 1 shows a flow chart of coupling calculation using Ansys and Fluent software.

2.1. Basic theory of MHD model

Lightning plasma was assumed to be in Local Thermodynamic Equilibrium (LTE) [9], so it can be described by a resistive Magneto Hydro Dynamics (MHD) model. Navier-Stokes equations and Maxwell's equations are coupled to simulate dynamic process of lightning plasma motion and extension. Momentum and energy conservation equations are modified by writing user-defined functions (UDF) and user-defined scalar (UDS) in fluid dynamics analysis software (Fluent ver.14.5, Ansys Inc.). Dynamics algorithm of Code Fluent solver is based on finite volume method which decomposes computing domain into discrete control volume in which convection diffusion Eq. (1) is solved. These convection diffusion equations can be written by

$$\frac{\partial \rho f}{\partial t} + \vec{\nabla}\cdot(\rho\vec{v}f) - \vec{\nabla}\cdot(\Gamma_f\vec{\nabla}f) = S_f \tag{1}$$

where ρ is fluid density, S_f is a source term and Γ_f is transport coefficient of f. MHD model combines current continuity equation with Maxwell-Ampere's law. In this model, Ohm's law (2) is simplified and only contains resistive term.

$$\vec{J} = \sigma\vec{E} \tag{2}$$

where $\vec{E}$, $\vec{J}$ and σ are electric field (V/m), current density (A/m^2) and electrical conductivity (S/m), respectively. Displacement current compared to diffusion current is assumed to be negligible due to current continuity. Movement of lightning channel is assumed to be slow enough that it can be seen as a static magnetic field. For this reason, dynamic electric field caused by self-induction phenomenon is neglected and electric field intensity is only related to electric potential ϕ.

$$\vec{E} = -\vec{\nabla}\phi \tag{3}$$

Current continuity can be expressed by diffusion equation related to electric potential, of which diffusion coefficient is conductivity and source term is zero. Current continuity equation is as follows.

$$-\vec{\nabla}\cdot(\sigma\vec{\nabla}\phi) = 0 \tag{4}$$

In the whole energy system, Joule heat $\vec{J}\cdot\vec{E}$ (W/m^3) is internal heat source and thermal radiation as a loss term corresponding to a net emission S_{rad} is defined in energy conservation equation. Joule heat generally plays a leading role to heat plasma. However, the net emission is more dominant in high energy regions. Net emission coefficients at atmospheric pressure have been taken from Naghizadeh-Kashani [13]. Energy conservation equation is written as

$$\frac{\partial \rho h}{\partial t} + \vec{\nabla}\rho h\vec{v} - \vec{\nabla}\cdot\frac{\lambda}{C_p}\vec{\nabla}h = \vec{J}\cdot\vec{E} - S_{rad} \tag{5}$$

where h, λ and C_p are enthalpy value, heat conductivity and specific heat capacity, respectively.

Magnetic field intensity B (T) and magnetic vector potential A (T m) are associated with

$$\vec{B} = \nabla\times\vec{A} \tag{6}$$

Magnetic vector potential is calculated using Maxwell-Ampere Eq. (7) expressed by current density J_i and vacuum permittivity μ_0.

$$-\vec{\nabla}\cdot(\vec{\nabla}A_i) = \mu_0 J_i \tag{7}$$

Lorentz force is the only source term in momentum equation.

$$\frac{\partial \rho\vec{v}}{\partial t} + \vec{\nabla}\cdot(\rho\vec{v}\times\vec{v}) = -\vec{\nabla}p + \vec{\nabla}\cdot\tau + \vec{J}\times\vec{B} \tag{8}$$

where p and τ are pressure and shear stress tensor, respectively.

In the above equation, enthalpy value, heat conductivity, specific heat capacity and density change with gas temperature and pressure. Thermodynamic properties and transport coefficient in range of wide temperature and pressure have been taken from Angola and Colonna [14].

2.2. Basic theory of fluid-structure interaction

The coupled nonlinear lightning problem is solved by a series of conventional serial staggered procedures (CSS) illustrated in Fig. 2, which allow MHD equations and electrical-thermal-structural equations to be solved by each different solver and update boundary information on interface. The coupling between multi-physical fields in this numerical calculation is very complex. Electromagnetic-thermal effect of magnetic fluid influences structural thermal response, which includes structural deformation and surface heating to change boundary conditions in fluid domain. Data exchange occurs at each time increment.